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ORIGINAL RESEARCH PAPER

Ambient air nitrogen dioxide concentration and the growing incidence of asthma in school-aged children

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ABSTRACT

BACKGROUND AND OBJECTIVES: Nitrogen dioxide, a significant air pollutant contributor to childhood asthma, is the focus of this study. In accordance with Sustainable Development Goals Target 3.9 and 11.6, this study plays a vital role in demonstrating the health effects of air pollution in developing nations, where such information is limited. The objectives of this study were to develop a more accurate early detection of nitrogen dioxide exposure related to asthma attacks to support more effective local asthma prevention and control strategies. This study explores the connection between nitrogen dioxide levels and asthma symptoms, including wheezing, in children residing in northeastern Bandung, Indonesia.

METHODS: Palmes's passive diffusion tubes measured weekly nitrogen dioxide measurements at 83 sampling sites to obtain the spatial and temporal concentration variations. The employment of a 30 x 30 meters' grid resolution model improved the accuracy of pollutant distribution, enabling consistent processing and interpretation of spatially resolved exposure data. The assessment of asthma symptoms was conducted using the International Study of Asthma and Allergies in Childhood questionnaire, administered to 842 individuals aged 6 to 12 years. The asthmatic children's residences were geocoded and linked to the modelled nitrogen dioxide concentration to assign individualized exposure values. Statistical analyses were performed to evaluate temporal trends, compare exposure groups, estimate wheezing risk, and assess spatial autocorrelation.

FINDINGS: The weekly nitrogen dioxide concentrations were persistently high, with a mean of 110.87 ± 42.38 micrograms per cubic meter. Significant nitrogen dioxide concentration spatial variation was found across the study area ($p < 0.001$). Locations close to significant roads recorded the highest nitrogen dioxide concentrations, surpassing 120 micrograms per cubic meter. Forty-seven (5.6 percent) of the 842 children surveyed had experienced asthma attacks. Thirty-seven of the 47 children lived in areas where nitrogen dioxide exposure levels exceeded 100 micrograms per cubic meter, indicating a strong association between elevated nitrogen dioxide concentrations and asthma symptoms ($p < 0.001$). In the region with the highest concentration, children aged nine and above suffered from more asthma attacks ($p = 0.026$). Analysis results demonstrated that asthmatic children living near major roads correlated spatially with high nitrogen dioxide concentrations. More asthma attacks occurred during periods when nitrogen dioxide levels exceeded 120 micrograms per cubic meter. The robust spatial alignment with established evidence validates a persuasive relationship that bolsters causal inference.

CONCLUSION: Children living near roadways are more prone to frequent asthma attacks. Apparent nitrogen dioxide concentration variations observed at fine spatial scales enable better detection of areas with elevated risk of asthma attacks, which provides detailed information for targeted health interventions. Future studies are being conducted based on these findings by incorporating longitudinal monitoring to gain a deeper understanding of causal pathways.

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NUMBER OF FIGURES 4

NUMBER OF TABLES 2

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INTRODUCTION

Sustainable Development Goals (SDG) Targets 3.9 and 11.6 aim to reduce death, illnesses and the environmental impact of cities with special attention to air quality by 2030. Human health is primarily at risk from air pollution, which is driven by a variety of pollutants produced by human activities (Crippa *et al.,* 2021). One of the air pollutants reported to cause health effects is nitrogen dioxide (NO_2), more commonly reported as nitrogen oxides (NO_x) for its combination with nitric oxide (NO) (Singh *et al.,* 2016). In many cities, road transport is the primary NO_2 source. Private cars contributed to 57 percent (%) of NO_2 emissions in road traffic in Hamburg (Ramacher and Karl, 2020). In Las Vegas, NO_2 levels rose within 20 meters (m) of roadways (Richmond-Bryant *et al.,* 2017). Nitrogen dioxide is a harmful gas that irritates the respiratory tract (Meulenbelt, 2016). Moreover, it has the potential to intensify bronchoconstriction and inflammation in the airways, possibly leading to a greater risk of infections affecting the respiratory organs (Petit *et al.,* 2017). The development of asthma is connected to NO_2 exposure, which causes airway inflammation, reduces airflow, and heightening the chances of new asthma cases (Anenberg *et al.,* 2022). These health risks are even more concerning in children due to a combination of several reasons. Factors include physiologies such as the immature immune system and still-developing vital organs, behaviors, and environmental influences. These elements, when combined, raise the propensity for infections and magnify the influence of pollutants on organs. Air pollutant exposure in children is higher than in adults because they spend more time outdoors (Gouveia *et al.,* 2018). Furthermore, because of their limited lung capacity, children tend to inhale a greater volume of air and pollutants, leading to respiratory complications, including asthma and wheezing (Olaniyan *et al.,* 2020). Recent meta-analyses reliably demonstrate a notable correlation between NO_2 exposure and asthma outcomes, especially among children. A study by Han *et al.* (2021) indicated that children exposed to NO_2 from traffic were more likely to develop asthma in children (meta-OR = 1.11, 95% CI: 1.06–1.17), with stronger effects observed in studies conducted in Asia. Similarly, another systematic review analysing 67 studies reported a pooled relative risk of 1.014 (95% CI: 1.008–1.020) per 10 micrograms per cubic meter ($\mu g/m^3$) increase in 24-hour (h) average NO_2 for asthma-related hospital admissions and emergency visits (Zheng *et al.,* 2021). An independent meta-analysis comprising 22 studies further validated a notable correlation between NO_2 and asthma exacerbations (RR = 1.024, 95% CI: 1.005–1.044) (Orellano *et al.,* 2017). These consistent findings across large-scale studies highlight the asthmatic relevance of NO_2, especially in urban environments with high traffic emissions. Although NO_2, Ozone (O_3), sulphur dioxide (SO_2), and fine particulate matter ($PM_{2.5}$) may have synergistic effects on health, NO_2 is still the most common pollutant linked to asthma pathophysiology (Mainka and Żak, 2022). A number of studies have examined the link between NO_2 levels in Indonesia and their health consequences at various spatial levels (Suryadhi *et al.,* 2020; Haryanto and Djafri, 2020; Prijanto and Hasan, 2024). These studies provided insight into the health risks associated with NO_2 in large urban areas. Suryadhi *et al.,* 2020 estimated NO_2 exposure using the Ministry of Environment passive samplers' data collected quarterly from 2009 to 2011 across 243 districts in 33 provinces. The NO_2 exposure data was combined with 2012 acute respiratory infection (ARI) data and averaged across provinces. At the provincial level, the concentrations of NO_2 were determined by averaging the minimum and maximum values. This study found an increase in the 18 % risk of ARI with the increase in NO_2 concentrations, which was valuable as a broad assessment of NO_2 exposure across Indonesia. A study by Haryanto and Djafri (2020) was performed in Jakarta to determine the high-risk zones for exposure to air pollution. The pollutants included NO_2, which used a concentration higher than 15 parts per billion (ppb) as the exposure limit. In Bandung, a study measured NO_2 at five health centers and found NO_2 associated with respiratory infections in children (Prijanto and Hasan, 2024). According to Suryadhi *et al.* (2020), the average NO_2 concentrations for the province were determined by taking the mean of the minimum and maximum values. Similarly, Haryanto and Djafri (2020) utilized data from five government monitoring sites to cover the Jakarta province of 662.33 square kilometers (km^2) with approximately 10 million populations. The exposure data collected from urban monitoring sites at the provincial level may not accurately depict individual exposure, since it overlooks the variations in pollution at intra-city

