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CASE STUDY

Health risk assessment through probabilistic sensitivity analysis of carbon monoxide and fine particulate transportation exposure

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ABSTRACT

BACKGROUND AND OBJECTIVES: The rising number of vehicles used for transportation, which is attributed to the steady increase in population, is known to be a major contributor of air pollution, which, in turn, can have adverse effects on the environment and human health. Therefore, in this study, we aimed to evaluate the concentration of carbon monoxide and fine particulate matter in the air and their potential health risks and further examine the use of probabilistic methods to simulate the sensitivity of people living in communities and school children to these pollutants.
METHODS: This study collected carbon monoxide and fine particulate matter samples from 32 stations near community houses and 14 sites near schools located along roads. Hazard quotient and target hazard quotient calculations were used to estimate the non-carcinogenic health risks associated with exposure to these substances for both community adults and school children. Finally, Monte Carlo simulations were applied to analyze the sensitivity and uncertainty risks.
FINDINGS: As per the results, the highest level of carbon monoxide was recorded in station 22, with 6729 microgram per cubic meter, while the lowest was in station 24, with 1037 microgram per cubic meter. Station 10 had the highest concentration of fine particulate matter at 116 microgram per cubic meter, as opposed to station 2 with the lowest level at 10 microgram per cubic meter. In children, the hazard quotient value for carbon monoxide was found to be highest at 3.013, with the lowest at 0.614. Similarly, the highest level of target hazard quotient for carbon monoxide in children was 7.370, whereas the lowest was 1.522. For fine particulate matter, the highest risk level was 0.180. Additionally, the highest, and lowest levels of target hazard quotient for fine particulate matter were 0.311 and 0.037, respectively. Deterministic and probabilistic approaches were used to assess the risks these pollutants impose on adults and school children based on their daily inhalation rate. The results revealed that the 5th and 95th percentiles of cancer risk for carbon monoxide in adults were 2.85 and 6.11, respectively, indicating medium risks. However, for fine particulate matter, the 5th, and 95th percentiles were 0.09 and 0.19, respectively, signifying lower risks. For school children, the percentiles for carbon monoxide and fine particulate matter were 1.20 and 2.50, respectively, demonstrating higher risks.
CONCLUSION: As per the results, it was determined that the hazard quotient risk for carbon monoxide in adults exceeded the standard, >1, thus posing a risk. Only three stations had hazard quotient values lower than 1, which is deemed of safe level. Most of the fine particulate matter risk assessment results had hazard quotient values lower than 1, indicating a safe level. However, all other 30 stations had exceeded the World Health Organization standard (>1), thus demonstrating risks. The likelihood of the inhabitants being at risk increased as the frequency of discrete exposure occurrences increased; this is evidenced by target hazard quotient calculation results for both carbon monoxide and fine particulate matter at the 32 monitored station areas. These results warrant that future research should focus on reducing carbon monoxide and fine particulate matter in the environment by fostering awareness among local and national stakeholders as well as the academe; this may allow South Tangerang to become a center of excellence for green schools in the area.

