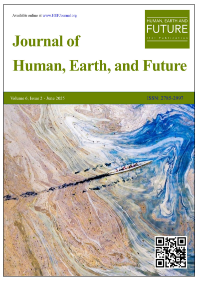
HUMAN, EARTH AND FUTURE
Ital Publication

ISSN: 2785-2997

Available online at www.HEFJournal.org

Journal of
Human, Earth, and Future

Vol. 6, No. 2, June, 2025



Health Risk Assessment of NO_2, $PM_{2.5}$ and PM_{10} Exposure in Children and Adolescents

Anwar Mallongi [1*], Aminuddin Syam [2], Sukri Palutturi [3], Wesam A. Madhoun [4], Sopa Chinwetkitvanich [5], Dede A. Musadad [6], Wahiduddin [7], Ernyasih [8], Ratna D. Puji Astuti [9], Annisa U. Rauf [10], Shubham Pathak [11]

[1] Department of Environmental Health, Faculty of Public Health, Hasanuddin University, Makassar, Indonesia.

[2] Department of Nutrition, Faculty of Public Health, Hasanuddin University, Makassar, Indonesia.

[3] Department of Health Policy and Administration, Faculty of Public Health, Hasanuddin University, Makassar, Indonesia.

[4] Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia.

[5] Department of Sanitary Engineering, Faculty of Public Health, Mahidol University, Bangkok, Thailand.

[6] Health Research Organization, National Research and Innovation Agency Republic of Indonesia, Jakarta Pusat, Indonesia.

[7] Department of Epidemiology, Faculty of Public Health, Hasanuddin University, Makassar, Indonesia.

[8] Faculty of Public Health, Universitas Muhammadiyah, Jakarta, Indonesia.

[9] Department of Environmental Health, Faculty of Public Health, Universitas Airlangga, Surabaya, Indonesia.

[10] Department of Health Behavior, Environment and Social Medicine, Faculty of Medicine, Public Health, and Nursing, Universitas Gadjah Mada, Yogyakarta, Indonesia.

[11] School of Accountancy and Finance, Center of Excellence in Sustainable Disaster Management (CESDM), Walailak University, Thai Buri, Tha Sala and 80160, Thailand.

Received 03 February 2025; Revised 12 May 2025; Accepted 16 May 2025; Published 01 June 2025

Abstract

Chronic exposure to nitrogen dioxide (NO_2), particulate matter ($PM_{2.5}$), and PM_{10} can have negative impacts on both environmental and human health. This research aimed to determine the levels of NO_2, PM_{10}, and $PM_{2.5}$ pollution in Makassar City and to assess the potential health risks for children and adolescents using the Monte Carlo Simulation (MCS) probabilistic approach for exposure to these pollutants in Makassar City, Indonesia. This analytic, cross-sectional study employed an MCS approach to evaluate health risks. The results showed higher NO_2 levels of 10.88 µg/m³ and 10.97 µg/m³ at stations 12 and 17 in Panakkukang and Borong, located near a truck parking area. Meanwhile, stations 21 in Tamalanrea Indah and 20 in Karampuang recorded higher PM_{10} levels of 24.8 and 30.14 µg/m³, respectively. The hazard quotient (HQ) was 12.4, 20.3, and 19.8 for NO_2, PM_{10}, and $PM_{2.5}$, respectively. Among children at the 5th and 95th percentiles, cancer risks for NO_2 were 13 and 34, corresponding to medium risk levels. In contrast, adolescents showed cancer risks of 102 and 223, indicating high risks. For adults, the sensitivity analysis for NO_2 revealed that the most significant factor contributing to health hazards was the length of exposure (ED) at 26.4%, followed by pollutant concentration (C) at 18.3%, exposure frequency (EF) at 17.8%, and inhalation rate at 17.2%, as shown in the sensitivity analysis chart. Overall, adolescents faced greater risks than children, with the highest HQ values in children being 8.98, 15.2, and 22.5 for NO_2, PM_{10}, and $PM_{2.5}$, respectively, which were lower than those observed in adolescents. The total hazard quotient (THQ) risks for NO_2, PM_{10}, and $PM_{2.5}$ were 12.4, 20.3, and 19.8, respectively. In conclusion, NO_2 and $PM_{2.5}$ pose significant health risks to adolescents.

Keywords: Hazard Quotient; Probability Toxic; Sensitivity Level; Chronic Exposure; Particulates.

* Corresponding author: rawnaenvi@gmail.com; anwar.mallongi@unhas.ac.id

http://dx.doi.org/10.28991/HEF-2025-06-02-02

1. Introduction

One of the primary contributors to air pollution has been identified as the transportation industry [1, 2]. According to the United States Department of Transportation (USDOT), transportation-related emissions in 2022 consisted of 61% carbon monoxide (CO), 53% nitrogen oxides (NO), 17% volatile organic compounds, and 13–15% particulate matter (PM) [3]. Road mobility is widely recognized as one of the leading and growing sources of air pollution. For the foreseeable future, road traffic will remain a significant contributor to air pollution in cities across Asia and Europe. Fine particulate matter ($PM_{2.5}$ and PM_{10}) and nitrogen dioxide (NO_2) from transportation are pollutants that substantially impact human exposure and urban air quality [4]. NO_2 has been associated with acute public health hazards, increased mortality rates, and significant economic burdens, making it a prominent environmental and health risk factor [5-7].

There is a strong correlation between greenhouse gas emissions, climate change, and the use of motorized vehicles on highways [8, 9]. Private automobiles and two-wheeled vehicles are the most common forms of transportation in urban areas, where the majority of people reside [7, 10, 11]. In 2019, ambient air pollution was estimated to have caused 4.2 million premature deaths worldwide. According to the World Health Organization (WHO), Southeast Asia and the Western Pacific region accounted for 89% of these early fatalities, predominantly occurring in low- and middle-income countries. Policies and investments aimed at promoting energy-efficient manufacturing, transportation, housing, and power generation could significantly reduce major sources of outdoor air pollution. Moreover, the availability of clean household energy would greatly help lower ambient air pollution levels in certain regions [12].

Air pollution has been a global problem for many years, posing serious threats to human health and the environment, and leading to both morbidity and mortality [13, 14]. Long-term and short-term exposure to ambient air pollution—including CO, NO_2, O_3, and PM—increases the risk of cardiovascular and respiratory disorders, reduces life expectancy, and contributes to years lived with disability [15–21]. Epidemiological studies have linked NO_2, PM_{10}, and $PM_{2.5}$ to decreased respiratory function and bronchitis in children with asthma [22]. Other research indicates that children are more susceptible to respiratory illnesses such as acute respiratory infections, pneumonia, and otitis media when exposed to NO_2, $PM_{2.5}$, and PM_{10} over the short term [23, 24]. Prolonged exposure further affects respiratory development and function [25-27].

Air pollution is the leading environmental health risk and is estimated to be responsible for more than 7 million deaths globally each year. In China, cooler climates and more significant seasonal temperature fluctuations have been associated with higher rates of child mortality in regions where NO_2 and $PM_{2.5}$ levels exceed safety thresholds [28]. The concentration of particulate matter in the air can increase by 15% with a 20°C rise in temperature [29]. Similarly, studies in the EU have found significant positive correlations between mortality and elevated levels of NO_2 and particulate matter [30]. Furthermore, particulate matter (PM), which varies in size but often has extremely fine particles, can be inhaled into the respiratory system, leading to cancer, reproductive and cardiovascular disorders, and problems affecting the central nervous and reproductive systems [31, 32].

Children are particularly vulnerable to air pollution from conception through adolescence. They have higher respiratory rates compared to adults and inhale more air relative to their body weight. Their shorter stature causes them to breathe air closer to the ground, where pollutants, especially those from vehicle emissions, are more concentrated. Higher levels of physical activity and faster breathing rates further increase their exposure. Additionally, children are more prone to mouth breathing than adults, allowing pollutants to penetrate deeper into the more permeable lower respiratory tract. The risks associated with pollution are heightened because children's bodies and organs, including their lungs, are still developing. Their immature immune systems also make them more susceptible to the harmful effects of pollutants [33, 34]. Exposure to NO_2, $PM_{2.5}$, and PM_{10} before birth raises the likelihood of babies being small for their gestational age (SGA) [35], having low birth weight [36], and facing a higher risk of preterm birth [37-39].

Makassar is a city with high population density and significant transportation activity, which can pose environmental health risks to vulnerable groups such as children. Therefore, the objectives of this study are: (1) to determine the levels of NO_2, PM_{10}, and $PM_{2.5}$ pollution in Makassar City; and (2) to evaluate the potential health risks to children and adolescents using the Monte Carlo Simulation (MCS) probabilistic approach for exposure to NO_2, PM_{10}, and $PM_{2.5}$.