and micro-scale levels. Likewise, short-term and location-limited measurements may not represent actual exposure. Children's main exposure likely occurs at home or school, with variability due to differing distances. Utilizing sparse measurement data in prior studies might cause discrepancies in both spatial and temporal aspects. This can potentially obscure local and individual variations in air pollution exposure and fail to capture NO_2 concentrations in short-term variations, which is critical for exposure assessment. Hence, it might not entirely reflect spatial and temporal variations in individual exposure. The increase in NO_2 concentrations in Bandung is due to densely populated areas and growing vehicular emissions. Nonetheless, the existing assessments of air quality are irregular and not continuous. The lack of a long-term continuous air quality monitoring system (AQMS) in Bandung makes it challenging to analyze changes and trends in pollution (Pontoh *et al.,* 2023). Taking into account the uneven distribution of NO_2 concentrations, this study holds the promise of markedly improving the accuracy of assessments regarding NO_2 exposure evaluations and their associated health effects. The study aims to fill data gaps in resource-limited areas by integrating direct air pollutant measurements with high-resolution spatial modeling. The field measurement was designed to represent the population's inhaled pollutant levels and a spatial interpolation technique to extend data coverage to unmonitored areas. Due to the densely built environment of the study area, accurate representation of fine-scale NO_2 exposure variations is only achievable through high-spatial resolution modeling. The fine grid resolution makes possible a more accurate location for exposure evaluations and health effect forecasts. This approach captures localized variations in NO_2 levels across different areas. Additionally, it improves the precision of exposure impact estimates on health. The study presents the first evaluation of NO_2 concentrations and their relationship with childhood asthma in Bandung City and becomes a significant step forward in understanding these issues. It furnishes a more comprehensive assessment of the spatial distribution of NO_2 through precise measurements in an urban setting, enhancing understanding of local exposure trends. In evaluating these variables, the geographical pattern of NO_2 air pollution and the relationship between school children's asthma become a good starting point for targeted public health intervention. Moreover, the uneven distribution of NO_2 concentrations across urban spaces that are captured in this study increases critical concerns about environmental equity. Children residing in the vicinity subjected to detrimental air pollutants encounter social inequality as their living conditions increase their health risk. Some often reside where exposure to high-risk environmental hazards is vulnerable to health burdens (Barnes *et al.,* 2019). Based on this background, this study purposes to evaluate the spatial variability of NO_2 concentrations. Subsequently, by local-scale measurement and modelling, the study investigates uneven NO_2 concentrations association with asthma occurrences among school-aged children. Demographic information along with the features of their living environments, including indoor conditions, are utilized to enhance a deeper insight into the connection between NO_2 exposure and asthma outcomes in children. The strategy employed in this study will contribute to enhancing the accuracy of early detection of NO_2 exposure associated with asthma attacks, allowing for more focused prevention and control initiatives. This study has been conducted in Bandung, West Java, Indonesia, in 2023.

MATERIALS AND METHODS

Study design and location

This study took place in the northeastern area of Bandung, West Java, Indonesia, of *Cibeunying Kidul* and *Kiaracondong* sub-districts, Bandung City, from July 29 to October 21, 2023. The population densities of the two subdistricts are 21,883.1 and 22,691.7 people per km^2, respectively (BPS Kota Bandung, 2023a, 2023b). These sub-districts are located near four major roads (Jalan Ahmad Yani, Jalan PHH Mustofa, Jalan Ibrahim Adjie, and Jalan Terusan Jakarta), which significantly contribute to air pollution (Yudison and Driejana, 2015). Transportation emissions pose an urgent challenge as the number of motorized vehicles in Bandung has surged from 1.252.230 units in 2011 to 1.571.795 units in 2020 (BPS Kota Bandung, 2021). The population density has increased over the years (BPS Kota Bandung, 2024), hence space limitations have resulted in minimal land-use changes over time.

NO_2 *data collection*

Palmes's passive diffusion tube (PDT) samplers measured NO_2 concentrations weekly. The sampling

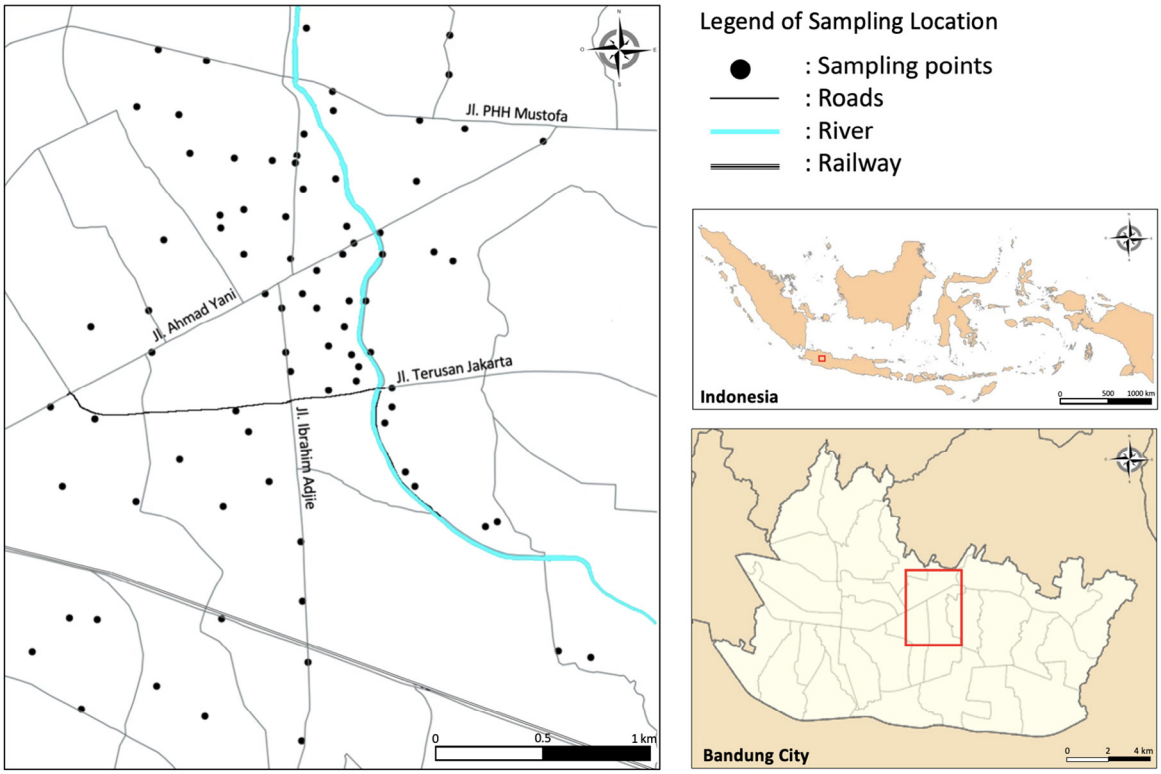

Fig. 1: Geographical location of the study area along with the sampling locations in Bandung, West Java, Indonesia (The map includes a scale bar (0-1 km) and a compass rose for spatial orientation)