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6

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2

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INTRODUCTION

The dependence of people on private vehicles instead of public transportation presents a significant public health challenge (Wang *et al.*, 2019; Gao *et al.*, 2020). The use of motorized vehicles on roads has been strongly linked to greenhouse gas emissions and climate change (Filigrana *et al.*, 2022; Bath *et al.*, 2022). In urban areas where the majority of the population resides (Sarigiannis *et al.*, 2016), private cars and two-wheeled vehicles are the most commonly used means of transportation (Nagpur *et al.*, 2016; Lin *et al.*, 2019). The transportation sector has been identified as a major contributor of air pollution (Roth *et al.*, 2019; Song *et al.*, 2021; Zeydan *et al.*, 2023). According to the US Department of Transportation (2022), emissions from transportation consist of 61 percent (%) carbon monoxide (CO), 53% nitrogen dioxide (NO_2), 17% volatile organic compound, and 13%–15% fine particulate matter ($PM_{2.5}$) and particulate matter (PM_{10}) (USDT, 2022). The primary source of traffic-related air pollution in ambient air is the combustion of fuel in vehicles, with CO, and $PM2_{.5}$ being the primary pollutants. Community exposure to pollutants depends on their physical activity and mode of transportation used, as well as the location of schools close to main roads for school children (Khreis, 2020). Vehicle emissions can disperse based on meteorological conditions such as wind speed and humidity (Li *et al.*, 2022; Sbai, *et al.*, 2022). Low wind speed causes the concentration of air pollution to remain in the area (Lai *et al.*, 2020), Air pollution is known to have significant negative impacts on human health (Requia *et al.*, 2018; Mak *et al.*, 2021). Street vendors and people living along the main road are among the most affected population groups. Children, elderly, and individuals with heart or lung conditions are more susceptible and have higher risk to the harmful effects of particle pollution. According to estimates, air pollution is responsible for 7 million premature deaths yearly (Mason *et al.*, 2020; Hein *et al.*, 2022). According to the World Health Organization (WHO), air quality guideline levels for $PM_{2.5}$ and CO in 2021 are set at 15 microgram per cubic meter (µg/m^3) and 4 µg/m^3, respectively (WHO, 2021). Meanwhile, the quality standard for CO for 1 hour is 10,000 µg/m^3, 8 hours is 4,000 µg/m^3, and $PM_{2.5}$ is 55 µg/m^3 (Government Regulations, 2021). Examining its inhalation process, CO pollutant enters the body and then binds to hemoglobin, forming a carboxyhemoglobin (COHb) complex, which is more potent than oxygen, impairing the body's ability to supply oxygen to tissues (USEPA, 2011). Concentrations higher than 10% can result in lightheadedness, dyspnea, confusion, headaches, nausea/vomiting, exhaustion, chest discomfort, and loss of consciousness (Soeroso *et al.*, 2020). Short-term exposure to CO has been linked to cardiovascular disease mortality and morbidity based on an epidemiological study (Tian *et al.*, 2018). At long-term and high exposure levels, death resulting from asphyxia may occur; at lesser levels, this may result in myocardial ischemia and rhythm disruption (Liu *et al.*, 2018). In China, short-term CO exposure in adults is associated with years of life lost (YLL). The findings showed that an increase of 1 milligram per cubic meter (mg/m^3) in CO concentrations was linked to a 2.08% increase in daily YLL from non-accidental causes, including coronary heart diseases, respiratory diseases, chronic obstructive pulmonary diseases, and cardiovascular diseases (Wang *et al.*, 2021). $PM_{2.5}$ is a specific type of airborne particle with an aerodynamic diameter of less than 2.5 µm and is known for its adverse effects on the environment and human health. Inhalation of $PM_{2.5}$ may result in serious health problems affecting vital organs such as the hearts and brain; this is common among children who are frequently exposed to this pollutant (Khanna *et al.*, 2018). Several epidemiology studies showed a connection between $PM_{2.5}$ and death rates, as well as cardiovascular and respiratory disorders (Li *et al.*, 2017). On-road transportation sources in New York City alone account for approximately 320 deaths per year, which is attributed to $PM_{2.5}$ exposure in adults and school children (Kheirbek *et al.*, 2016). Higher wind speeds facilitate the diffusion of $PM_{2.5}$ in the air, decreasing its concentration. In a study conducted in Nantong, China, it was determined that wind speed between 2 and 4 meters per second (m/s) could reduce the concentration of $PM_{2.5}$ in the air (Xu *et al.