2. Material and Methods

This study is analytical in nature, employing a cross-sectional design and utilizing a health risk assessment approach based on the Monte Carlo Simulation (MCS) statistical model. Average concentrations of NO_2, $PM_{2.5}$, and PM_{10} were measured along the main Antang road in Makassar City. Health risk analysis was conducted to estimate the potential health hazards to children and adolescents from both carcinogenic and non-carcinogenic exposures to NO_2, $PM_{2.5}$, and PM_{10}. Additionally, meteorological data—including temperature, humidity, wind direction, and wind speed—were collected at the same location.

2.1. Study Area

The magnitude of NO_2, PM10, and PM2.5 was observed over a 15-day period in the months of March through April 2024. 22 stations from Tamalanrea Indah, Panakkukang, Mariso, Tamalate, and 8 other subdistricts were assessed, as presented in Figure 1.

2.2. Sampling Design

The research samples consisted of both environmental and human data. Environmental samples, including measurements of NO_2, $PM_{2.5}$, and PM_{10}, were collected directly over three days across 22 locations: Tamalanrea Indah, Abdullah Daeng Sirua, Panakkukang Boulevard, Bj. Minasa, Tamarunang, Panambungan, Tj. Bunga, Masjid Kuba, Somba Opu, Penghibur, Sumba, Urip S.1, Urip S.2, Leimena, Antang Raya, Ujung Bori, Toddopuli Raya, Borong, Pandang Raya, Karampuang, Tamalanrea 2, and Tamalanrea. Sampling of $PM_{2.5}$ and PM_{10} was conducted using a High Volume Air Sampler (HVAS), while NO_2 was measured using an impinger. Each day, levels of NO_2 and particulate matter with aerodynamic diameters equal to or less than 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$) were recorded. These data were analyzed alongside meteorological information such as temperature, relative humidity, wind direction, and wind speed.

Human samples comprised a minimum of 66 respondents, with three individuals randomly selected from each location. Data from human subjects were collected through interviews using a structured questionnaire. Informed consent was obtained for adolescents and children, with consent forms signed by their guardians, and participant identities were kept confidential. The questionnaire included questions addressing individual characteristics and health issues experienced by respondents. Additionally, body weight measurements were recorded.

The inclusion criteria for the study participants were ages 11–15 for children and 16–24 for adolescents, residence in Makassar for at least three years, and willingness to participate in the research.

2.3. Data Analysis

The potential health risk analysis was conducted based on guidelines from the Indonesian Ministry of Health, using the collected analytical data. Researchers examined the geographical distribution of NO_2, PM_{10}, and $PM_{2.5}$ using ArcGIS software (version 10.8). The questionnaire gathered information on personal details, employment history, daily routines, smoking habits, indications of dust exposure, and aspects related to health, safety, and the environment.

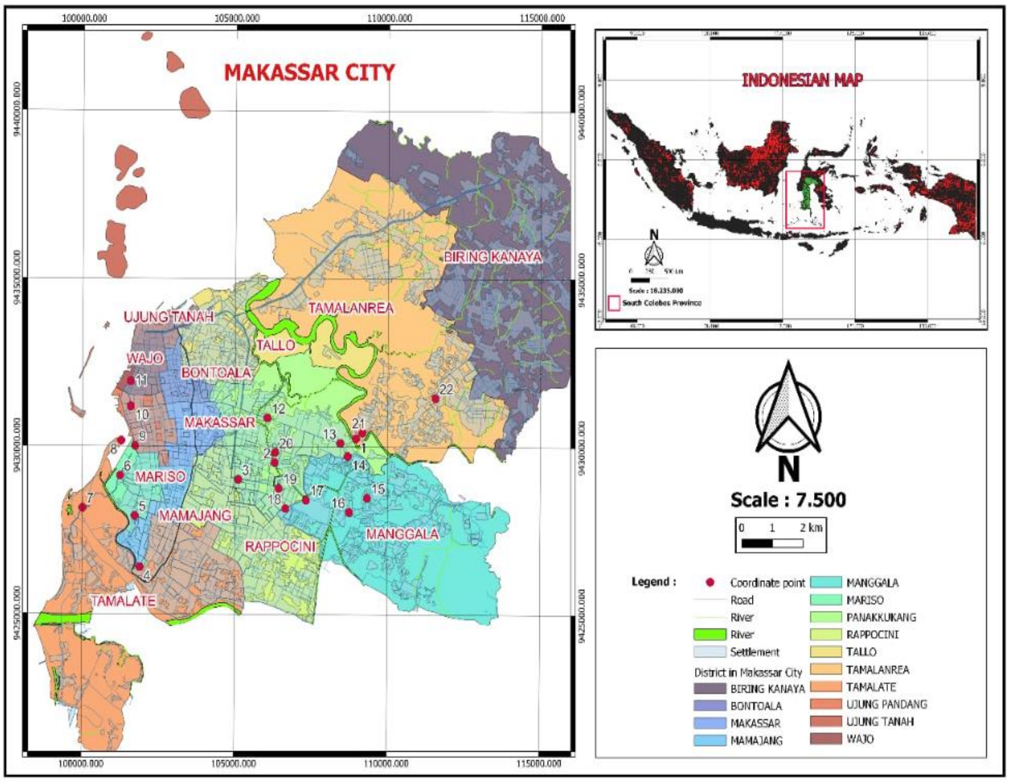


Figure 1. Map of sampling location

2.4. Analyzing the Risks to Non-Cancerous Human Health

Adolescents and schoolchildren were found to have similar non-carcinogenic risks associated with exposure to $PM_{2.5}$ and NO_2. The analysis determined the amount of lead and $PM_{2.5}$ that an individual should inhale daily, as inhalation is the primary route of exposure. Therefore, the health risk assessment focused on this exposure pathway [39]. Equations 1 and 2 illustrate the non-carcinogenic risk analysis for the inhalation route.

$$\text{ADDinh} = \frac{\text{C}\times\ln h_{rate}\times\text{EF}\times\text{ED}\times\text{ET}}{\text{BW}\times\text{AT}} \quad (1)$$

where: ADDinh represents the average daily doses of NO_2, $PM_{2.5}$, and PM_{10} (μg/kg/day); C is the concentration of NO_2, $PM_{2.5}$, and PM_{10} in the air (μg/m³); Inhrate is the inhalation rate, with the USEPA default values set at 9 m³/day for children and 14.9 m³/day for adolescents for residential exposure; EF is the frequency of $PM_{2.5}$ exposure, assumed to be 350 days per year. The USEPA default value for exposure duration (ED) is 24 years for adolescents and 6 years for children. Body weight (BW) is defined as 63.01 kg for adolescents and 34.55 kg for children. AT refers to the average time (ED × 365 days/year) used for estimating non-carcinogenic risk. For $PM_{2.5}$ inhalation, the reference concentration (RfC) is 10 μg/kg/day. An HQ value greater than one indicates that long-term exposure to $PM_{2.5}$ is not safe for the general public.

$$\text{HQinh} = \frac{ADDinh}{RFC} \quad (2)$$

2.5. Statistical Analysis

The analysis conducted was a univariate analysis to determine the frequency distribution of respondents' body weight, which was then incorporated into the individual health risk assessment using the hazard quotient (HQ) formula. An HQ value greater than 1 indicates that chronic exposure to NO_2, $PM_{2.5}$, and PM_{10} is unsafe and poses a health risk to individuals.

3. Results

3.1. Measurement of the Levels of NO_2, $PM_{2.5}$, and PM_{10}

Air quality parameters were measured using a monitoring method, with concentration measurements of NO_2, $PM_{2.5}$, and PM_{10} conducted continuously over a 24-hour period. The results showed variations in the concentrations of NO_2, $PM_{2.5}$, and PM_{10} at different times of the day, with higher levels observed in the mornings and evenings, coinciding with increased vehicle traffic. The guidelines and reference values for these pollutants are presented in Table 1.

Table 1. The recommended guideline value for each pollutant

Pollutant	Guideline value	Averaging time	Guideline reference
Particulate mattaer ($PM_{2.5}$)	5 μg/m³ 15 μg/m³	Annual 24-hour	World Health Organization (WHO), 2021
Particulate mattaer (PM_{10})	15 μg/m³ 45 μg/m³	Annual 24-hour	World Health Organization (WHO), 2021
Carbon monoxide	4 mg/m³	24-hour	World Health Organization (WHO), 2021
Nitrogen dioxide	10 μg/m³ 25 μg/m³	Annual 24-hour	World Health Organization (WHO), 2021
Sulfur dioxide	40 mg/m³	24-hour	World Health Organization (WHO), 2021
Formaldehyde	0.1 mg/m³	30-minute	World Health Organization (WHO), 2010
Polycyclic aromatic hydrocarbons	8.7×10^{-5} per ng/m³	24-hour	World Health Organization (WHO), 2010
Ozon	60 μg/m³	24-hour	World Health Organization (WHO), 2010
Lead	0.5 μg/m³	Annual	(WHO); Regional Office for Europe, 2000
Cadmium	0.0002 mg/kg	24-hour	World Health Organization (WHO), 2010

Table 1 presents the recommended guideline values for each pollutant, including the three pollutants examined in this research, with their respective 24-hour guideline values: NO_2 at 25 μg/m³, $PM_{2.5}$ at 15 μg/m³, and PM_{10} at 45 μg/m³.