of NO_2 was conducted simultaneously for 12 weeks (July 29 – October 21, 2023) at 83 measurement sites distributed across a 12 km^2 area (Fig. 1). The multiple points aimed to represent the small-scale spatial variation of NO_2 concentrations to reflect community exposure. The Palmes PDT is 71.0 millimeters (mm) in length and 11.0 mm in diameter (Zechmeister *et al.,* 2020). The caps made of polyethylene, which covered the top and bottom of the tube were unreactive to the reaction. Two stainless four-pore meshes per mm with a diameter of 12 mm held the absorbent solution at the closed end and were put inside the passive sampler cap. To provide the absorbent solution for NO_2 impregnation, 0.44 grams (g) sodium hydroxide (NaOH) and 3.95 g sodium iodide (NaI) were dissolved in methanol in 50 milliliters (mL) volumetric flask (Ngoasheng *et al.,* 2021). To enable free air circulation, the sampler was placed 1.5 to 3 meters (m) above the ground. Duplicate PDTs were deployed at each measurement location, with an additional 10% blank of the total deployed PDTs for quality control. The tubes were housed in a protective casing to lessen the effects of wind turbulence and to protect the tube from sunlight and rainwater. During the study period, consistent dry season conditions likely minimized variability due to weather-related factors (BMKG, 2023a). During the sampling phase, NO_2 molecules are drawn into the tube and are secured as nitrite ions in the absorbent solution via a diffusion process. Upon sampling, NO_2 was extracted from the exposed sample using 5 mL of Saltzman solution to quantify the concentration absorbed by the sampler. The sample was left in the dark for an hour until the solution created a pink azo dye complex. The amount of nitrite absorbed by the absorbent solution was quantified using a spectrophotometer at 550 nanometers (nm) wavelength (Gordon and Liptak, 2018). The validation of this approach is perceived as strong, highlighted by a prior study that identified a notable positive correlation coefficient of 0.84 in relation to the reference method (Estiri *et al.,* 2023).

Asthmatic data collection

Respondents for asthma data collection were selected from children residing within the areas covered by the NO_2 concentration mapping. Data regarding respondent characteristics and asthma symptoms was gathered through a survey questionnaire. The questionnaire was based on the International Study of Asthma and Allergies in Childhood (ISAAC) (Del-Rio-Navarro *et al.*, 2020) and was translated into *Bahasa Indonesia*. A certification of ethics for the research protocol guaranteed the quality of the study, the security of the data, and the rights of research subjects to their information. All asthma symptom data were obtained through parent/guardian-completed questionnaires. Only responses with signed informed consent were analyzed. To protect privacy, all geocoded residential data were anonymized and stored securely. The residential locations of children were not mapped using precise coordinates. Instead, symbolic markers were used to represent approximate residential areas. This makes certain that specific homes cannot be recognized, while permitting the examination of spatial clustering. The ethics approval was granted by the Research Ethics Committee of *Padjadjaran* University. To ensure quality assurance (QA), the questionnaire was pretested on 100 trial respondents who met the same criteria as the study population. Following the validation process, the approved questionnaires were distributed to the guardians of elementary school-aged children from two schools located within the study area. A method of sampling that is proportional to the size of the population was utilized to gather research samples from the complete population of 905 students. Random samples from each class were taken based on their respective proportions. The questionnaire included an informed consent section from the parents/guardians, and only responses with complete informed consent were further analyzed. Asthma status (ever/never) was assessed using the standardized ISAAC questionnaire. To capture recent asthma during a 12-week monitoring period, asthma symptoms in children were recognized by repeated episodes of cough, wheezing, and shortness of breath. This method refers to the Indonesian Paediatric Society in the National Asthma Guideline (Indonesian Paediatric Society, 2022), which is easily recognized by caregivers. To maintain uniformity in reporting, teachers from the school health unit, who are trained, confirmed the symptom episodes that parents reported using these criteria. This method uses community-based surveillance approaches (Benka-Coker *et al.*, 2018) and improves the use of questionnaire-based symptom identification, especially in large-scale population studies.

NO_2 *spatial distribution*

The interpolation method can generate the spatial distribution of pollutant concentrations to determine exposure level (Yudison and Driejana, 2015) and indicate the pollutant concentration in the subjects' residential area. This technique is more compatible with the measured concentration and yields superior representations of spatial patterns (Kamboj *et al.*, 2022). Nitrogen dioxide concentration data were interpolated at a 30 m × 30 m resolution based on the Indonesian Multiscale Grid System for Environmental Data using the inverse distance weighted (IDW) method, which effectively models concentrations around monitoring sites (Yudison and Driejana, 2015). Yadav and Ganguly (2025) revealed that IDW generated more accurate assessments of air quality than other techniques, such as Kriging, especially in cases where pollutants are distributed more uniformly across space. Therefore, the IDW method was chosen in this study to interpolate NO_2 exposure due to its suitability for relatively simple spatial patterns and moderate monitoring density. The 30 m × 30 m resolution model captures fine-scale spatial variability, including local factors such as land use, traffic density, and meteorological conditions. It is intended to be suitable for various urban settings that possess comparable features. The interpolation was performed using quantum geographic information system (QGIS) software (version 3.42). The locations of asthmatic children's houses were overlaid on the interpolated NO_2 concentration map to assess exposure distribution. The locations of the children-houses were checked to ensure they correspond with the actual building sites in the geographic information system (GIS), to reduce positional inaccuracies. Spatial linkage was confirmed by overlaying geocoded points onto the NO_2 exposure map to ensure each location accurately intersects with the corresponding modelled concentration grid.

Statistical test

Statistical analyses were performed to analyze

weekly fluctuations in NO_2 levels, investigate differences between concentration tiers, and estimate NO_2 concentrations at the residences of children suffering from asthma. All analyses were performed using Minitab® Statistical Software, licensed to *Institut Teknologi Bandung*.

Robustness check

To examine the spatial distribution of ambient NO_2 exposure among asthmatic children, a global Moran's I spatial autocorrelation analysis was performed using QGIS. Spatial relationships were defined via the k-nearest neighbours (KNN) method, which determines the closest features to a given location based on Euclidean distance. This technique facilitates adaptable definitions of neighborhoods and is successful in recognizing spatial clusters of adjacent features (Hu *et al.,* 2016). To evaluate the robustness and sensitivity of the spatial clustering patterns, the analysis was repeated using a range of K values (Abu Alfeilat *et al.,* 2019). For each number of nearest neighbouring locations (K), a spatial weights matrix was generated to calculate Moran's I, its expected value in a randomly spatially structured condition, and associated Z-scores and p-values. Calculation at an alpha (α) = 0.001 significance level and for multiple neighbourhood sizes was done to ensure that the identified spatial clustering was not an artefact of one definition of the neighbourhood. This technique provides greater assurance while ensuring the results remain consistent and interpretable.

