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PROBABILISTICS AND SENSITIVITY OF AIR POLLUTION EXPOSURE TO STUDENTS IN INDUSTRIAL AREA

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ABSTRACT

Background: Air pollution is responsible for significant global morbidity and mortality. Industrial areas are a major source of air pollution due to various activities such as coal combustion, vehicle movement, and particle emissions from raw material processing. Children attending schools near industrial areas are more vulnerable to the impacts of air pollution because their activities in the school environment increase their exposure to pollutants.

Objective: To determine the probabilistic simulation and sensitivity of air pollution exposure to students in industrial areas using Monte Carlo simulation.

Method: The method used in this study is a literature review. Data collection was carried out through online database searches such as: Pubmed and Science Direct . The keywords used in the article search were "Air pollution", "Effects of air pollution on children's health", "Air pollution in industrial areas" and "Monte Carlo simulation". The inclusion criteria for quantitative and qualitative research types, the target population is air pollutants with ambient air parameters, published in the last 5 years (2020-2024) articles using English and articles in original, full-text and open access form. The exclusion criteria were articles that were not relevant to the topic of discussion.

Results: Exposure to air pollution from industrial areas around schools increases the risk of impaired lung function, respiratory symptoms, and cognitive impairment in children.

Conclusion: Strict environmental mitigation and management efforts are needed to protect students' health from the long-term impacts of industrial air pollution.

Keywords: Air Pollution, Students, Respiratory Diseases, Industry

INTRODUCTION

Air pollution is a significant contributor to global morbidity and mortality (Vonk & Roukema, 2022). There are many pollutants in the atmosphere, such as sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), particulate matter 2.5 ($PM_{2.5}$), and particulate matter 10 (PM_{10}), which are mostly caused by industrial activities (Lin et al., 2022). Industries identified as potential sources of $PM_{2.5}$ include the iron and steel sector, cement manufacturing, petrochemical production, paper and pulp industry, flour milling, textiles, asbestos production, insecticide manufacturing, and electronics fabrication (Mallongi et al., 2021). In addition to industrial activities and vehicle mobility, daily activities such as smoking, household activities and cooking also contribute to the production of CO, NOx, and readily detectable organic compounds (VOCs) (Maung et al., 2022). Some specific pollutants have detrimental effects on human health such as, ischemic heart disease, stroke, chronic obstructive pulmonary disease, asthma, lung carcinoma, and acute respiratory infections (Tiotiu et al., 2020).

It is generally explained that exposure to air pollution has negative effects on human health, including an increased risk of death and morbidity from respiratory diseases such as asthma and respiratory infections (Yang et al., 2021). People with existing health conditions, such as the elderly, people with chronic diseases, and children, are more susceptible to serious complications from air pollution (Wang et al., 2024). Among the groups most at risk are children, because their respiratory systems are still developing and are more sensitive to harmful substances in the air (Garcia et al., 2021). Therefore, on days with high levels of air pollution, children, who are the most vulnerable population, are expected to avoid outdoor activities, travel by public transportation, or stay at home to minimize the risk of exposure (Yu & Zhang, 2023).

Based on data from the World Health Organization , it is reported that 1.8 billion children worldwide breathe polluted air and it has been linked to adverse effects on their health and physical development, such as respiratory diseases such as asthma and acute respiratory infections (WHO, 2021). Asthma is one of the main respiratory diseases. This disease is also the most common non-communicable disease in children and causes a huge economic and disease burden worldwide. Asthma is estimated to affect around 14% of children worldwide, with the reported prevalence continuing to increase (Tian et al., 2024).

Industrial areas are a major source of air pollution due to various activities such as coal combustion, vehicle mobilization, and particle emissions from raw material processing activities. Children who attend schools around industrial areas are more vulnerable to the impacts of air pollution because their activities in the school environment increase their exposure to pollutants (Shen et al., 2021). Physical activities such as running and exercising increase the respiratory rate, causing children to inhale more pollutants than when they are at rest (Castagna et al., 2022). Continuous exposure to pollution during school activities can trigger respiratory disorders such as coughing, shortness of breath, and decreased concentration in learning due to the irritating effects on the respiratory system (Roche et al., 2024).