3.2. Measurement of Physical Environmental Condition

In addition to measuring the levels of NO_2, $PM_{2.5}$, and PM_{10}, this study also assessed the physical environmental conditions, as presented in Table 2.

Table 2. The physical environmental condition of humidity, temperature, wind speed and direction in Makassar city, 2024

Station	Humidity	Temperature	Wind speed	Wind direction	Latitude	Longitude
1	45	32	17	West	-5.144873º	119.473914º
2	42	33	18.5	West	-5.151229º	119.449873º
3	43	31	16	Northwest	-5.155724º	119.439146º
4	48	32	14.8	Northwest	-5.17921º	119.410036º
5	48	32	13	West	-5.16539º	119.408593º
6	45	31	11.1	West	-5.154554º	119.404314º
7	47	32	12	Northwest	-5.163247º	119.393212º
8	51	28	9.3	Northwest	-5.145169º	119.404672º
9	61	28	5.6	North	-5.146598º	119.408711º
10	60	29	7.7	North	-5.135943º	119.40749º
11	56	27	62	East	-5.129185º	119.40748º
12	61	28	7.4	East	-5.139227º	119.447779º
13	53	27	44	East	-5.146064º	119.469274º
14	37	33	13	Northeast	-5.149598º	119.471455º
15	38	30	12	Northeast	-5.160859º	119.477146º
16	37	29	13	East	-5.164661º	119.471817º
17	35	31	15	Northeast	-5.161332º	119.459112º
18	37	33	13	East	-5.163574º	119.453042º
19	35	30	11.1	North	-5.158152º	119.451058º
20	33	32	13	North	-5.14853º	119.450034º
21	33	32	13	North	-5.143284º	119.475757º
22	34	30	14	North	-5.134058º	119.497343º

Table 2 presents measurements of the physical environmental conditions in Makassar City, including humidity, temperature, wind direction, and wind speed. All variables showed variation, with humidity ranging between 31–61%, temperature between 27–33°C, wind speed between 5.6–62 m/s, and wind direction as detailed in Table 2.

3.3. Measurement of Magnitude Concentration of NO_2, PM_{10} and $PM_{2.5}$

Table 3 presents the measurement results for NO_2, PM_{10}, and $PM_{2.5}$, which were obtained while driving along designated routes using authorized real-time internet monitors. Complementing these measurements were readings of temperature, humidity, wind direction, wind speed, and data from the global positioning system. In accordance with quality assurance guidelines for mobile measurements, all 22 monitoring trips were conducted on weekdays along consistent routes through Makassar City's congested roads. The measurements were taken during regular business hours, between 09:00 and 16:00.

Furthermore, field measurements indicated that the mean concentrations of $PM_{2.5}$, PM_{10}, and NO_2 exceeded the WHO air quality standards in the locations surveyed. The WHO Air Quality Guidelines (WHO-AQGs) specify limits for NO_2, $PM_{2.5}$, and PM_{10} of 16 µg/m³, 5 µg/m³, and 12 µg/m³, respectively, for both short-term (24-hour average) and long-term (annual average) exposures [40]. The concentrations of NO_2, $PM_{2.5}$, and PM_{10} observed during this study were higher than both the WHO AQG limits and the air quality standards established in Indonesia [41]. The spatial distributions of these pollutants are shown in Table 3, highlighting differences in the levels of NO_2, $PM_{2.5}$, and PM_{10} between Makassar City and other regions.

Table 3. The magnitude concentration of NO_2, PM_{10} and $PM_{2.5}$ in Makassar City, 2024

Station	NO_2 µg/m³	PM_{10} µg/m³	$PM_{2.5}$ µg/m³	Latitude	Longitude
1	2.91	13.55	7.62	-5.144873°	119.473914°
2	4.07	11.92	6.48	-5.151229°	119.449873°
3	1.5	20.2	29.5	-5.155724°	119.439146°
4	1.0	20.0	30.0	-5.17921°	119.410036°
5	9.0	14.32	10.26	-5.16539°	119.408593°
6	6.34	12.55	6.95	-5.154554°	119.404314°
7	3.21	10.82	4.66	-5.163247°	119.393212°
8	7.37	13.73	7.83	-5.145169°	119.404672°
9	6.77	12.44	7.11	-5.146598°	119.408711°
10	1.0	22.0	9.0	-5.135943°	119.4049°
11	1.3	22.1	30.8	-5.129185°	119.40748°
12	10.88	18.89	7.42	-5.139227°	119.447779°
13	6.6	10.49	5.92	-5.146064°	119.469274°
14	2.91	18.52	10.8	-5.149598°	119.471455°
15	7.71	21.93	9.01	-5.160859°	119.477146°
16	2.44	23.67	15.13	-5.164661°	119.471817°
17	10.97	12.22	10.03	-5.161332°	119.459112°
18	0.23	12.86	4.93	-5.163574°	119.453042°
19	7.8	18.42	9.31	-5.158152°	119.451058°
20	2.16	30.14	19.31	-5.14853°	119.450034°
21	2.96	24.8	15.3	-5.143284°	119.475757°
22	0.19	12.71	4.8	-5.134058°	119.497343°

Table 3 shows that the highest NO_2 concentrations were recorded at station 12 in Panakkukang and station 17 in Borong, both located near a local medium-sized industrial area, with levels of 10.88 µg/m³ and 10.97 µg/m³, respectively. Higher PM_{10} levels were observed at station 21 in Tamalanrea Indah and station 20 in Karampuang, with concentrations of 24.8 µg/m³ and 30.14 µg/m³, respectively. These areas, situated on a flat alluvial plain, are primarily inhabited by merchants who operate businesses along the streets. Moreover, elevated levels of these pollutants in roads, residential areas, and certain schools may be attributed to the dispersion of $PM_{2.5}$ from various vehicles and small-scale industrial activities. The highest $PM_{2.5}$ concentration was recorded at station 11 in Pattunuang, with a value of 30.8 µg/m³.

3.4. Noncarcinogenic Risks Assessment for Children and Adolescents

Two age groups were included in determining the non-carcinogenic risk ratios for NO_2, PM_{10}, and $PM_{2.5}$: children and adolescents over the age of sixteen. The method was used to calculate the estimated daily intake (EDI) of NO_2, PM_{10}, and $PM_{2.5}$ from air, as inhalation of polluted air was considered the most significant exposure route. The health risk assessment (HRA) primarily focused on this pathway, with the results presented in Figure 2.