RESULTS AND DISCUSSION

NO_2 *temporal and spatial analysis*

The duplicate PDTs resulted in the precision range of NO_2 measurements at 83 locations over 12 weeks from 92.59% to 95.27 %, with an average of 93.61%. The average precision means an average variation of approximately 6.39%, lower than the <7% duplicate relative standard deviation in the previously reported study (Masey *et al.,* 2017). In Fig. 2, the temporal variation over a period of 12 weeks is displayed, with each week's data collected from 83 sampling points. The minimum average concentration of 101.97 ± 39.22 µg/m³ was observed in week 1. Meanwhile, the maximum average concentration of 117.06 ± 44.62 µg/m³ was found in week 10. The median values for NO_2 concentrations remained relatively stable, with the highest median of 111.33 µg/m³ in week 10 and the lowest median of 95.8 µg/m³ in week 7. For the entire 12-week period, the average NO_2 concentration was 110.87 ± 42.38 µg/m³. The average NO_2 concentration peaked at 270.21 µg/m³ in week 7, while the lower-than-average values varied from 24.59 µg/m³ in week 2 to 55.29 µg/m³ in week 6. The Kruskal-Wallis's test was utilized to analyze variations in the weekly mean NO_2 levels over a period of 12 weeks. The statistical analysis yielded a p-value of 0.443 (> 0.05), suggesting no significant temporal variation in NO_2 concentrations, hence NO_2 levels were consistently high throughout the study period.

The 12-week mean concentrations of NO_2 at

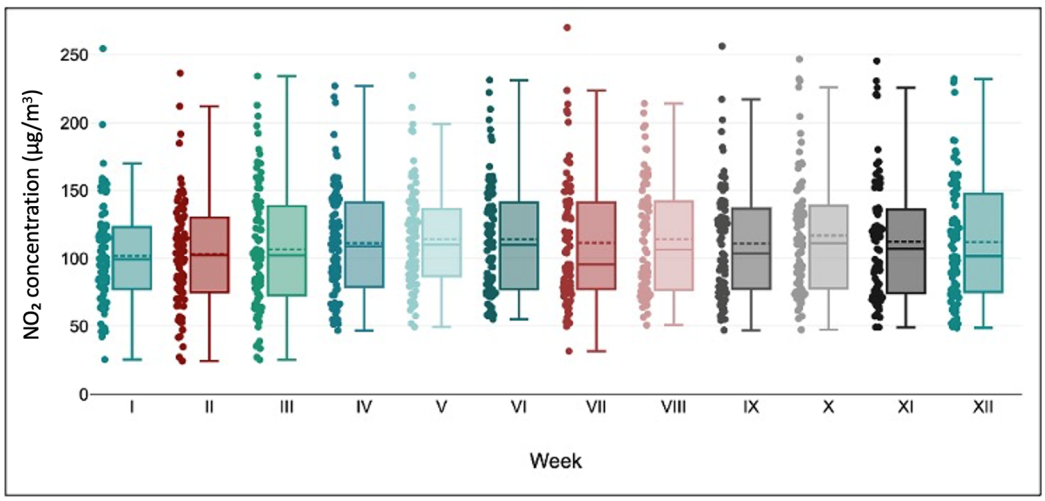

Fig. 2: Weekly Concentration of NO_2 (µg/m³) over 12 weeks
(Each bar represents weekly mean conce ntrations measured from 47 locations)

each sampling point across the study area were systematically classified into four categories to investigate the spatial variability based on scientifically justified thresholds. The critical reference level is set at 100 µg/m^3, highlighting its association with severe health consequences. Consequently, it functions as the foundational assessment standard for evaluating the necessity of implementing further monitoring actions to safeguard human health (Meulenbelt, 2016). Furthermore, the 120 µg/m^3 threshold marks the initial level associated with a higher NO_2 concentration found in downtown (Kijewska, 2016). The classification then adopts a 10 µg/m^3 incremental approach, according to Meng *et al.* (2021). The thresholds and the 10 µg/m^3 increment are applied in a systematic classification that resulted in Group 1 (>120 µg/m^3), Group 2 (111–120 µg/m^3), Group 3 (100–110 µg/m^3), and Group 4 (<100 µg/m^3). The IDW interpolation results indicated that the NO_2 level pattern always remained higher in areas near major roads. Locations close to rivers exhibited marginally diminished levels of NO_2, possibly due to the impact of rivers and water bodies on local airflow, which helps in the distribution of pollutants. This suggests that the proximity to water bodies may enhance air quality by facilitating air movement and minimizing pollutant buildup. The natural flow path has a cooling effect, reducing air pollution concentration locally (Guo *et al.,* 2023). Furthermore, bodies of water may chill the area, reducing the possibility of pollutants accumulating close to the ground (Shi *et al.,* 2020). Nonetheless, the significant effects of urban planning and traffic pollution render the river's moderating influence minimal and insignificant. This is because, even while natural characteristics are present, high-traffic locations have higher NO_2 concentrations.

As a short-lived pollutant, NO_2 remains concentrated near emission sources, serving as a key indicator of urban air pollution. In urban areas, NO_2 primarily originates from transportation fossil fuel combustion, which could contribute up to 80% of ambient NO_2 (Achakulwisut *et al.,* 2019). Several studies also reported high weekly NO_2 concentrations over 100 µg/m^3, such as 150 µg/m^3 in Holyoke, US (Beltran *et al.,* 2024), and 139 µg/m^3 in Accra, Ghana (Wang *et al.,* 2022), which were slightly higher but comparable to this finding. The increase in NO_2 levels in urban regions with fast-growing populations correlates with the escalation of transport-related emissions. On a global scale, since the 2000s, the average annual NO_2 concentration has increased by 71% in densely populated regions (Sicard *et al.,* 2023). Because of transportation-related activities, NO_2 concentrations in large European cities were above the annual NO_2 World Health Organization (WHO)'s air quality standard (40 µg/m^3) (Casquero-Vera *et al.,* 2019). Cities in south Asia also experienced significant increases in NO_2 concentrations. The growth in vehicle sales, intensified by the significant amount of traffic congestion, releases NO_x concurrently (Duncan *et al.,* 2016). NO_x emissions primarily originate from high-temperature reactions between nitrogen (N_2) and oxygen (O_2) during combustion (Wu *et al.,* 2020). Nitrogen dioxide in gaseous form can combine with other pollutants to produce secondary particulate matter, such as aerosols, that lower air quality and present health risks, particularly in urban settings (Lin *et al.,* 2019). These pollutants, particularly in city environments, create serious health threats, especially for those suffering from asthma. Sustained high temperature throughout the research period was another factor that might contribute to the elevated NO_2 concentrations. Peroxy-acyl nitrates and other long-lived reactive nitrogen compounds dissociate more quickly in hot temperatures (Romer *et al.,* 2018). During the measurement period, the highest weekly average temperature was 34 degrees Celsius (°C) in the 11th and 12th week measurements (BMKG, 2023b). West Java Province has been affected by a drought, going 50 days in a row without any rain. During this period, there was a notable reduction in rainfall, averaging only 8% (BMKG, 2023a). The dry season in Indonesia at the time of the measurement was drier than usual due to the combined impacts of El Niño and a positive Indian Ocean Dipole (IOD). It is well understood that a decrease in rainfall leads to a higher concentration of pollutants in the atmosphere (Liu *et al.,* 2024). The relatively stable weather throughout the study period suggests that spatial and temporal variations in NO_2 concentrations are predominantly driven by traffic emissions. This stable atmospheric context reinforces the notion that the NO_2 patterns observed are a result of local emissions rather than short-lived weather phenomena. The accuracy of PDT measurements for NO_2 is affected by humidity, especially in tropical environments. While low relative humidity (RH) can lead to potential underestimation