*, 2020). In western China, $PM_{2.5}$ and CO concentrations are lowest in the summer and greatest in the winter (Yang *et al.*, 2019). Similar to Beijing, China, high CO concentrations have been associated with a rise in transportation vehicles in the area and high $PM_{2.5}$ concentrations in Henan due to increased humidity and low wind speeds direction (Liu *et al.*, 2022). According to air quality simulation results, despite traffic limitations, CO concentrations did not decrease in most parts of China due to heavy traffic emissions (Zou *et al.,* 2023). In a study conducted in Bogota, it was found that shorter trip periods and lower exposure concentrations in the cabin led to reduced inhalation doses of $PM_{2.5}$ and CO among TransMiCable users (Ricardo *et al.,* 2023). In Cambodia, the housing, transportation, and waste sectors are identified as the major contributors to the country's total national $PM_{2.5}$ and CO emissions, which are projected to increase by 50 to 150% by 2030, primarily due to the rising transportation emissions. However, reducing these emissions has been seen to prevent over 900 premature deaths (Sokharavuth *et al.,* 2022). In Gilgit-Baltistan, high transportation emissions led to the highest concentrations of $PM_{2.5}$ and CO during summer, negatively affecting children (Hussain *et al.,* 2023). In Viadana, Italy, there was a significant increase of 30% in cases of childhood pneumonia, with $PM_{2.5}$ as the contributing factor (Panunzi *et al.,* 2023). Meanwhile, in Turkey, the concentration of $PM_{2.5}$ in Sanliurfa Elementary School was measured at 31.8 $\mu g/m^3$, which posed significant short-term risk of asthma symptoms (10.9%, 2.4%–19.6%) and long-term prevalence of bronchitis (19.5%, 2.2%–38.8%) in children with asthma. Those children will have a high risk of illness as they are more easily exposed to polluted environments such as pollution (Sahin *et al.,* 2022). In China, a research examining the health risks of adults found short-term exposure to $PM_{2.5}$ is associated with increased insulin resistance and poor glucose homeostasis, with every 10 g/m^3 increase in the 3-day $PM_{2.5}$ moving average was associated with an increase in Fasting Insulins (FINS) (95% CI: 2.35, 6.05), HOMA-B (95% CI: 3.66, 8.26), and HOMA-IR (95% CI: 1.41, 4.64) (Peng *et al.,* 2022). Exposure to $PM_{2.5}$ was also found to reduce liver function by 17.06 (95% CI: 31.53, 2.58) for every 10 $\mu g/m^3$ increase in $PM_{2.5}$ (2-day lag) (Xu *et al.,* 2022). Furthermore, in a study conducted in Wuhan, China, short-term exposure to CO, and $PM2_{.5}$ was determined to have negatively impacted the liver function of people residing in the city's urban areas (Qiu *et al.,* 2021). Due to increasing urbanization and economic growth, motor vehicle usage has risen, significantly increasing $PM_{2.5}$ in emerging nations such as Indonesia. In fact, the yearly average $PM_{2.5}$ level in Indonesia has exceeded the WHO's recommended range by 17 $\mu g/m^3$ since 2022, highlighting its negative impact on public health (Greenstone *et al.,* 2022). In a study conducted in Batam city, $PM_{2.5}$ levels were determined to be as high as 45 ug/m^3 and CO levels to be 35.83 ppm, which might have resulted in the increasing respiratory problems and cardiovascular diseases among the public (Yodi *et al.,* 2019). In Malaysia, to achieve an annual reduction in the overall pollutant emission intensity, the school has constructed and maintained a smart house and a sizable solar parking lot with a capacity of 10 MW, which employs solar- and wind-powered electricity and promotes the use of bicycles and electric scooters (Naderipour *et al.,* 2021). The city of South Tangerang, with its high residential density, industrial areas, and rapid trade growth, and also known as an education center for school children, has been heavily affected by air pollution caused by the increased number of transportation vehicles. In fact, it has been found to be the most polluted city in Indonesia, with high levels of CO and $PM_{2.5}$. The rise in motorized transportation in the area has been identified as one of the leading contributors of air pollution, with data from 2017 to 2018 showing a direct correlation between air pollution, transportation, industrial activities, and human health disturbance disorders (Listyarini *et al.,* 2020). Thus, in this current study, we aimed to assess the levels of $PM_{2.5}$ and CO in the ambient air and evaluate any of their potential effects on health and to then apply probabilistic approaches to determine how communities and school children are affected by these emitted pollutants. This study has been carried out in seven districts of South Tangerang city, Indonesia, in 2023.