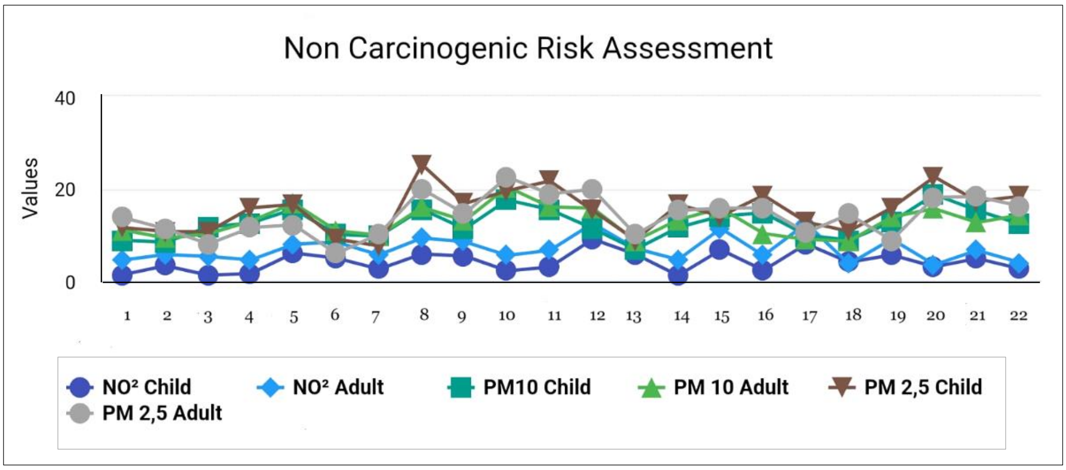


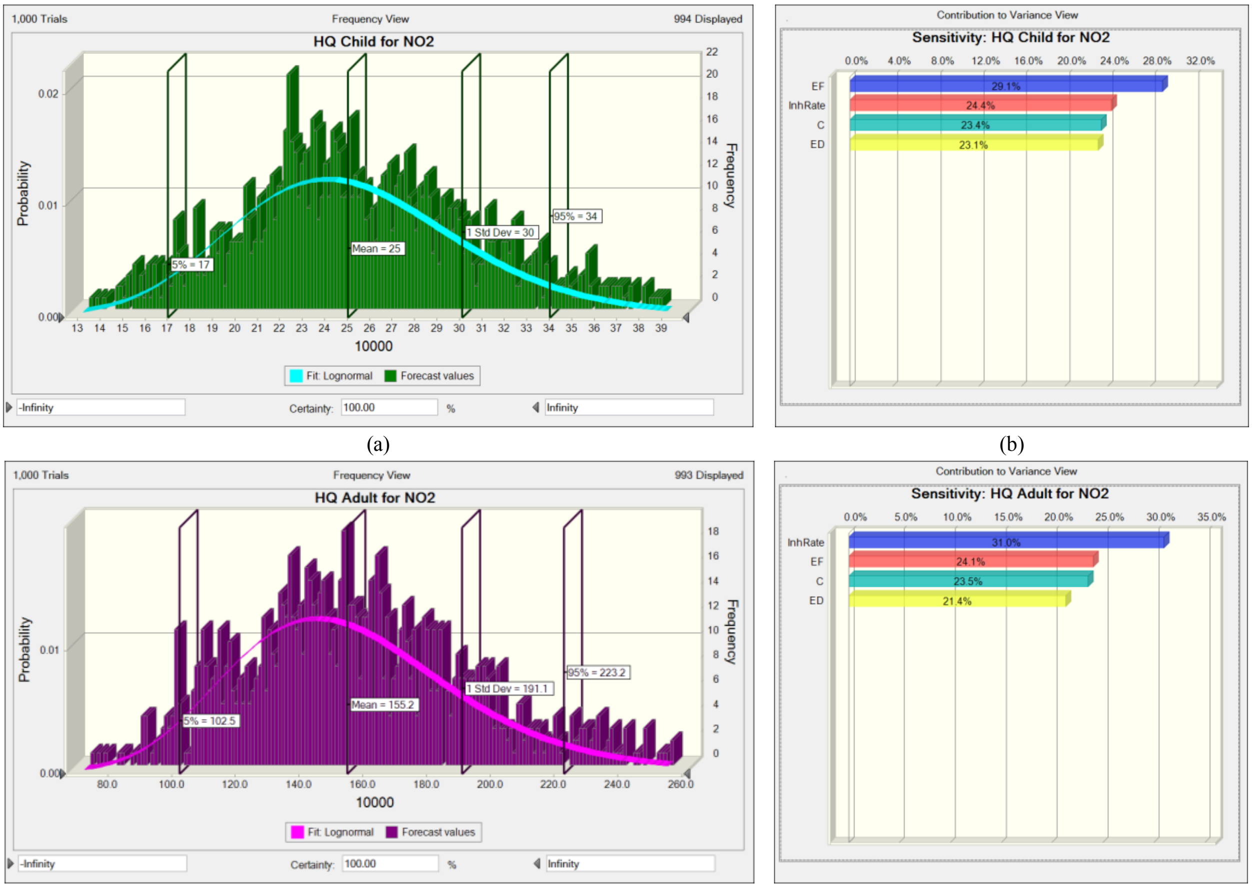
Figure 2. Noncarcinogenic risks assessment for children and adolescents due to expose of NO_2, PM10 and PM2.5 in Makassar City

3.5. Risks Calculation Using Monte Carlo Simulation (MCS)

In this study, the hazards associated with NO_2, PM_{10}, and $PM_{2.5}$ were examined using uncertainty analysis and Monte Carlo simulation. The MCS model is a respected, advanced, and reliable technique that provides precise and accurate point estimates of risk.

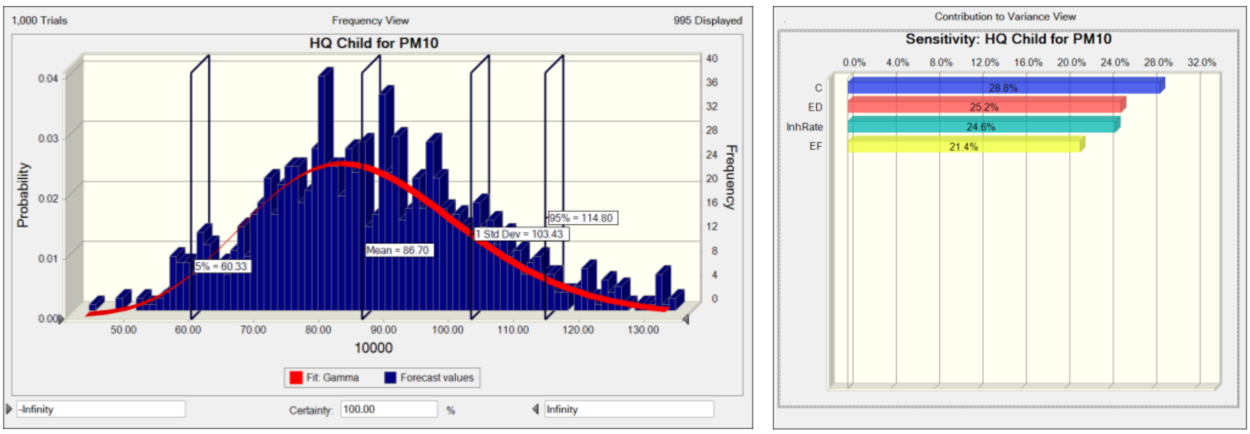
The HQ risk values were calculated based on the daily inhalation rates for both adolescents and children, using deterministic and probabilistic (Monte Carlo simulation) methods. The probability of a child developing cancer at the 5th and 95th percentiles was 13 and 34 for NO_2, indicating moderate risks, whereas for adolescents, the values were 102 and 223, indicating high risks.

According to the sensitivity analysis, the most significant factor contributing to health risks in adolescents was the duration of exposure (ED) at 26.4%, followed by concentration (C) at 18.3%, exposure frequency (EF) at 17.8%, and inhalation rate (IR) at 17.2%, as shown in the sensitivity analysis chart. In contrast, for children, concentration (C) and EF of NO_2 contributed the most at 21.2%, followed by IR at 20.6%, and ED at 17.6%.



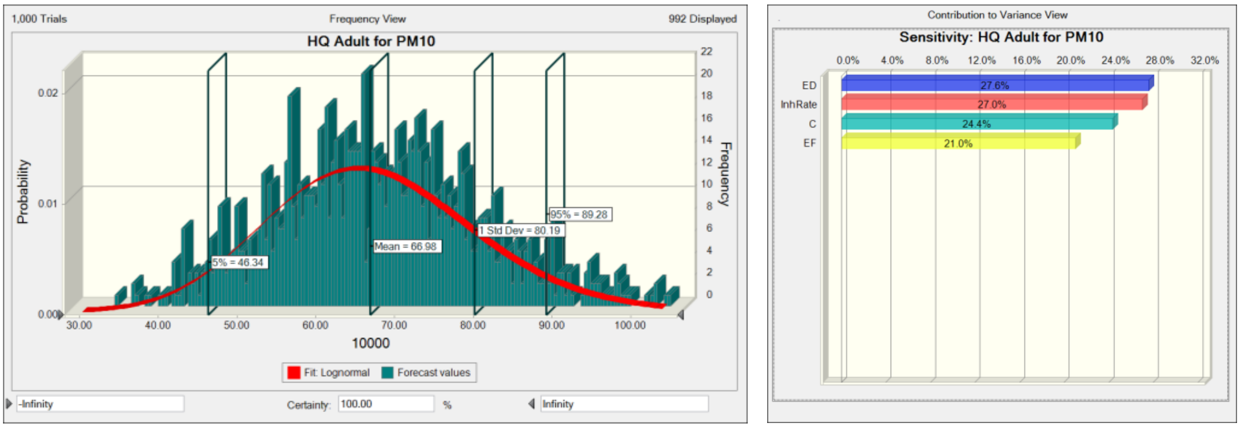
(c) (d)

Figure 3. (a) Probability HQ of children for NO_2, (b) Sensitivity HQ of children for NO_2, (c) Probability HQ of adult for NO_2, and (d) Sensitivity HQ of adult for NO_2



(a) (b)