Air pollutants with a size of less than 5 μm can enter the alveoli of the lungs and settle there. Meanwhile, particles with a size of more than 5 μm can interfere with the upper respiratory tract and can cause eye irritation. The main route of exposure to pollutants to the human body is through breathing (Xu et al., 2016). Pollutants are easily soluble in water so they can be absorbed in the nose and mostly enter the respiratory tract. Small sulfate particles can penetrate to the alveoli of the lungs and other narrow areas. SO2 pollutants $_{can}$ cause irritation to the respiratory tract by causing swelling of the mucous membranes, as well as obstructing airflow in the respiratory tract. In addition to breathing, pollutants, especially SO2 gas, $_{can}$ penetrate the human body through the skin and eyes, especially in humid environmental conditions. Symptoms of irritation that can occur include a feeling of (Zhang et al., 2021).

Several previous studies have highlighted the impact of air pollution on the respiratory health of children living and attending school near industrial areas. A study conducted in New Mexico showed that children living near industrial areas had a higher risk of developing lung disease and experiencing low birth weight (LBW) due to inhalation of emissions from factory chimneys (Gong et al., 2023). Furthermore, another study showed high concentrations of NO_2 , $PM_{2.5}$, and $PM_{10\ exposure}$ in residential areas near industrial areas in Viadana, Italy. This suggests that people living near industrial areas are exposed to a mixture of air pollutants (Marcon et al., 2021a).

Theoretically, to identify the level of pollution and distribution of air emissions, a form of modeling is required. Efforts to prevent heavy metal pollution require a health risk assessment using a Monte Carlo simulation model. This modeling allows for the estimation of a value based on the distribution of sample data (Mallongi & Ernyasih, 2023). The application of this model is expected to reduce the amount of air emissions, thereby preventing or minimizing the negative impacts of air pollution on human health and the environment.

Based on the negative impact of air pollution on the respiratory health of these students and the existence of previous research on pollutants in the air contaminated by various types of pollutants in the air. For this reason, research based on literature studies is needed related to " **Probabilistic and Sensitivity of Air Pollution Exposure to Student Health in Industrial Areas** " so that it can be a recommendation for improvement and further evaluation for companies and governments, related to efforts to reduce sources of exposure and the impacts that may arise.

METHOD

The method used in writing this article is a literature review, which involves examining a number of international scientific articles. The primary sources used are online journal databases that provide articles in PDF format, such as PubMed and Science Direct from Elsevier . To ensure the information obtained remains relevant and up-to-date, the literature analyzed primarily comes from publications within the last five years, namely between 2021 and 2025.

There are 15 articles that meet the inclusion criteria, namely: 1) quantitative and qualitative research types and other relevant research; 2) the target population is air pollutants with ambient air parameters; 3) published between 2020-

2025; 4) Using English-language articles; and 5) Articles in full text form . The following word combinations used in search : " Air Pollution ", " Impact of Air Pollution AND humans AND air ", " Impact of exposure from industrial AND air AND the environment", "Risk analysis due to air pollution exposure on humans",, "Impact air pollution AND children AND air", "Impact air pollution AND school AND air ", and "Monte Carlo Simulation ". The following is a prism diagram filtering literature presented in Figure 1:

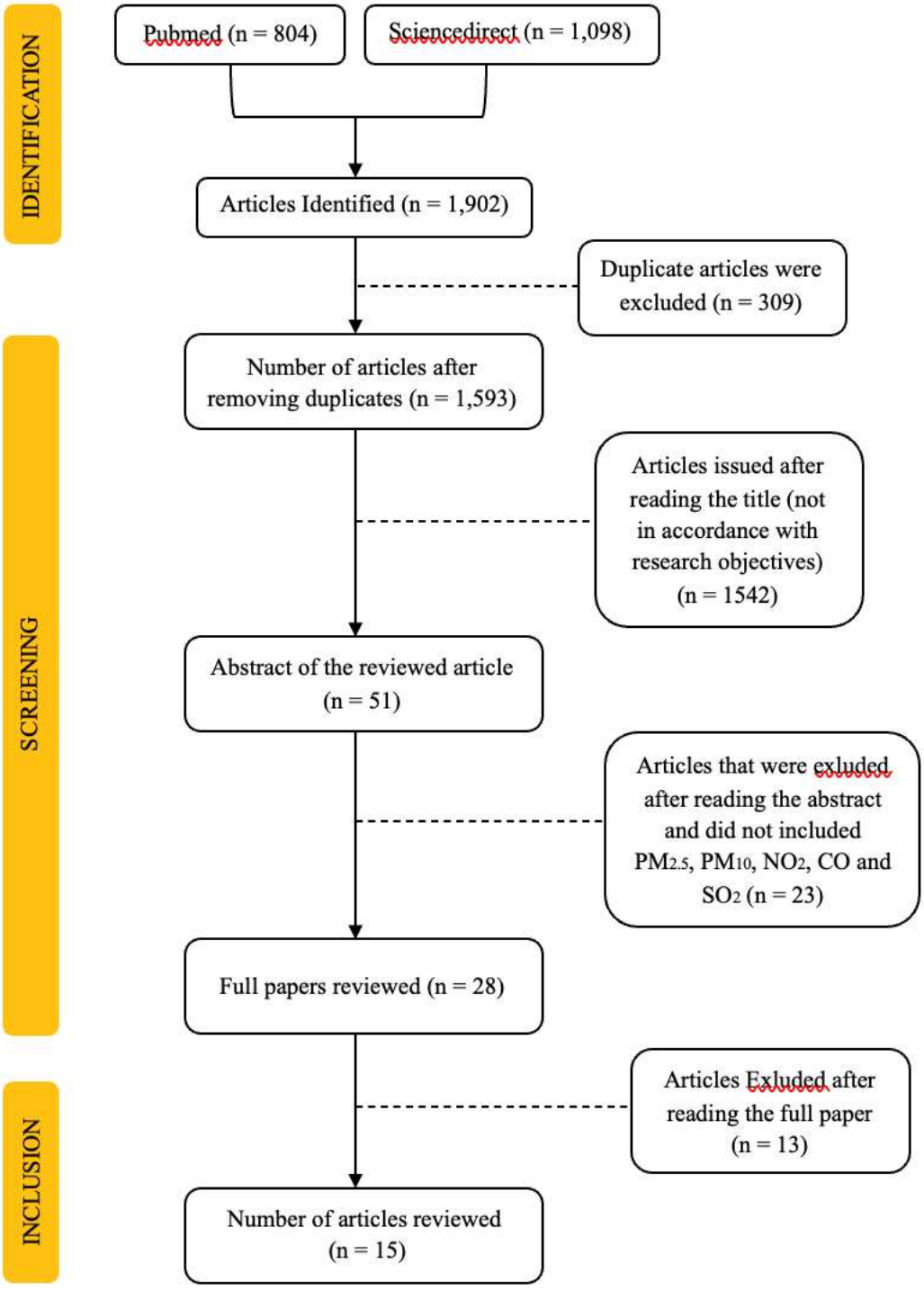

Figure 1. Prisma Study Flow Diagram

RESULTS AND DISCUSSION

Based on results of literature review on 15 articles , author get results that in pollution air cause health problems breathing especially for students who attend school around area industry . The articles analyzed own theme main , such as " Disease breathing and disorders function lungs in students consequence pollution air ", "The process of spreading pollutants in schools around area industry ", " analysis risk health pollution air on students " and " Monte Carlo Simulation Results on exposure pollution air in students ". Presented in the following table:

Table 1. Respiratory Diseases/Lung Function Disorders in Students Due to Air Pollution