MATERIALS AND METHODS

Study method

This analytic observational research of cross-sectional study design was conducted using a Monte Carlo simulation (MCS) statistical model through the health risk assessment approach. Health risk analysis is used to estimate human health risks, both carcinogenic, and non-carcinogenic. CO and $PM_{2.5}$ concentrations were measured from February to March 2023 at 32 points in 7 sub-districts, namely, North Serpong, Serpong, Pondok Aren, Ciputat, East Ciputat, Pamulang, and Setu. Meteorological data such as temperature, humidity, wind direction, and wind speed at the same sites were also collected. Respondents were residents who live along the road and school children whose schools were located

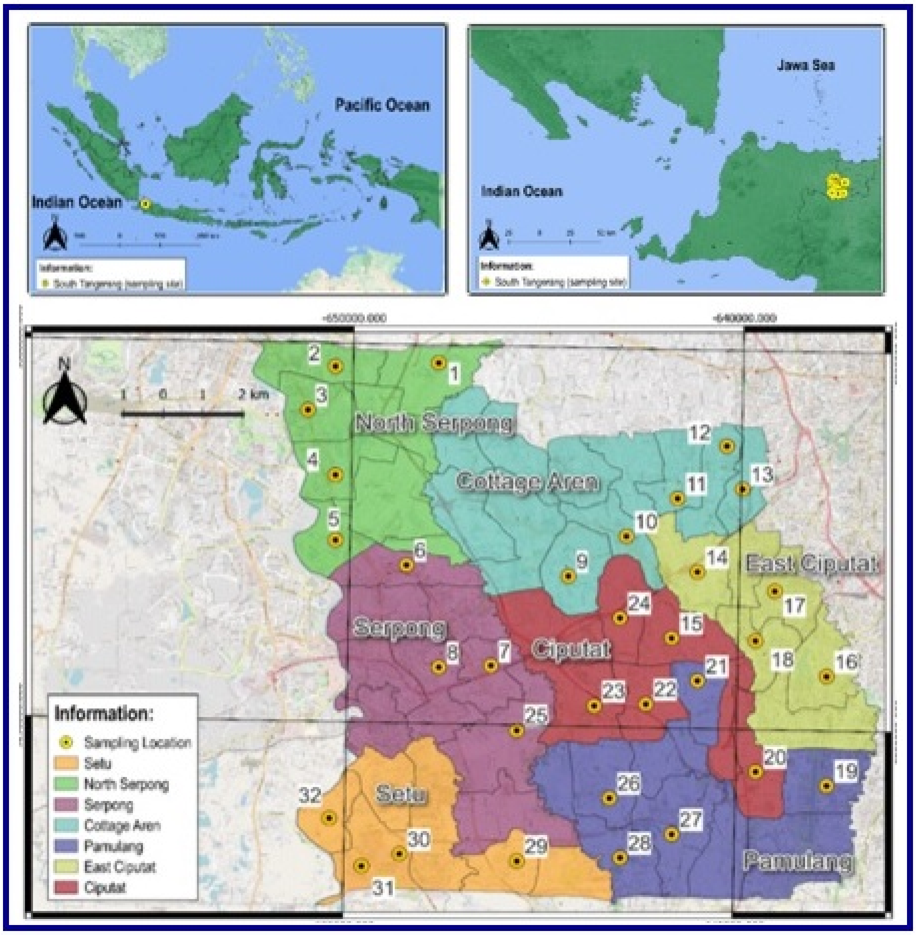

Fig. 1: Geographical location of the study area and the locations of the CO and PM$_{2.5}$ samples in 7 sub-districts of South Tangerang, Indonesia

close to this region. The inclusion criteria for adults were aged 26–45 years old and worked or lived in the main road area for at least 3 years; two respondents were taken per environmental sample point. Exclusion criteria were those who withdrew during the interview. Meanwhile, the inclusion criteria for children were aged 9–15 years and minimum grade of 4–6 in elementary school; at least 4 respondents were taken per school at 14 elementary schools located in the 7 sub-districts.

Study area

The study area situated in the province of Banten, Indonesia, specifically in South Tangerang city, comprised seven sub-districts, namely, North Serpong, Serpong, Pondok Aren, Ciputat, East Ciputat, Pamulang, and Setu. According to satellite imagery, the area's coordinates are 106°38' to 106°47' east longitude and 6°13' to 6°22' south latitude with a population of 1.3 million, as shown in Fig. 1. In total, 32 samples were collected, and measured from 32 points.

Sampling process

For a period of 32 days (January to February 2023), CO, and PM $_{2.5}$ levels were measured every day, and these data were combined with meteorological data including temperature, relative humidity, wind direction, and speed for analysis. Sampling of CO and PM$_{2.5}$ levels was carried out directly using a CO meter for CO samples and a high volume air sampler for $PM_{2.5}$. This study focused on seven households in each district that were located in close proximity to a major road in the southeast. The air quality in this area was influenced by various factors, such as emissions from heavy-duty trucks that distributed industrial products and raw materials, as well as from vehicles on major road. Yellow and white dusts are frequently found on the terraces of homes in the study area, particularly in the mornings, even in the absence of a blowing wind carrying dust. This study focused on a densely populated neighborhood that is home to street vendors, which comprised an industrial zone where factories operate continuously, as shown in Fig. 1.