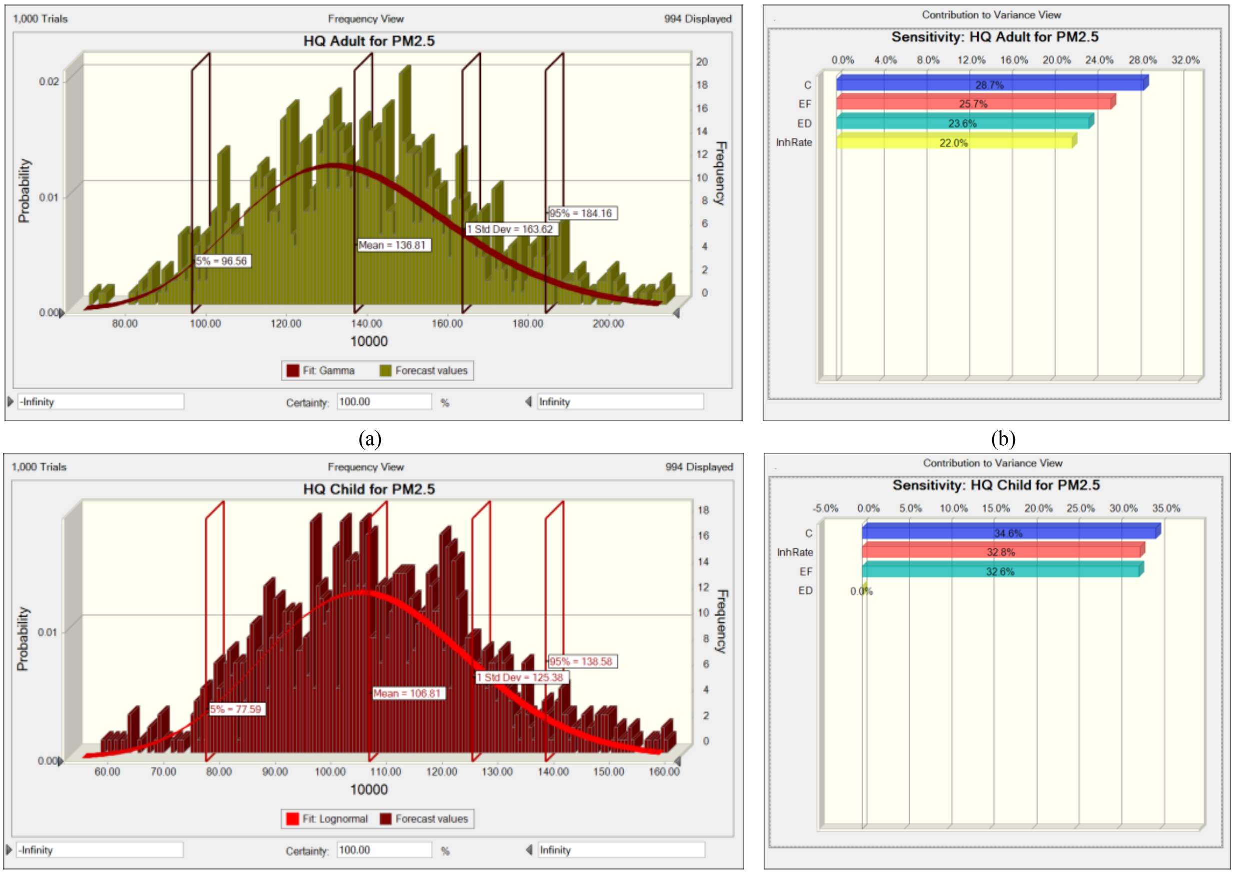
Figure 4. (a). Probability HQ of children for PM_{10}, (b). Sensitivity HQ of children for PM_{10}



(a) (b)

Figure 5. (a). Probability HQ of adult for PM_{10}, (b). Sensitivity HQ of adult for PM_{10}

In Figure 3(a), for children, the inhalation rate (IR) of PM_{10} (21.8%), concentration (C), and exposure duration (ED) (20.9%) made significant contributions. This suggests that the greatest impact on the risk of developing adverse health effects in children was due to exposure to, and concentration of, PM_{10} pollution. Therefore, optimal strategies should focus on reducing the rate of inhalation and the duration of exposure at affected locations, along with regular monitoring of industrial emissions near residential areas. This indicates that as the number of discrete exposure events increases, so does the potential risk to residents. Because PM_{10} pollution may contain hazardous substances, both children and adolescents should limit their activities and wear protective gear to reduce their exposure to this type of pollution. Body weight (BW) contributed negatively, suggesting it was of minor importance and could potentially be disregarded. Additionally, HQ risk values based on daily inhalation rates for both adolescents and children were calculated using deterministic and probabilistic (Monte Carlo simulation) methods. The probability of cancer risk in adult communities was found to be 2.85 and 6.11 for NO_2 at the 5th and 95th percentiles, demonstrating moderate risks, while the values for PM_{10} and $PM_{2.5}$ were 0.09 and 0.19, also indicating moderate risks. According to the sensitivity chart in Figure 4, the inhalation rate (IR) of PM_{10} accounted for 23.3%, exposure duration (ED) for 23.3%, exposure frequency (EF) for 18.9%, and concentration (C) for 16.0%. These were the most significant factors contributing to increased health risks in adolescents.



(a) (b) (c) (d)

Figure 6. (a). Probability HQ of Adult for $PM_{2.5}$, (b) Sensitivity HQ of Adult for $PM_{2.5}$, (c) Probability HQ of children for $PM_{2.5}$ and (d) Sensitivity HQ of children for $PM_{2.5}$

In Figure 5, the values of children's HQ risks were determined based on their daily inhalation rates. The probability of cancer risk associated with $PM_{2.5}$ in children was 96.58 and 184.18 at the 5th and 95th percentiles, respectively, indicating moderate risks. In contrast, Figure 6 shows that for adolescents, the values were 77.58 and 138.56, indicating high risks.

Additionally, according to the sensitivity chart in Figure 5, concentration (C) accounted for 56.7%, exposure duration (ED) for 21.6%, exposure frequency (EF) for 19.9%, and inhalation rate (IR) for PM_{10} for 19.3%. These were identified as the most significant factors contributing to increased health risks in adolescents.

3.6. Limitation

A limitation of this research design is determining the number of iterations required to achieve the desired level of confidence and precision.

4. Discussion

4.1. The Magnitude Concentration of NO_2, PM_{10} and $PM_{2.5}$ in Makassar City

The current study provided a comprehensive evaluation of transportation emissions and the exposure of vehicle occupants to NO_2, PM_{10}, and $PM_{2.5}$, as well as the variables influencing human health for individuals living along the busy roads of Makassar City. Environmental factors affect emission levels and the frequency of NO_2 exposure, which may influence NO_x partitioning. As previously observed, there is a positive association between outdoor $PM_{2.5}$ and PM_{10} levels and ambient temperature [42].

According to Table 3, the highest NO_2 levels were recorded at station no. 12 in Panakkukang and station no. 17 in Borong, near a truck parking site, with concentrations of 10.88 µg/m³ and 10.97 µg/m³, respectively. Additionally, higher PM_{10} levels were found at station 21 in Tamalanrea Indah and station 20 in Karampuang, with values of 24.8 and 30.14 µg/m³, respectively. For in-vehicle NO_2 and $PM_{2.5}$, road traffic conditions were minor predictors, with $PM_{2.5}$ being the second most significant predictor. Huang et al. [43] also observed in Los Angeles that traffic density impacted $PM_{2.5}$ and NO_2 levels inside vehicles. Other studies similarly reported that vehicle density contributes to increased concentrations of NO_2 and particulate matter [44-47].

A study conducted in Northern Thailand found that the proportion of the population who died from cardiac illnesses and lung cancer due to $PM_{2.5}$ pollution was approximately 0.04% and 0.06%, respectively [48]. The burden of outdoor air pollution is disproportionately higher in low- and middle-income nations, where 89% of the 4.2 million premature deaths worldwide occur. The WHO regions of the Western Pacific and South-East Asia bear the highest burden. The significant contribution of air pollution to cardiovascular disease and mortality is reflected in the latest burden estimates [48]. Additional research indicates that low-income communities are more likely to experience morbidity and mortality due to exposure to $PM_{2.5}$, PM_{10}, and NO_2 [49, 50].

According to another study, the three-year average concentrations for PM2.5, NO_2, and O_3 were 38.63 (±12.83) parts per billion volume (ppbv), 135.90 (±47.82) ppbv, and 68.95 (±39.86) µg/m³, respectively (Kazemi et al., 2024). In Iran, the total number of natural deaths attributed to NO_2 and PM2.5 across all years was 4,391 and 4,061, respectively. The current document also provides more precise findings regarding the causal relationship between mortality among Medicare beneficiaries (aged 65 years and older) and long-term exposure to PM2.5, even at levels equal to or below 12 µg/m³ [51]. It was observed that accounting for the other two pollutants slightly reduced the causal effects of PM2.5 exposure while slightly increasing the causal effects of NO_2 exposure on all-cause mortality when comparing results from multi-pollutant and single-pollutant models. In contrast, the outcomes for O_3 remained largely unchanged [52-54].