of NO_2 due to incomplete chemical reactions (Heal *et al.,* 2019), higher RH generally favors this chemical conversion and improves NO_2 uptake efficiency. However, excessive humid conditions, which are typical in tropical climates like Indonesia, may cause the NaOH/NaI solution to absorb excess moisture. It can reduce the concentration of the reagent and impact its stability during long exposure durations. In this study, all PDT samplers were protected within shielded cases designed to guard against direct rain, sunlight, and wind turbulence, with an exposure duration of no more than 7 days. This approach contributed to sustaining the chemical stability of the absorbent solution while reducing environmental interference. Although direct RH measurements were unavailable at every sampling location, the consistently high humidity during the monitoring period is expected to have supported effective NO_2 capture. Overall, the use of protective cases and the ambient conditions suggest that environmental effects on the measurement accuracy were mitigated to a considerable extent.

Asthma symptoms and spatial exposure to NO_2

842 children completed the survey, with a questionnaire response rate of 93%. This study found that 5.6% of children experienced wheezing, whereas 3.6% experienced wheezing in the previous 12 months. In total, 3.2% of children have been diagnosed with asthma or have a history of asthma verified by a physician. The residences of children suffering from asthma were geocoded and subsequently placed on the spatial distribution map of the modelled NO_2 concentration field. As depicted in Fig. 3 a significant number of children's residences were found in regions of elevated concentration. In total, 37 asthmatic children lived in areas with NO_2 concentrations greater than 100 µg/m³ (Table 1) in

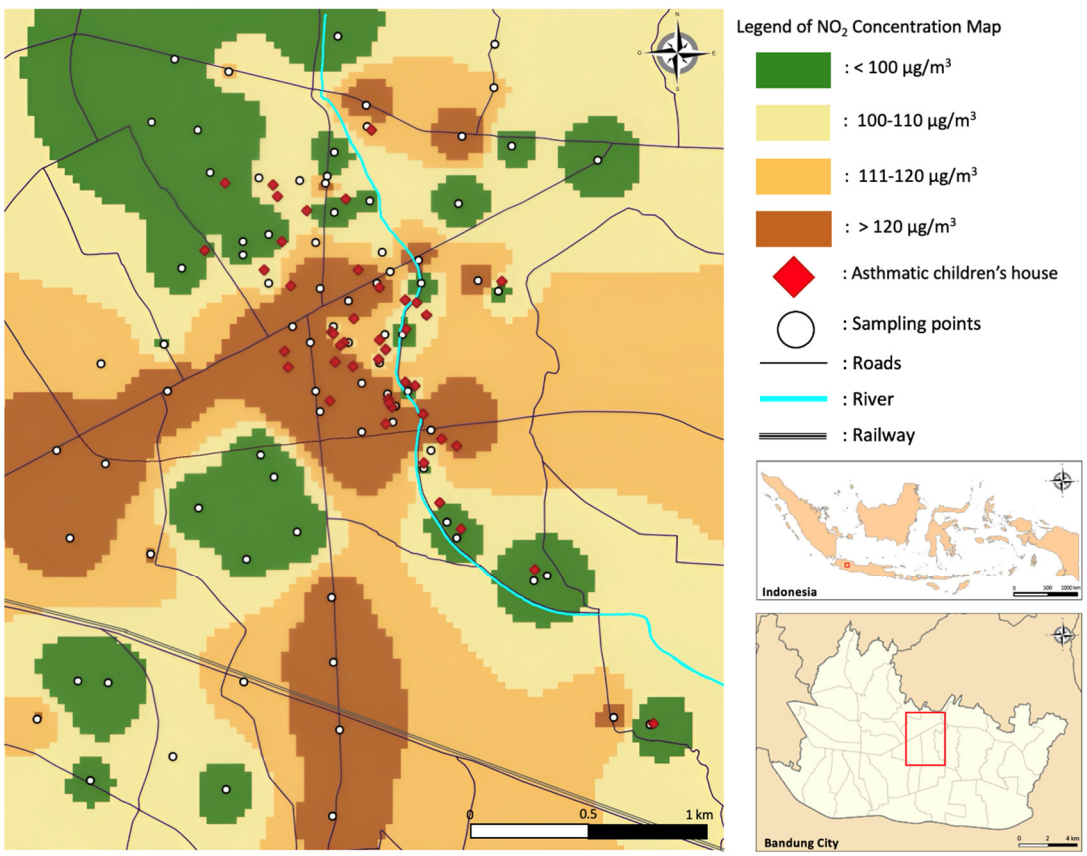

Fig. 3: Map of the 12-week average NO_2 concentration (µg/m³) interpolation, sampling points, and asthmatic children's house location (The map includes a scale bar (0-1 km) and a compass rose for spatial orientation)

Table 1: Tukey-Kramer NO_2 mean differences based on IDW interpolation at measurement locations and asthmatic children's houses across exposure groups

Group (NO_2 exposure)	N	Mean ± standard deviation (SD)	95% confidence interval (CI)	Tukey grouping
Measurement Locations				
1 (>120 µg/m³)	29	151.89 ± 25.20	145.45, 158.32	A
2 (111–120 µg/m³)	6	113.91 ± 2.17	99.76, 128.05	B
3 (100–110 µg/m³)	11	104.53 ± 4.05	94.09, 114.98	B
4 (<100 µg/m³)	37	80.10 ± 12.86	74.41, 85.80	C
Asthmatic Children's Houses				
1 (>120 µg/m³)	17	139.08 ± 15.66	134.18, 143.98	A
2 (111–120 µg/m³)	5	118.34 ± 1.85	109.31, 127.37	B
3 (100–110 µg/m³)	15	105.64 ± 3.36	100.42, 110.85	B
4 (<100 µg/m³)	10	92.49 ± 4.94	86.10, 98.88	C