No.	Title	Study Design	Results	Disease	Source
1	Impact of industrial pollution on children's lungs: A comparative analysis of pulmonary function in critically polluted and non-polluted areas in western India	Cross-sectional with group control	Decline function lungs students in industrial areas (FEF 25–75% decreased by 530 ml; FEV1/FVC decreased by 3.9%) compared to non- polluting areas	Lung dysfunction, respiratory disease due to industrial pollution	(Kashyap et al., 2023)
2	Impact of air pollution on educational attainment for respiratory health treated students: A cross sectional data linkage study	Cross-sectional data linkage	Increase in NO_2 (10 μ g/m³), decrease in student exam scores by 0.044 z-score. Effect significant especially for students without asthma /SAR.	Asthma, SAR (Seasonal Allergic Rhinitis), respiratory disorders cognitive consequence pollution air	(Mizen et al., 2020)
3	Association between ambient air pollution and childhood respiratory diseases in low- and middle-income Asian countries: A systematic review	Systematic review 41 studies observational)	$PM_{2.5}$, PM_{10}, NO_2, SO_2, CO and O_3 improvement significant risk disease children's respiratory tract (infection , asthma , bronchitis).	Upper respiratory tract disease, lung infection, asthma	(Ibrahim et al., 2021)
4	Industrial outdoor pollution and humans health: a systematic review and meta-analysis	Systematic Review and Meta- Analysis from 30 studies (23 cross-sectional, 7 panel)	Exposure smell from source industry increase risk symptom breathing like cough and phlegm (OR = 1.27; 95% CI: 1.10–1.44), especially in the community near factory or farm intensive .	Symptom breathing down (cough) chronic , asthma , disorders function lungs), with more effects strong in children age school that remains near facility industry .	(Guadalupe-Fernandez et al., 2021)

Pollution air has in a way consistent identified as factor significant risk For development disturbance health breathing in children age school . Exposure contaminants environment such as $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3 play role important in emergence various disease breathing , including asthma , bronchitis , infection channel breathing part above , and disturbance function lungs (Li et al., 2024).

Students who live and attend school in the marked areas with improvement level pollution air , especially in the area industry , shows greater vulnerability big to decline capacity lungs , difficulty breathing and disease channel breathing chronic (Rastegar et al., 2024). Consequence from pollution air beyond health physically , in terms of significant influence quality life child in a way as a whole , including disturbance in the educational process Because increasing absence and reduction concentration . Empirical evidence from a series study show that disturbance breathing in children age school No only temporary but can give influence Long term on growth , development lungs , and problems health chronic in adulthood . As a result , pollution air must considered as threat critical for health children in need attention urge in policy health and education , especially about action prevention and intervention early in environment academic .

In short , the findings from fourth studies This underline statement that children is the most vulnerable demographic to effect bad pollution air , which manifests No only through challenge health related physical with condition lungs and breathing but also through effect detrimental to function cognitive and developmental academic (Chang et al., 2023). Therefore that , initiative proactive like improvement quality air near school , monitoring health lungs in a way regular , and implementation policy zoning environment clean has become important For protect generation upcoming from risk long - lasting health .

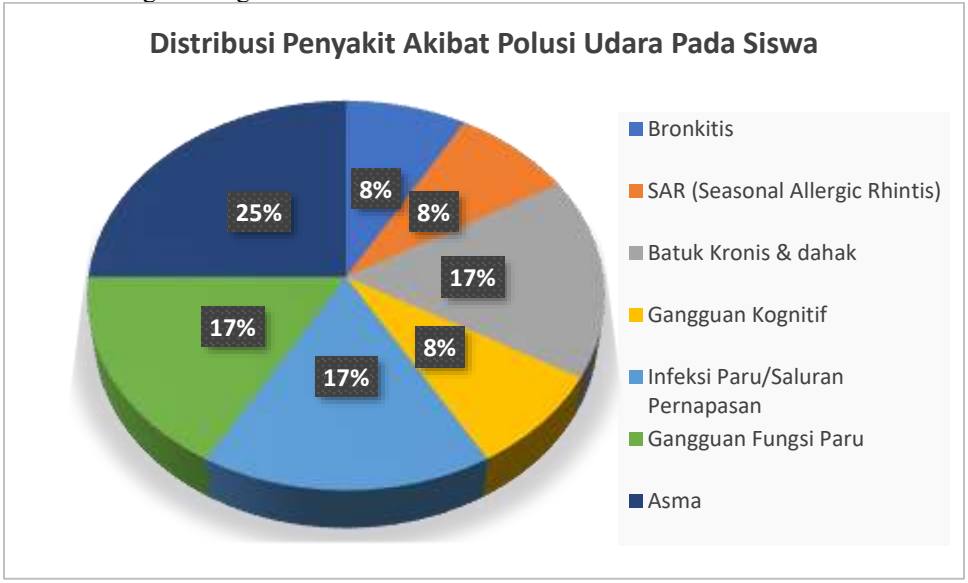

Figure 1. Distribution of Diseases Caused by Air Pollution Among Students in Industrial Areas