Increased wind speeds facilitate the faster and wider dispersion of NO_2 and PM_{10} particulate matter in the atmosphere, thus reducing PM2.5 concentrations [55-57]. Other findings indicate that winds between two and four meters per second can raise PM2.5 levels in Nantong, China. In western China, summer is characterized by the lowest CO concentrations and the highest PM2.5 levels, while Beijing records high CO concentrations [58].

Moreover, the hourly averages of PM_{10} and $PM_{2.5}$ concentrations in Table 3 show similar fluctuation patterns, particularly up to around 15:00 in the afternoon. After this time, particle number concentrations remain steady, but the hourly mean concentrations decrease. This discrepancy may result from different particle sources, counts, and lifetimes. Additionally, NO_2 levels, which are lower than those of PM_{10} and $PM_{2.5}$, can originate from various sources, with submicrometer particles often emitted directly from moving vehicles. During the early nighttime hours, particle concentrations remain relatively stable, whereas NO_2 gas concentrations vary considerably. This phenomenon is attributed to reduced atmospheric mixing at night and the development of a lower nocturnal boundary layer [59-61].

4.2. Monte Carlo Simulation

Considering the observed levels of exposure, Monte Carlo Simulation (MCS) determines the probability of ecological or health effects by analyzing the relationship between exposure frequency and environmental or health outcomes. It also characterizes the degree of uncertainty associated with the estimated risks. In this study, MCS was employed to examine factors contributing to the uncertainty around the anticipated risk and to quantify both risk and exposure. The simulation analysis was conducted using Microsoft Excel 2019 in conjunction with Oracle Crystal Ball software, version 11.1.2.

Among children, the NO_2 levels at the 5th and 95th percentiles were 13 and 34, indicating medium risks. For adolescents, the levels were 102 and 223, suggesting high risks. The hazard quotients (HQs) for $PM_{2.5}$, PM_{10}, and NO_2 were evaluated for both adolescents and children. The results of the MCS simulation demonstrated that the likelihood of cancer risk occurrence for children at the 5th and 95th percentiles for NO_2 was 13 and 34, respectively, indicating medium hazards. Elevated levels of NO_2, PM_{10}, and $PM_{2.5}$ suggest a greater potential threat to both adult and pediatric health. As shown in the results, the sensitivity analysis for adults revealed that the duration of exposure (ED) was the most significant factor contributing to increased health risks in adolescents (26.4%). This was followed by concentration (C) at 18.3%, exposure frequency (EF) at 17.8%, and inhalation rate (IR) at 17.2%, according to the sensitivity chart. In contrast, for children, the highest contributions came from NO_2 concentration (C) and exposure frequency (EF) at 21.2%, followed by inhalation rate (IR) at 20.6%, and exposure duration (ED) at 17.6%.

The elevated HQ values observed for children and adolescents throughout much of the year in Indonesia are largely attributed to dusty weather conditions, primarily resulting from traffic emissions. Additionally, monitoring was conducted in June, which is considered to have the windiest days of the year. Prevailing winds significantly influence the distribution of airborne particulate matter. Consequently, communities located near major roads and exposed to natural wind currents tend to accumulate more dust [19, 20]. This aligns with other studies indicating that gases and particulate matter tend to accumulate more in the surrounding air and on ground surfaces [62].

5. Conclusion

The study's findings clearly demonstrate that the concentrations of PM_{10} and NO_2 are not reliable indicators of particle number concentrations. The relationship between PM_{10}, NO_2, and particle count varies throughout the day. A substantial correlation between particle number concentration and NO_2 is observed only at night and during the morning rush hour, whereas this relationship weakens considerably in the afternoon. The average hourly regression slope also fluctuates significantly over time, indicating a weak overall correlation between NO_2 and particle count.

Similarly, the regression slope and correlation between $PM_{2.5}$ and particle number concentration show that $PM_{2.5}$ is a poor predictor of particle number. Moreover, NO_2 and $PM_{2.5}$ pose significant health risks for adolescents, while PM_{10} presents a higher risk for children. The relationship between $PM_{2.5}$ and particle count is influenced solely by wind speed, whereas the relationship between NO_2 and particle count is affected by both wind speed and rainfall.

The study's results also suggest that effective control strategies for managing particle number concentrations should take into account current air quality guidelines, which are primarily based on mass concentrations of emissions.

6. Declarations

6.1. Author Contributions

Conceptualization, A.M.; methodology, A.S., S.P., and W.; formal analysis, W.A.M., R.D.P.A., and A.U.R.; investigation, E.; data curation, D.A.M., S.C., and Sh.P.; writing—original draft preparation, A.M.; writing—review and editing, A.M., A.S., S.P., W.A.M., S.C., D.A.M., W., E., R.D.P.A., A.U.R., and Sh.P.; supervision, A.S. and S.P. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgments

The authors express their gratitude to Risky for his assistance with data collecting and to the laboratory team for their appropriate analysis of the materials.

6.5. Ethical Approval

This research has been designed with attention to the principles of research ethics in accordance with applicable guidelines. This study was approved by the Hasanuddin University Health Research Ethics Commission under protocol number 28920093022.

6.6. Informed Consent Statement

Not applicable.

6.7. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

7. References

[1] Song, H., Deng, S. X., Lu, Z. Z., Li, J. H., Ba, L. M., Wang, J. F., Sun, Z. G., Li, G. H., Jiang, C., & Hao, Y. Z. (2021). Scenario analysis of vehicular emission abatement procedures in Xi'an, China. Environmental Pollution, 269. doi:10.1016/j.envpol.2020.116187.

[2] Zeydan, & Zeydan. (2024). Impacts of travel bans and travel intention changes on aviation emissions due to Covid-19 pandemic. Environment, Development and Sustainability, 26(2), 4955–4972. doi:10.1007/s10668-023-02916-8.

[3] USDT. (2010). Transportation Statistics Annual Report (TSAR). U.S. Department of Transportation (USDT), Washington D.C., United States.

[4] Srisang, W., Jaroensutasinee, K., Jaroensutasinee, M., Khongthong, C., Piamonte, J. R. P., & Sparrow, E. B. (2024). PM2. 5 IoT Sensor Calibration and Implementation Issues Including Machine Learning. Emerging Science Journal, 8(6), 2267-2277. doi:10.28991/ESJ-2024-08-06-08.

[5] Matthaios, V. N., Kang, C. M., Wolfson, J. M., Greco, K. F., Gaffin, J. M., Hauptman, M., Cunningham, A., Petty, C. R., Lawrence, J., Phipatanakul, W., Gold, D. R., & Koutrakis, P. (2022). Factors Influencing Classroom Exposures to Fine Particles, Black Carbon, and Nitrogen Dioxide in Inner-City Schools and Their Implications for Indoor Air Quality. Environmental Health Perspectives, 130(4), 47005. doi:10.1289/EHP10007.

[6] Eum, K. Do, Kazemiparkouhi, F., Wang, B., Manjourides, J., Pun, V., Pavlu, V., & Suh, H. (2019). Long-term NO2 exposures and cause-specific mortality in American older adults. Environment International, 124, 10–15. doi:10.1016/j.envint.2018.12.060.

[7] Fenech, S., & Aquilina, N. J. (2020). Trends in ambient ozone, nitrogen dioxide, and particulate matter concentrations over the Maltese Islands and the corresponding health impacts. Science of the Total Environment, 700, 134527. doi:10.1016/j.scitotenv.2019.134527.

[8] Ernyasih, E., Mallongi, A., Daud, A., Palutturi, S., Stang, S., Thaha, A. R., Ibrahim, E., & Al Madhoun, W. (2023). Health risk assessment through probabilistic sensitivity analysis of carbon monoxide and fine particulate transportation exposure. Global Journal of Environmental Science and Management, 9(4), 933–950. doi:10.22035/gjesm.2023.04.18.

[9] Filigrana, P., Levy, J. I., Gauthier, J., Batterman, S., & Adar, S. D. (2022). Health benefits from cleaner vehicles and increased active transportation in Seattle, Washington. Journal of Exposure Science and Environmental Epidemiology, 32(4), 538–544. doi:10.1038/s41370-022-00423-y.

[10] Bhat, T. H., Farzaneh, H., & Toosty, N. T. (2022). Co-Benefit Assessment of Active Transportation in Delhi, Estimating the Willingness to Use Nonmotorized Mode and Near-Roadway-Avoided PM2.5 Exposure. International Journal of Environmental Research and Public Health, 19(22), 1–22. doi:10.3390/ijerph192214974.