Data analysis

The United States Environmental Protection Agency (USEPA) has employed human health risk analysis to calculate the health risk of CO and $PM_{2.5}$ exposure for those living near the pollutant point sources including along the main road or dwelling areas. Since inhalation is the primary route for CO and $PM_{2.5}$, this route was assessed by applying formulation of hazard quotient (HQ) and target hazard quotients (THQ) to calculate the magnitude of individual health risks.

Non-carcinogenic human health risk assessment

The non-carcinogenic risk ratio for CO and $PM_{2.5}$ was determined for two age ranges, that is, elementary school students between the ages of 10–16 and adults older than 16 years old. The estimated daily intake of CO and $PM_{2.5}$ was calculated through inhalation as it is considered as the primary exposure route. Therefore, the health risk analysis focused on this pathway. The non-carcinogenic risk analysis equation for the inhalation route is shown in Eqs. 1, 2, and 3 (Edlund *et al.*, 2021; Rauf *et al.*, 2021; 2022; Azhdarpoor *et al*., 2019; USEPA., 1989).

$$ADD_{inh} = \frac{C \times Inh_{rate} \times EF \times ED \times ET}{BW \times AT} \quad (1)$$

$$HQ = \frac{ADD_{inh}}{RfC} \quad (2)$$

$$THQ = \frac{EF \times ED \times IR \times C}{RfC \times BW \times AT} \times 10^{-3} \quad (3)$$

where

ADD: Acceptable daily dose of CO and $PM_{2.5}$ microgram per kilogram/day (µg/kg/d)

HQ: Hazard quotient

C: Ambient of CO and $PM_{2.5}$ concentration (µg/m^3).

Inhrate: Inhalation rate of people for CO, (Ministry of Health of Indonesia Republic) set default value 0.83 m^3/day (adult) and 0.5 m^3/day (children) (Ministry of Health, 2012)

Inhrate: Inhalation rate of people for $PM_{2.5}$, USEPA default value 14.9 m^3/day (adult) and 9 m^3/day (children) (USEPA, 1989)

EF: CO and $PM_{2.5}$ residential exposure frequency for 350 days/year (USEPA, 1991)

ED: Exposure duration, USEPA default value for adult is 24 years old and is 6 years old (Rauf *et al.*, 2022)

BW: Body weight for adult (63.01 kg) and children (34.55 kg) (Rauf *et al.*, 2022; Mallongi, *et al*., 2023)

A: Average time (ED x 365 days/years for non-carcinogenic risk estimation)

RfC: Reference concentration for CO is 46.3 µg/kg/d, and $PM_{2.5}$ inhalation is 10 µg/kg/d (Novirsa and Achmadi., 2012). When HQ value is greater than 1, it means that chronic exposure to CO and $PM_{2.5}$ is not safe for the general population. Future health effects can be non-carcinogenically dangerous to the population, or the risk is minor when the HQ value is lower than 1.

The Monte Carlo simulation

The association between CO, $PM_{2.5}$, and the likelihood of human health risk was determined by examining the distribution of the major variables. The cumulative distribution is expressed in the 5th and 95th percentiles if HQ or THQ < 1 is stating the safe exposure limit for CO, $PM_{2.5}$. Additionally, using Eq. 4, a sensitivity test was conducted to ascertain the element that has the most impact on THQ value in order to create an effective risk management strategy for the population (Millard, *et al*., 1998; Mallongi, *et al.,* 2023).

$$Y = h(X) = h(X_1, X_2, \ldots, X_n) \quad (4)$$

The results were presented as both a probability risk (uncertainty) graph and a variable sensitivity graph. The MCS was conducted using Oracle Crystal Ball software version 11.1.12 rev, which is an add-in for Microsoft Excel 2019. Microsoft was used to compute the risk and the average CO and $PM_{2.5}$ concentrations. The Monte Carlo approach used in the simulation allows for the propagation of uncertainty associated with the input distributions (Ferson., 1996). A collection of spreadsheet-based programs associated with Microsoft Excel called Crystal Ball was used to run the MCS in order to determine any uncertainties in calculating the health quotient. The sensitivity analysis approach was used to evaluate the relative importance of variance in each input parameter to the overall variance in risk (Stroeve *et al*., 2009). This approach provided insights into which input parameters had a greater influence on the uncertainty of the outcome (Soleimani *et al.*, 2020).