The diagram shows that asthma is the disease with the largest prevalence, accounting for 25%. This observation suggests that asthma represents the most significant effect of air pollution exposure on students' health. Asthma is classified as a chronic respiratory condition that indicates a high sensitivity to pollutants such as $PM_{2.5}$, which are prevalent in environments characterized by elevated levels of air pollution. In addition to asthma, chronic cough and phlegm, respiratory infections, and impaired lung function each account for 17% of the overall disease distribution. These three conditions typically arise as a consequence of irritation and inflammation of the respiratory tract, triggered by prolonged exposure to emissions from industrial activities and vehicular sources. Together, bronchitis, Seasonal Allergic Rhinitis (SAR), and cognitive impairment each account for 8% of the overall prevalence. Despite their lower prevalence, these conditions still show a significant correlation with poor air quality. The findings regarding cognitive impairment are particularly important, as they indicate that air pollution not only affects the respiratory system but can also compromise cognitive function and affect students' academic performance.

Table 2. Distribution of Pollutants in Schools around Industrial Areas

No.	Title	Distribution Process	Existence	Source
1	Low-cost sensor-based investigation of CO_2 and volatile organic compounds	CO_2 pollutants increase drastic during school hours consequence activity students and ventilation poor ventilation mechanic reduce	CO_2 detected increase drastic moment class ongoing ; source originate from activity students and materials building ;	(Sørensen & Kristensen, 2024)

No.	Title	Distribution Process	Existence	Source
	in classrooms: Exploring dynamics, ventilation effects and perceived air quality relations	concentration compared to ventilation experience .	ventilation bad cause accumulation daily .	
2	A review of relevant parameters for assessing indoor air quality in educational facilities	Spread pollutant influenced by location building (near road / industry), ventilation that is not adequate , and activities the triggering resident release particles and gases to air in class .	$PM_{2.5}$, PM_{10} , NO_2, O_3, CO, and VOCs come from from outside (then across , industry) and within (activities students , furniture , materials cleaner); concentration varies depends location and type room .	(Branco et al., 2024)
3	Evaluation of Different Natural Ventilation Strategies by Monitoring the Indoor Air Quality Using CO_2 Sensors	CO_2 concentrations rise rapidly in the classroom with ventilation bad and many students ; effectiveness ventilation experience depends duration open windows / doors and density room .	CO_2 increases along amount students and activities physical ; ventilation experience No always effective ; time pause and opening window influence level accumulation of CO_2 in class .	(Sánchez-Fernández et al., 2023)
4	Spatial variability of nitrogen dioxide and formaldehyde and residential exposure of children in the industrial area of Viadana, Northern Italy	NO_2 is emitted strongly from wood-burning industry chimneys and waste incineration; formaldehyde from particleboard resins. Higher concentrations are found within a radius of <1.7 km from the industry, forming hot spots around the factories.	Annual NO_2 concentrations reached 26.9 µg/m³ and formaldehyde up to 2.2 µg/m³ in the immediate area of the factory. Children within a radius of <1.7 km experienced exposure more tall compared to those who live	(Marcon et al., 2021b)

Fourth journal scientific in a way simultaneously show that distribution pollutant air in school happen in a way active Because interaction activity students , design schools and systems ventilation (Rawat & Kumar, 2024). During school hours , the level of CO_2 and VOCs concentrations indicate quite an improvement large amount caused by the increase metabolism students , density room , as well as activity like breathing , talking , and moving all of which produce gas emissions . Improper ventilation adequate , good consequence window closed or system mechanical that is not function , prevent expenditure pollutants , culminating in the accumulation pollutants that have an impact poor in quality air in room .