[11] Nagpure, A. S., Gurjar, B. R., Kumar, V., & Kumar, P. (2016). Estimation of exhaust and non-exhaust gaseous, particulate matter and air toxics emissions from on-road vehicles in Delhi. Atmospheric Environment, 127, 118–124. doi:10.1016/j.atmosenv.2015.12.026.

[12] W.H.O. (2021). WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Recommendations on classical air pollutants. World Health Organization, Geneva, Switzerland.

[13] Lin, W. Y., Hsiao, M. C., Wu, P. C., Fu, J. S., Lai, L. W., & Lai, H. C. (2020). Analysis of air quality and health co-benefits regarding electric vehicle promotion coupled with power plant emissions. Journal of Cleaner Production, 247, 119152. doi:10.1016/j.jclepro.2019.119152.

[14] Burnett, R., Chen, H., Szyszkowicz, M., Fann, N., Hubbell, B., Pope, C. A., Apte, J. S., Brauer, M., Cohen, A., Weichenthal, S., Coggins, J., Di, Q., Brunekreef, B., Frostad, J., Lim, S. S., Kan, H., Walker, K. D., Thurston, G. D., Hayes, R. B., … Spadaro, J. V. (2018). Global estimates of mortality associated with longterm exposure to outdoor fine particulate matter. Proceedings of the National Academy of Sciences of the United States of America, 115(38), 9592–9597. doi:10.1073/pnas.1803222115.

[15] Mebrahtu, T. F., Santorelli, G., Yang, T. C., Wright, J., Tate, J., & McEachan, R. R. (2023). The effects of exposure to NO2, PM2.5 and PM10 on health service attendances with respiratory illnesses: A time-series analysis. Environmental Pollution, 333(2). doi:10.1016/j.envpol.2023.122123.

[16] Cui, C., Sadeghifar, H., Sen, S., & Argyropoulos, D. S. (2013). Toward thermoplastic lignin polymers; Part II: Thermal & polymer characteristics of kraft lignin & derivatives. BioResources, 8(1), 864–886. doi:10.15376/biores.8.1.864-886.

[17] Orellano, P., Reynoso, J., Quaranta, N., Bardach, A., & Ciapponi, A. (2020). Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: Systematic review and meta-analysis. Environment International, 142. doi:10.1016/j.envint.2020.105876.

[18] Bakri, S., Apriliani, A. P., Kurniawaty, E., & Mayaquezz, H. (2024). Environmental and Demographic Effects on Vector Borne Disease Incidence: Welfare Role on DHF Reduction. Journal of Human, Earth, and Future, 5(1), 34-50. doi:10.28991/HEF-2024-05-01-03.

[19] Rauf, A. U., Mallongi, A., Daud, A., Hatta, M., Amiruddin, R., Stang, S., Wahyu, A., & Astuti, R. D. P. (2022). Spatial Distribution and Ecological Risk of Potentially Toxic Elements in Maros Regency, Indonesia. Carpathian Journal of Earth and Environmental Sciences, 17(1), 93–100. doi:10.26471/cjees/2022/017/203.

[20] Astuti, R. D. P., Mallongi, A., Amiruddin, R., Hatta, M., & Rauf, A. U. (2021). Risk identification of heavy metals in well water surrounds watershed area of Pangkajene, Indonesia. Gaceta Sanitaria, 35, S33–S37. doi:10.1016/j.gaceta.2020.12.010.

[21] Tsanov, E., Valchev, D., Ribarova, I., & Dimova, G. (2024). Quality of Harvested Rainwater from a Green and a Bitumen Roof in an Air Polluted Region. Civil Engineering Journal, 10(5), 1589-1605. doi:10.28991/CEJ-2024-010-05-015.

[22] Melén, E., Zar, H. J., Siroux, V., Shaw, D., Saglani, S., Koppelman, G. H., Hartert, T., Gern, J. E., Gaston, B., Bush, A., & Zein, J. (2024). Asthma Inception: Epidemiologic Risk Factors and Natural History across the Life Course. American Journal of Respiratory and Critical Care Medicine, 210(6), 737–754. doi:10.1164/rccm.202312-2249SO.

[23] Lee, S. Y., Jang, M. J., Oh, S. H., Lee, J. H., Suh, M. W., & Park, M. K. (2020). Associations between particulate matter and otitis media in children: A meta-analysis. International Journal of Environmental Research and Public Health, 17(12), 1–16. doi:10.3390/ijerph17124604.

[24] Ziou, M., Tham, R., Wheeler, A. J., Zosky, G. R., Stephens, N., & Johnston, F. H. (2022). Outdoor particulate matter exposure and upper respiratory tract infections in children and adolescents: A systematic review and meta-analysis. Environmental Research, 210, 112969. doi:10.1016/j.envres.2022.112969.

[25] Rosser, F., Forno, E., Kurland, K. S., Han, Y. Y., Mair, C., Acosta- Pérez, E., ... & Celedón, J. C. (2020). Annual SO2 exposure, asthma, atopy, and lung function in Puerto Rican children. Pediatric pulmonology, 55(2), 330-337. doi:10.1002/ppul.24595.

[26] Qin, P., Luo, X., Zeng, Y., Zhang, Y., Li, Y., Wu, Y., Han, M., Qie, R., Wu, X., Liu, D., Huang, S., Zhao, Y., Feng, Y., Yang, X., Hu, F., Sun, X., Hu, D., & Zhang, M. (2021). Long-term association of ambient air pollution and hypertension in adults and in children: A systematic review and meta-analysis. Science of the Total Environment, 796, 148620. doi:10.1016/j.scitotenv.2021.148620.

[27] Lim, H. M., Ryoo, S. W., Hong, Y. C., Kim, S. T., Lim, Y. H., & Lee, D. W. (2022). Association between Long-Term Exposure to Fine Particulate Matter and Asthma Incidence among School-Aged Children. Atmosphere, 13(9), 1430. doi:10.3390/atmos13091430.

[28] Ji, J. S., Liu, L., Zhang, J. (Jim), Kan, H., Zhao, B., Burkart, K. G., & Zeng, Y. (2022). NO2 and PM2.5 air pollution co-exposure and temperature effect modification on pre-mature mortality in advanced age: a longitudinal cohort study in China. In Environmental Health: A Global Access Science Source, 21(1), 1–14. doi:10.1186/s12940-022-00901-8.

[29] Leão, M. L. P., Zhang, L., & da Silva Júnior, F. M. R. (2023). Effect of particulate matter (PM2.5 and PM10) on health indicators: climate change scenarios in a Brazilian metropolis. Environmental Geochemistry and Health, 45(5), 2229–2240. doi:10.1007/s10653-022-01331-8.

[30] Brągoszewska, E., & Mainka, A. (2022). Impact of Different Air Pollutants (PM10, PM2.5, NO2, and Bacterial Aerosols) on COVID-19 Cases in Gliwice, Southern Poland. International Journal of Environmental Research and Public Health, 19(21), 14181. doi:10.3390/ijerph192114181.

[31] Manisalidis, I., Stavropoulou, E., Stavropoulos, A., & Bezirtzoglou, E. (2020). Environmental and health impacts of air pollution: a review. Frontiers in public health, 8, 14. doi:10.3389/fpubh.2020.00014.

[32] Ponzano, M., Schiavetti, I., Bergamaschi, R., Pisoni, E., Bellavia, A., Mallucci, G., Carmisciano, L., Inglese, M., Cordioli, C., Marfia, G. A., Cocco, E., Immovilli, P., Pesci, I., Scandellari, C., Cavalla, P., Radaelli, M., Vianello, M., Vitetta, F., Montepietra, S., … Sormani, M. P. (2022). The impact of PM2.5, PM10 and NO2 on Covid-19 severity in a sample of patients with multiple sclerosis: A case-control study. Multiple Sclerosis and Related Disorders, 68, 104243. doi:10.1016/j.msard.2022.104243.

[33] Osborne, S., Uche, O., Mitsakou, C., Exley, K., & Dimitroulopoulou, S. (2021). Air quality around schools: Part I - A comprehensive literature review across high-income countries. Environmental Research, 196(January), 110817. doi:10.1016/j.envres.2021.110817.

[34] Parasin, N., Amnuaylojaroen, T., & Saokaew, S. (2023). Exposure to PM10, PM2.5, and NO2 and gross motor function in children: a systematic review and meta-analysis. European Journal of Pediatrics, 182(4), 1495–1504. doi:10.1007/s00431-023-04834-3.

[35] Pun, V. C., Dowling, R., & Mehta, S. (2021). Ambient and household air pollution on early-life determinants of stunting—a systematic review and meta-analysis. Environmental Science and Pollution Research, 28(21), 26404–26412. doi:10.1007/s11356-021-13719-7.