*Groups that do not share the same letter indicate a significant difference (Tukey-Kramer, $p < 0.001$)

the northern part of Kiaracondong sub-district. The sub-district is an area surrounded by three large roads (Jalan A. Yani, Jalan Ibrahim Adjie, and Jalan Terusan Jakarta) with dense traffic that contributes significantly to air pollution. The significant quantity of motor vehicles present in the vicinity is probably the main contributor to NO_2 emissions, leading to elevated levels of pollutants close to their residences. One-way ANOVA test investigated whether there was a difference between the concentration range groups. The study identified a considerable disparity ($p < 0.001$) in NO_2 levels among the four groups of concentration ranges, which is depicted in the IDW modeling map in Fig. 3. The *post-hoc* Tukey-Kramer test was used to further identify which groups were significantly different in all measurements area. The test result indicated that Group 1 (Mean = 151.89 µg/m³) had significantly higher NO_2 levels than all other groups. In contrast, Group 4 (Mean = 80.10 µg/m³) had the lowest concentrations and also differed significantly from other groups. However, the tests found no significant difference between Group 2 (113.91 µg/m³) and Group 3 (104.53 µg/m³) ($p > 0.05$) (Table 1). The findings indicated that the peak NO_2 levels observed in Group 1 corresponded to sampling locations near major roads, where the primary source of emissions is vehicle traffic (Fig. 3). The high concentrations also coincided with most of the children's house locations with asthma symptoms. Conversely, Group 4, demonstrating much lower concentrations, had a lesser number of children with asthma. The study also identified notable disparities in NO_2 levels and the number of residences of asthmatic children among the four groups ($p < 0.001$). Group 1 exhibited the highest mean NO_2 concentration (139.08 ± 15.66 µg/m³). There were 17 asthmatic children's houses in the Group 1 area. Groups 2 and 3 showed intermediate values, with no significant difference between them (Tukey-Kramer test), each had 5 and 15 asthmatic children's houses. Conversely, Group 4, which was associated with residential zones situated at a greater distance from emission sources, exhibited the lowest concentration (92.49 ± 4.94 µg/m³). It also had the least number of asthmatic children houses compared to other groups with concentrations larger than 100 µg/m³ (Table 1). These findings confirm that the NO_2 distribution spatial pattern aligns with the proximity to traffic as the source of air pollution exposure.

Table 2 summarizes participant demographics and household characteristics stratified by NO_2 exposure group. Participant age distribution varied significantly across NO_2 exposure groups (Kruskal–Wallis, $p = 0.032$), with children aged nine and above predominantly residing in a high-exposure zones. Age was also significantly associated with total asthma attacks during the 12-week monitoring period (Negative Binomial Regression, $p = 0.026$). It appears that this relationship is predominantly caused by the spatial aggregation of older children in locations with increased NO_2 concentrations. Thus, the elevated asthma burden is more related to greater exposure to NO_2 pollution. Cheng *et al*. (2019) indicated a greater burden among older children, possibly due to cumulative exposure, increased time outdoors, or age-related susceptibility. Additional investigation is required to assess how age influences asthma exacerbations in this region characterized with elevated NO_2 levels. Other variables showed no statistically significant differences but exhibited

Table 2: Participant characteristics by NO_2 exposure group

Variables	Group 1 (>120 µg/m³)	Group 2 (111–120 µg/m³)	Group 3 (100–110/ µg/m³)	Group 4 (<100 µg/m³)	p-value for asthmatic symptom	p-value for total asthma attack
	n (%)	n (%)	n (%)	n (%)		
Age (years)					0.032*	0.026*
≥ 9	12 (70.6)	5 (100)	6 (40.0)	5 (50.0)		
< 9	5 (29.4)	0 (0)	9 (60.0)	5 (50.0)		
Sex					0.791	0.328
Female	5 (29.4)	2 (40.0)	7 (46.7)	4 (40.0)		
Male	12 (70.6)	3 (60.0)	8 (53.3)	6 (60.0)		
Cooking fuel type					NA	NA
LPG	17 (100)	5 (100)	15 (100)	10 (100)		
Kerosene/firewood	0 (0)	0 (0)	0 (0)	0 (0)		
Indoor smokers in family					0.422	0.544
No	6 (35.3)	2 (40.0)	2 (13.3)	2 (20.0)		
Yes	11 (64.7)	3 (60.0)	13 (86.7)	8 (80.0)		
Ventilation during cooking					0.689	NA
Open window	16 (94.1)	5 (100)	13 (86.7)	9 (90.0)		
Close window	1 (5.9)	0 (0)	2 (13.3)	1 (10.0)		
Ventilation during hot weather					0.197	1
Open window	17 (100)	4 (80.0)	15 (100)	10 (100)		
Close window	0 (0)	1 (20.0)	0 (0)	0 (0)		
Vehicle warm-up at home					0.19	0.478
No	17 (100)	5 (100)	13 (86.7)	10 (100)		
Yes	0 (0)	0 (0)	2 (13.3)	0 (0)		
Household size					0.929	NA
≤ 3 persons	2 (11.8)	1 (20.0)	2 (13.3)	2 (20.0)		
> 3 persons	15 (88.2)	4 (80.0)	13 (86.7)	8 (80.0)		
Residential density					0.472	0.395
Not dense	12 (70.6)	2 (40.0)	11 (73.3)	8 (80.0)		
Dense	5 (29.4)	3 (60.0)	4 (26.7)	2 (20.0)		
Presence of pets (dog/cat)					0.753	0.476
No	13 (76.5)	4 (80.0)	11 (73.3)	9 (90.0)		
Yes	4 (23.5)	1 (20.0)	4 (26.7)	1 (10.0)		
Transportation method to school					0.767	0.671
On foot	13 (76.5)	4 (80.0)	10 (66.7)	6 (60.0)		
Vehicle	4 (23.5)	1 (20.0)	5 (33.3)	4 (40.0)		
Commute time to school					0.4	0.351
≤ 5 minutes	8 (47.1)	1 (20.0)	4 (26.7)	2 (20.0)		
> 5 minutes	9 (52.9)	4 (80.0)	11 (73.3)	8 (80.0)		

*Statistically significant at $p < 0.05$

patterns of interest. All households reported using liquefied petroleum gas (LPG) for cooking, with no use of kerosene or firewood. Another observation is that most individuals practiced open-window ventilation during cooking; however, in Group 3, 13.3% did not participate in this practice, which raises potential concerns in areas with high exposure. Similarly, window opening during hot weather is common, which may facilitate outdoor NO_2 infiltration, particularly in polluted environments (Grigorieva and Lukyanets, 2021). Some variables were marked as not applicable (NA) in the statistical

tests due to limited variation or small subgroup sizes. For instance, all households utilized LPG, and none of the participants indicated the use of alternative fuels, which limits inferential analysis. Although these variables could not be statistically analysed, they remain important contextual factors in understanding indoor environmental quality. The prevalence of indoor smoking was noted in multiple groups, especially Groups 3 and 4, yet the differences did not reach statistical significance. Nonetheless, second-hand smoke is still a major contributor to respiratory health risk (Shargorodsky *et al.,* 2015). These findings demonstrate the dynamic relationship between environmental exposures and home behaviors. Living in a neighborhood with high exposure sets a baseline risk that may be lessened or intensified by typical ventilation and indoor smoking behaviors; other factors including household composition, pet ownership, residential density, mode of transportation, and commuting time showed no significant differences but should be retained for future exposure evaluations.