Particulate matter , including PM_{10} and $PM_{2.5}$, can also penetrate from environment external to in infrastructure schools , especially near road highway or area industry (Buchholz et al., 2021). Particles This enter to room class through gap or moment ventilation experience opened , so that make things worse quality air in institutions education . Research more carry on has set that efficacy mitigation pollutant in a way significant influenced by the type ventilation used , with ventilation cross and system mechanical proven Far more effective than only open One window or door (Cabovská et al., 2022).

In conclusion that distribution pollutants inside institution education No solely consequence from source external ; a number of large is also produced internally , is greatly influenced by the effectiveness ventilation , activities students , and characteristics architecture buildings . As a result , interventions aimed at For increase quality air inside room class must adopt approach comprehensive which includes factors This For grow atmosphere healthy and conducive learning .

Table 3. Analysis Health Risks of Air Pollution for Students

No.	Title	Results	Existence	Source
1	Effect of ambient air PM $_{2.5}$ -bound heavy metals on blood metal(loid)s and children's asthma and allergy pro-inflammatory (IgE , IL-4 and IL-13) biomarkers	Exposure metal heavy (As, Cr, Hg, Pb) in PM $_{2.5}$ is related with increased biomarkers of allergy and asthma in children , suggesting activation system pro - inflammatory immune system breathing .	PM $_{2.5}$ in industrial areas tall content metal heavy (As, Cr, Hg, Pb); exposure through breathing cause improvement level metal in blood children .	(Zahedi et al., 2021)
2	Air pollution and cortical myelin T1w/T2w ratio estimates in school-aged children from the ABCD and NeuroSmog studies.	Exposure to PM and NO $_2$ potential bother development brain children , especially the myelination process nerves , although findings between location Not yet consistent in a way statistics .	Exposure term long against PM $_{10}$ and NO $_2$ in the environment city influence structure brain children , especially in areas with concentration tall particles .	(Szwed et al., 2025)
3	An application of low-cost sensors to monitor children's exposure to air pollution at five schools in Queensland, Australia	Exposure to PM $_{2.5}$ and CO in the environment school show risk significant health especially from source local (such as fire bushes & dust), with potential influence function lungs and cognition .	PM $_{2.5}$ and CO were detected in the school area. with contribution significant from source local (fire) bushes , dust land); exposure level varies between location school .	(Pradhan et al., 2024)
4	Urban environment and children's health: An umbrella review of exposure response functions for health impact assessment	PM $_{2.5}$, PM $_{10}$, NO $_2$ proven significant increase risk disturbance breathing , birth premature , low birth weight low , and asthma ; used as a basis for Health Impact Assessment (HIA) of children in urban environments .	Concentration of PM $_{2.5}$, PM $_{10}$, NO $_2$ recorded high in urban areas and industry ; meta- analysis study show connection consistent between exposure and disturbance health child .	(Wies et al., 2024)

Fourth researched journals give description comprehensive about danger related health with pollution air For children age schools , which include aspect from function immunity and health neurological until problem breathing and development overall .

Exposure to particulates fine (PM $_{2.5}$) and metal heavy like arsenic (As), chromium (Cr), mercury (Hg), and lead (Pb) can trigger activation of pro- inflammatory biomarkers , such as improvement concentration IgE , IL-4, and IL-13, which are involved in response allergies and asthma in the population child (Gui et al., 2024). This matter show existence response excessive immunity in organisms that if maintained from time to time , can trigger problem health chronic .

Furthermore, air pollution has a detrimental effect on children's central nervous system. Neuroimaging studies have shown that exposure to PM and NO_2 can potentially disrupt cortical myelination, a crucial process in nerve signal transmission. Despite differences in statistical results, the evidence suggesting impaired brain development caused by pollution is significant and cannot be ignored.

Air quality monitoring studies in educational institutions using low-cost sensors revealed that elevated concentrations of PM $_{2.5}$ and carbon monoxide (CO) near schools can result in chronic exposure for children, potentially leading to reduced lung function, the onset of respiratory disease, and reduced cognitive abilities (Kim & Sohanchyk, 2022).