[36] Ghosh, R., Causey, K., Burkart, K., Wozniak, S., Cohen, A., & Brauer, M. (2021). Ambient and household PM2.5 pollution and adverse perinatal outcomes: A meta-regression and analysis of attributable global burden for 204 countries and territories. PLoS Medicine, 18(9), 1–22. doi:10.1371/journal.pmed.1003718.

[37] Nyadanu, S. D., Dunne, J., Tessema, G. A., Mullins, B., Kumi-Boateng, B., Bell, M. L., Duko, B., & Pereira, G. (2024). Maternal exposure to ambient air temperature and adverse birth outcomes: An umbrella review of systematic reviews and meta-analyses. Science of the Total Environment, 917, 119465. doi:10.1016/j.scitotenv.2024.170236.

[38] Yu, Z., Zhang, X., Zhang, J., Feng, Y., Zhang, H., Wan, Z., Xiao, C., Zhang, H., Wang, Q., & Huang, C. (2022). Gestational exposure to ambient particulate matter and preterm birth: An updated systematic review and meta-analysis. Environmental Research, 212(Pt C), 113381. doi:10.1016/j.envres.2022.113381.

[39] Rauf, A. U., Mallongi, A., Hatta, M., Astuti, R. D. P., & Malik, T. G. (2024). Integrating dynamic modeling into health risk analysis to reduce the exposure of potentially hazardous elements. International Journal of Environmental Science and Technology, 21(13), 8617–8634. doi:10.1007/s13762-024-05537-4.

[40] Matthaios, V. N., Harrison, R. M., Koutrakis, P., & Bloss, W. J. (2023). In-vehicle exposure to NO2 and PM2.5: A comprehensive assessment of controlling parameters and reduction strategies to minimise personal exposure. Science of the Total Environment, 900, 900 165537. doi:10.1016/j.scitotenv.2023.165537.

[41] Government Regulations, (2021). Government Regulation of the Republic of Indonesia Number 22 of 2021 concerning the Implementation of Environmental Protection and Management. Republik Indonesia, Jakarta, Indonesia.

[42] Shaltout, A. A., Kadi, M. W., Abd-Elkader, O. H., & Boman, J. (2024). Environmental and health risks of potentially toxic elements in ambient PM10 in Jeddah, Saudi Arabia. International Journal of Environmental Science and Technology, 21(8), 6261–6274. doi:10.1007/s13762-023-05405-7.

[43] Huang, S., Li, H., Wang, M., Qian, Y., Steenland, K., Caudle, W. M., Liu, Y., Sarnat, J., Papatheodorou, S., & Shi, L. (2021). Long-term exposure to nitrogen dioxide and mortality: A systematic review and meta-analysis. Science of the Total Environment, 776. doi:10.1016/j.scitotenv.2021.145968.

[44] Jia, C., Li, W., Wu, T., & He, M. (2021). Road traffic and air pollution: Evidence from a nationwide traffic control during coronavirus disease 2019 outbreak. Science of the Total Environment, 781, 146618. doi:10.1016/j.scitotenv.2021.146618.

[45] Guaman, M., Roberts-Semple, D., Aime, C., Shin, J., & Akinremi, A. (2022). Traffic Density and Air Pollution: Spatial and Seasonal Variations of Nitrogen Dioxide and Ozone in Jamaica, New York. Atmosphere, 13(12), 2042. doi:10.3390/atmos13122042.

[46] Krall, J. R., Thornburg, J., Zhang, T., Pollack, A. Z., Lee, Y. C., McCombs, M., & Henneman, L. R. F. (2024). Short-Term Associations of Road Density and Road Features with In-Vehicle PM2.5 during Daily Trips in the Washington, D.C. Metro Area. Environments, 11(7), 135. doi:10.3390/environments11070135.

[47] Zhao, S., Fan, Y., Zhao, P., Mansourian, A., & Ho, H. C. (2024). How do taxi drivers expose to fine particulate matter (PM2.5) in a Chinese megacity: a rapid assessment incorporating with satellite-derived information and urban mobility data. International Journal of Health Geographics, 23(1), 9. doi:10.1186/s12942-024-00368-5.

[48] Dominici, F., Zanobetti, A., Schwartz, J., Braun, D., Sabath, B., & Wu, X. (2022). Assessing Adverse Health Effects of Long-Term Exposure to Low Levels of Ambient Air Pollution: Implementation of Causal Inference Methods. Research Report (Health Effects Institute), 211, 1–56.

[49] Al-Kindi, S. G., Brook, R. D., Biswal, S., & Rajagopalan, S. (2020). Environmental determinants of cardiovascular disease: lessons learned from air pollution. Nature Reviews Cardiology, 17(10), 656–672. doi:10.1038/s41569-020-0371-2.

[50] Janjua, S., Powell, P., Atkinson, R., Stovold, E., & Fortescue, R. (2019). Individual-level interventions to reduce personal exposure to outdoor air pollution and their effects on long-term respiratory conditions. Cochrane Database of Systematic Reviews, 10. doi:10.1002/14651858.CD013441.

[51] Kazemi, Z., Jonidi Jafari, A., Farzadkia, M., Amini, P., & Kermani, M. (2024). Evaluating the mortality and health rate caused by the PM2.5 pollutant in the air of several important Iranian cities and evaluating the effect of variables with a linear time series model. Heliyon, 10(6), e27862. doi:10.1016/j.heliyon.2024.e27862.

[52] Klompmaker, J. O., Janssen, N. A., Bloemsma, L. D., Marra, M., Lebret, E., Gehring, U., & Hoek, G. (2021). Effects of exposure to surrounding green, air pollution and traffic noise with non-accidental and cause-specific mortality in the Dutch national cohort. Environmental health, 20, 1-16. doi:10.1186/s12940-021-00769-0.

[53] Ma, Y., Nobile, F., Marb, A., Dubrow, R., Stafoggia, M., Breitner, S., Kinney, P. L., & Chen, K. (2024). Short-Term Exposure to Fine Particulate Matter and Nitrogen Dioxide and Mortality in 4 Countries. JAMA Network Open, 7(3), E2354607. doi:10.1001/jamanetworkopen.2023.54607.

[54] Kasdagli, M. I., Orellano, P., Pérez Velasco, R., & Samoli, E. (2024). Long-Term Exposure to Nitrogen Dioxide and Ozone and Mortality: Update of the WHO Air Quality Guidelines Systematic Review and Meta-Analysis. International Journal of Public Health, 69(1607676). doi:10.3389/ijph.2024.1607676.

[55] Afifa, Arshad, K., Hussain, N., Ashraf, M. H., & Saleem, M. Z. (2024). Air pollution and climate change as grand challenges to sustainability. Science of the Total Environment, 928, 172370. doi:10.1016/j.scitotenv.2024.172370.

[56] Purnomo, A., Andang, A., Badriah, S., Paryono, E., Sambas, A., & Umar, R. (2024). Influence of Wind Speed and Direction on the Performance of Low-Cost Particulate Matter Sensors. Environment and Ecology Research, 12(4), 446–455. doi:10.13189/eer.2024.120409.

[57] Zoran, M. A., Savastru, R. S., Savastru, D. M., & Tautan, M. N. (2020). Assessing the relationship between surface levels of PM2.5 and PM10 particulate matter impact on COVID-19 in Milan, Italy. Science of the Total Environment, 738, 139825. doi:10.1016/j.scitotenv.2020.139825.

[58] Xu, G., Ren, X., Xiong, K., Li, L., Bi, X., & Wu, Q. (2020). Analysis of the driving factors of PM2.5 concentration in the air: A case study of the Yangtze River Delta, China. Ecological Indicators, 110, 105889. doi:10.1016/j.ecolind.2019.105889.

[59] Soleimanpour, M., Alizadeh, O., & Sabetghadam, S. (2023). Analysis of diurnal to seasonal variations and trends in air pollution potential in an urban area. Scientific Reports, 13(1), 21065. doi:10.1038/s41598-023-48420-x.

[60] Kiseleva, O., Kalthoff, N., Adler, B., Kossmann, M., Wieser, A., & Rinke, R. (2021). Nocturnal atmospheric conditions and their impact on air pollutant concentrations in the city of Stuttgart. Meteorological Applications, 28(6), 1–23. doi:10.1002/met.2037.

[61] Gu, Y., Fang, T., & Yim, S. H. L. (2024). Source emission contributions to particulate matter and ozone, and their health impacts in Southeast Asia. Environment International, 186, 108578. doi:10.1016/j.envint.2024.108578.

[62] Baensch-Baltruschat, B., Kocher, B., Stock, F., & Reifferscheid, G. (2020). Tyre and road wear particles (TRWP) - A review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment. Science of the Total Environment, 733, 137823. doi:10.1016/j.scitotenv.2020.137823.