Robustness assessment of NO_2 concentration and asthma cases spatial distributions

A global Moran's I test was used to evaluate the spatial clustering of asthmatic children in relation to similar NO_2 exposure levels. The index ranges from -1 to +1, where values greater than zero indicate clustering of asthmatic children's house and NO_2 concentration, and values below zero indicate dispersion (O'Leary *et al*., 2016; Kumari *et al.,* 2019), or uncorrelated asthma cases with NO_2 concentration. A notably high Moran's I, along with a substantial z-score and a low p-value, implies that locations with elevated NO_2 levels are likely to spatially correlate with a greater residential presence of children suffering from asthma. Fig. 4 presents the results of the spatial autocorrelation analysis using Moran's I across a range of spatial neighborhood definitions (K = 1 to K = 46). The analysis shows a consistent and statistically significant positive spatial autocorrelation in NO_2 exposure among children with asthma for K = 1 to K = 36. In the KNN method, the parameter K refers to the number of closest neighbouring asthmatic locations considered for each sampling point. KNN spatial weights were applied with K values ranging from 1 to 46. This number accounts for all possible neighbours, excluding the focal point itself, given that the dataset contains 47 sampling locations. In the context of spatial analysis regarding NO_2 and asthma, the z-score denotes the potential for spatial

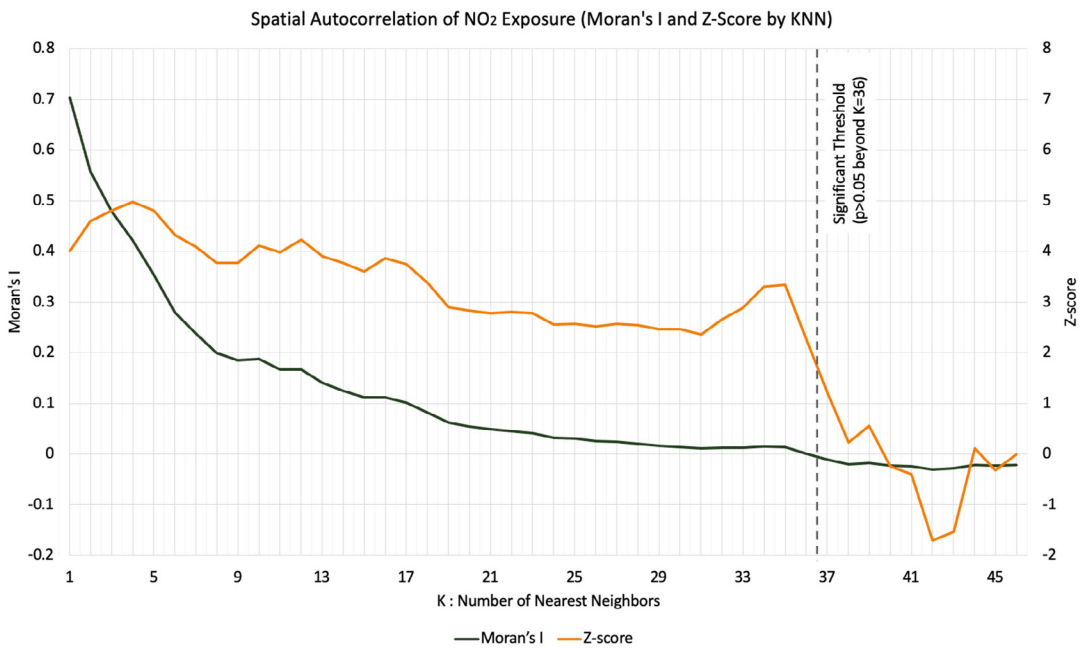

Fig. 4: Spatial autocorrelation of NO_2 exposure by k-nearest neighbor size (Statistical significance is based on corresponding Z-scores and p-values)

clustering, where a high positive z-score indicates that areas with increased NO_2 levels are likely prone to having a greater number of asthma cases. Corresponding Z-scores remain statistically significant ($p < 0.05$), indicating high confidence in the non-randomness of the clustering pattern. The highest Z-score (4.977) was found at K = 4, showing that a cluster of four closely located houses shows a strong spatial correlation with high NO_2 concentrations, indicating a localized clustering pattern. Nonetheless, when the distance between locations expands (with higher K values), the correlation diminishes, and the variability in NO_2 levels becomes less uniform, implying that a uniform spatial pattern is absent at a broader scale. These findings suggest that children with asthma tend to live in spatial clusters that correspond to areas with higher NO_2 concentrations, indicating a non-random spatial structure of exposure in urban settings. This imbalanced distribution reveals an environmental injustice, with some communities being more severely impacted by air pollution and its health consequences. Children residing in some neighborhoods, especially those near large highways, disproportionately carry the burden of increased NO_2 levels, which will heighten respiratory health risks such as asthma. This spatial condition corresponds with prior findings that underscores the influence of localized air pollution in influencing health disparities (Lindgren *et al.,* 2016).

The high NO_2 concentration and asthma, particularly in children living near the roads, suggest a strong association between asthma and exposure to traffic-related air pollution (TRAP), particularly NO_2. In densely populated urban areas, more individuals tend to live near roadways to enhance accessibility. This circumstance also increases the risk for children, where frequent outdoor activities will raise their exposure to air pollution. In an area of Bandung City characterized by high NO_2 levels (greater than 120 µg/m^3), fourteen asthmatic children lived in houses adjacent to a traditional market bustling with street vendors, a typical site of traffic congestion. Previous studies also found asthma exacerbation in hospital outpatients with increased NO_2 concentrations (Kowalska *et al.,* 2020). A retrospective cohort study also found an increased risk of asthma attacks after exposure to NO_2 at an early age (Kuiper *et al.,* 2021). The risk of new and persistent asthma was higher in people living <200 m from the main road (Bowatte *et al.,* 2018). Moreover, indoor NO_2 levels might be forecasted using outdoor concentration measurements in homes situated near major thoroughfares (Yudison and Driejana, 2011). This is particularly relevant for assessing asthma risk in children living in homes near major roadways. Urban inhabitants are likely to encounter a greater risk of asthma as a result of high mobility, the surge in transportation emissions, and the ongoing patterns of urbanization. Weekly interpolated raster data identified asthma attacks among 47 children that occurred specifically during weeks when the NO_2 concentration at their residential locations reached or exceeded 120 µg/m^3. These pollution-linked asthma cases were recorded in week 3 (2 children), week 4 (1 child), week 5 (2 children), week 6 (3 children), and weeks 7, 11, and 12 (1 child each). Despite the relatively low figures, the steady emergence of asthma episodes in the context of high pollution exposure was demonstrated. The need for timely response interventions is urgent in the management of asthma cases. Real-time NO_2 monitoring data in an area will provide air quality in a timelier manner to predict potential asthma risk. This monitoring activity is essential for developing successful public health interventions. Policymakers and urban planning authorities can implement targeted initiatives for specific areas, such as upgrading air quality monitoring systems and decreasing vehicle emissions in proximity to homes and educational institutions. In addition, the health sector can prioritize services in high-risk areas by acknowledging that certain communities are more impacted than others. This study had certain limitations. Firstly, the cases of asthmatic children were used to assess risk instead of prevalence, which is generally designated for comparing risk or likelihood. Second, the asthmatic condition was determined by self-report rather than the doctor's diagnosis or more objective measures such as spirometry or peak expiratory flow meter. Asthma management in Indonesia is commonly constrained by issues of underdiagnosis or inaccurate reporting, potentially causing the prevalence to be underestimated (Triasih *et al.,* 2023). To overcome these challenges, our study employed the ISAAC questionnaire, a widely accepted and validated tool for large-scale epidemiological studies. In addition, childhood asthma is commonly marked by repeated episodes of coughing, wheezing, and shortness