Overall, the systematic review conducted through an umbrella review shows that exposure to PM $_{2.5}$, PM $_{10}$, and NO_2 is consistently associated with an increased risk of preterm birth, low birth weight, asthma, and respiratory infections (Rosser, 2024). These results are crucial as foundational evidence for Health Impact Assessments (HIA) designed to protect vulnerable child populations from the adverse effects of polluted urban environments.

Table 4. Monte Carlo Simulation Results on Air Pollution Exposure in Students

No.	Title	Monte Carlo Simulation Results	Source
1	Application of Monte Carlo simulation and quantitative microbial risk approach to investigate seasonal variation of airborne particulate matter and bioaerosols in medical waste management department and wastewater treatment plant of Iranian hospitals	Simulation This covers analysis sensitivity that shows that the parameters of $PM_{2.5}$ concentration and duration exposure (ED) has most significant impact to evaluation health workers . This means that variation in these parameters can cause results different risks , highlighting importance accurate data collection and analysis	(Tangestani et al., 2025)
2	New concentration-response functions for seven morbidity endpoints associated with short-term $PM_{2.5}$ exposure and their implications for health impact assessment	Children shows a higher RR tall For asthma compared to group age others , indicating greater vulnerability big to pollution air . Areas with low $PM_{2.5}$ concentration more sensitive to election form CRF function , meaning the nonlinear model provides estimate far- reaching impact more big compared to the log-linear model in the region .	(Ru et al., 2023)
3	Schools' air quality monitoring for health and education: Methods and protocols of the SAMHE initiative and project	The simulation also shows that $PM_{2.5}$ comes from from outside tend decrease with fast after ventilation , however peak concentration tall can happen consequence activity intense students , such as move inside class , which causes particle dust rises again to air	(Chatzidiakou et al., 2023)

The study by Tangestani et al. (2025) makes a significant contribution by integrating Monte Carlo simulations and the quantitative microbiological risk approach (QMRA) in the context of Iranian hospitals, specifically medical waste management units and wastewater treatment plants. The simulations revealed that $PM_{2.5\ concentration}$ and exposure duration are the most sensitive parameters affecting worker health risk estimates. This means that small fluctuations in these parameters can have a significant impact on the final risk outcome, highlighting the importance of data accuracy and strict monitoring in air quality evaluation in high-risk work environments.

Monte Carlo simulations in a study conducted by Ru et al. (2023) were used to estimate uncertainty in concentration-response functions (CRFs) related to $PM_{2.5\ exposure}$. The goal was to generate a range of model uncertainty through relative risk (RR) predictions at various $PM_{2.5\ levels}$. The results were calculated in the 5th and 95th percentiles to illustrate the range of RR uncertainty. This simulation emphasizes the importance of considering model uncertainty in air health impact assessments to ensure more accurate and reliable results.

Monte Carlo simulation results from a study conducted by Chatzidiakou et al. (2023) showed that ventilation plays a dominant role in determining pollutant concentrations in classrooms, as indicated by the exponential decrease in CO_2 levels when the room is empty. This method was also used to separate pollution components originating from outdoors (e.g., PM from traffic) and from indoors (e.g., student activity causing resuspension of dust particles). In this case, the indoor-outdoor concentration ratio (I/O ratio) was used to identify the extent to which classrooms protect against external exposure. The simulation also showed that outdoor $PM_{2.5}$ tends to decrease rapidly after ventilation, but high concentration peaks can occur due to intense student activity, such as moving around the classroom causing dust particles to rise back into the air.

CONCLUSION

Exposure to air pollution from industrial areas, particularly around schools, has been shown to increase the risk of health problems in children, including impaired lung function, asthma, and respiratory tract irritation. Pollutants such as $PM_{2.5}$, PM_{10} , NO_2, CO, and SO2 , and heavy metals such as nickel and chromium, can spread through the air and accumulate in classrooms, especially in buildings with poor ventilation. Children who live or attend school near industrial areas show higher levels of exposure, which can have long-term impacts on the respiratory system, immune system, and brain development. Therefore, mitigation measures such as air quality monitoring, improved school ventilation, and strict environmental management are essential to protect children's health and prevent the chronic impacts of industrial air pollution.

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