of breath (Indonesian Paediatric Society, 2022). These symptoms are typically detected by parents or caregivers, which aids in the early recognition of asthma symptoms, even when clinical testing is not conducted. Given the limited access to healthcare and diagnostic services in many parts of Indonesia, this symptom-based approach is both necessary and practical for community-level asthma identification. Second, IDW was selected due to its simplicity, computational efficiency, and suitability for capturing spatial patterns within the specific context of our study area, where monitoring data are relatively dense and spatial variation is moderate. Unlike Kriging, IDW does not explicitly model spatial autocorrelation, which may limit its performance in areas with complex spatial heterogeneity or sparse data coverage. Compared to land-use regression (LUR), IDW also does not incorporate covariates such as traffic intensity, land use type, or meteorological factors (Dirgawati *et al.,* 2015). The lack of these predictors indicates that IDW might not completely account for all sources of spatial variability. However, IDW provides a practical balance between accuracy and computational simplicity according to data availability and the scope of this study. It is essential to understand that alternative spatial interpolation techniques yield comparable results, but they are based on distinct assumptions and inputs; hence, their outcomes are not directly interchangeable. Third, while this study statistically evaluated several sociodemographic and indoor environmental factors, residual confounding may still exist. Aspects such as parental asthma history, exposure to indoor allergens (including dust mites or mold), and the condition of housing were not directly evaluated and may require inclusion in upcoming studies. These factors could be crucial for a thorough understanding of asthma. Future studies should consider measuring these variables for a more comprehensive analysis. A more comprehensive study is currently underway using cohort epidemiological design. In this study, NO_2 exposure and childhood asthma incidence are followed up at multiple intervals to more accurately predict asthma incidence and prevalence based on the representation of children's residential areas. Nevertheless, this study helps identifying high-risk regions, and supporting more focused health policies for asthma prevention and further investigation. Building on this, the follow-up study monitors weekly NO_2 concentrations alongside weekly asthma symptoms using a community-based surveillance method (Benka-Coker *et al.,* 2018). This design facilitates a clearer comprehension of the relationship between short-term fluctuations in air pollution relate to asthma attacks in children. Clinical examinations were conducted by health professionals at certain intervals to support more accurate diagnosis. The spatial patterns and exposure levels identified in the current study have informed the sampling strategy and exposure classification in the cohort, making it more targeted and policy relevant.

CONCLUSION

The weekly NO_2 concentrations in Bandung were relatively high, indicating a significant level of air pollution. The high-resolution spatial modeling improved the spatial coverage and temporal representation of passive sampler NO_2 measurements. The interpolation found high NO_2 concentration measurement sites on the roadsides. Transportation-related fuel burning is likely to contribute significantly to atmospheric NO_2 concentrations. Although the presence of a river may somewhat lessen local concentrations, its mitigating effect was negligible when compared to the significant influence of traffic emissions and urban design. The concentration pattern indicates that vehicle-related fuel combustion is a dominant contributor. The extended dry season observed during the study intensified these trends by decreasing rainfall and restricting atmospheric purification. As a result, pollutants were able to accumulate more easily. To improve geographical resolution and analytical accuracy and enable more methodical processing of environmental data, this study employed a 30 m x 30 m grid-based spatial methodology. This technique boosts the efficiency of spatial interpolation, facilitating a more precise assessment of population exposure and the distribution of pollutants. The enhanced spatial detail provided by the fine-resolution grid system also enabled clearer identification of exposure patterns in residential areas, particularly those with vulnerable populations such as children. Children are likely to develop asthma due to significant exposure to pollution from traffic. Some children experienced asthma attacks in the observed area, while others experienced wheezing in the last 12 months. Statistical analyses demonstrated significant differences in NO_2 concentration levels across different

exposure areas and in the spatial distribution of asthmatic children's homes. Regions characterized by elevated NO_2 concentrations close to major transport corridors reported the highest incidence of asthma among residents. This spatial gradient confirms the dominant influence of traffic emissions on air pollution exposure at the neighborhood level. The spatial analysis confirms older children living in high-exposure zones experienced asthma attacks during the monitoring period. However, this pattern is more likely the result of growing exposure to severely polluted locations rather than age being the primary cause. Spatial autocorrelation analysis (Moran's I) confirmed significant clustering of NO_2 exposure and asthma cases at the neighbourhood level. This emphasizes the disproportionate environmental burden on children in polluted areas. By Identifying these trends, city authorities and urban planners can direct their attention to the areas that are most affected. For instance, they can stop housing construction that is situated too near to heavily trafficked roads, enhance greenery to assist in filtering air pollutants, or refine traffic management to diminish emissions. Clustering also helps identify the potential locations for health surveillance. Improving air quality surveillance is crucial for safeguarding vulnerable groups. These findings suggest that neighbourhood environmental factors, such as traffic closeness and urban infrastructure, control air pollution exposure and its associated health burden. However, several limitations should be taken into account while considering these findings. Asthma symptoms were based on parental reports without clinical confirmation, and NO_2 exposure data were collected only at a single point in time. Although these were associated with a history of wheezing and the frequency of asthma episodes throughout the 12-week monitoring period, such limitations may affect the robustness and clarity of the observed relationships. Future research should aim to include clinical diagnoses and longer-term exposure tracking to strengthen the evidence base and better inform policy and targeted health interventions. An ongoing cohort-based epidemiological study aims to explore further the link between NO_2 exposure and children's health outcomes using updated data.

AUTHOR CONTRIBUTIONS

P.N. Sari prepared in data curation, formal analysis, investigation, visualization, and writing the original manuscript. Driejana, the corresponding author, contributed to conceptualization, methodology, resource management, supervision, validation, manuscript review, rewriting and editing. A.P. Yudison supervised air quality sampling, analysis methodology and manuscript review. Dwi Agustian provided advice for health data acquisition, health data analysis and manuscript review. A.B. Kurnia contributed to NO_2 investigation. A. Riqqi provided advice for geospatial analysis, review and rewriting. All authors contributed substantial edits to the final version of the article, read and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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☐ Negative AI Statement

The author(s) declared that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
α	Alpha
µg/m³	Microgram per cubic meter
AQMS	Air quality monitoring system
ARI	Acute respiratory infections
g	Grams
GIS	Geographic information system
IDW	Inverse distance weighted
IOD	Indian Ocean Dipole
ISAAC	International Study of Asthma and Allergies in Childhood
K	Number of nearest neighboring locations
km²	Square kilometer
KNN	K-nearest neighbours
LPG	Liquefied petroleum gas
LUR	land-use regression
m	Meter
mL	Milliliters
mm	Millimeters
N_2	Nitrogen
NaI	Sodium iodide
NaOH	Sodium hydroxide
nm	Nanometers
NA	Not applicable
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_2	Oxygen molecule
O_3	Ozone
PDT	Passive diffusion tube
$PM_{2.5}$	Fine particulate matter
ppb	Part per billion
QA	Quality assurance
QGIS	Quantum geographic information system
RH	Relative humidity
SDG	Sustainable development goal
SO_2	Sulphur dioxide
TRAP	Traffic-related air pollution
WHO	World Health Organization

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