RESULTS AND DISCUSSION

Meteorological data

Several variables can influence air pollution, with wind direction, and speed being key contributors to its spread. These elements can cause the pollution to disperse in both horizontal and vertical directions. South Tangerang city is situated adjacent to DKI Jakarta; it has a relatively flat topography, with an average slope of 0%–3% and an elevation range of 0–25 dpl. Meteorological data, including temperature, humidity, wind speed, and direction, are obtained from the online database of the Meteorology, Climatology, and Geophysics Agency of Indonesia (BMKG). The temperature in the studied area ranged from 20°C to 42°C, with an average of 28°C. Relative humidity varied between 61% and 96%, with an average of 73%, while wind speeds ranged from 0.11 m/s to 4 m/s, with an average of 2 m/s. An overview of wind speed is shown in Fig. 2.

The wind rose plot is utilized to analyze wind

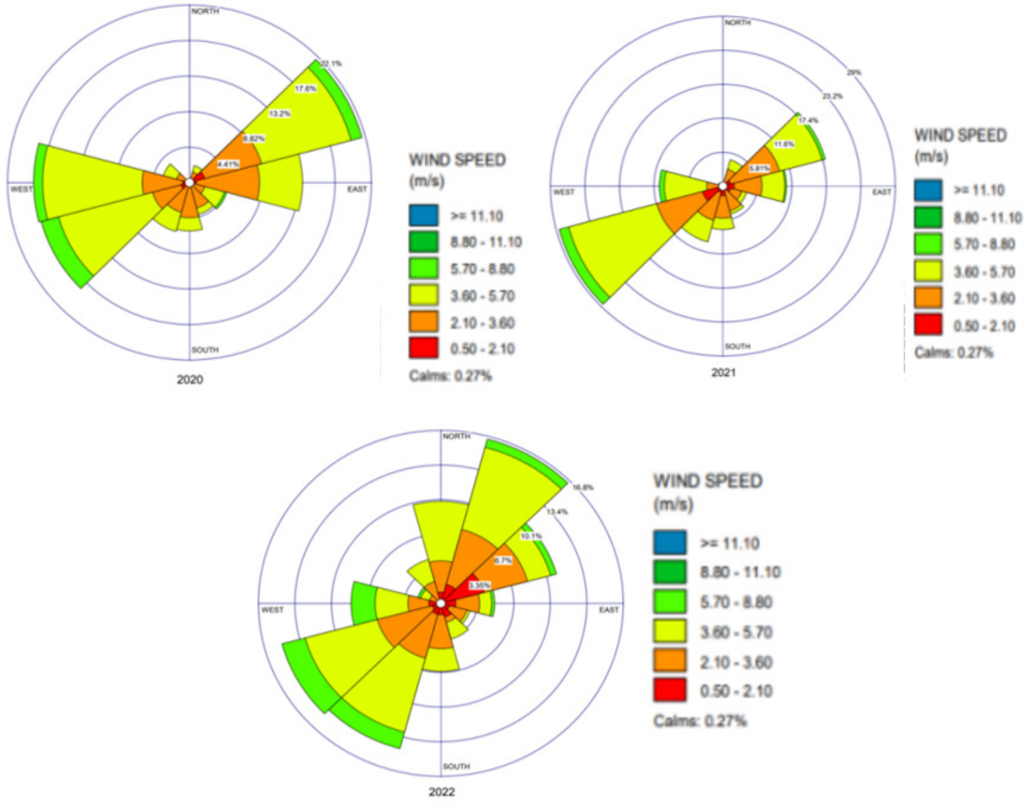

Fig. 2: Annual wind conditions in South Tangerang city in 3 years from 2020 to 2022

conditions using WRPLOT 8.0.2, with a visualization of 106° for a period of 3 years (2020–2022). The wind pattern is quite consistent, but in 2021, the highest frequency direction is southwest, while for 2020, and 2022, the highest frequency direction is northeast. Wind direction is known to affect the concentration of pollutants, particularly when blowing toward highways. The average wind speed is also consistent from 2020 to 2023, with moderate speeds of 50.3%, 43%, and 41.6% in 2020, 2021, and 2022, respectively. Meteorological factors play a critical role in determining air quality. In metropolitan areas of China, for example, moderate wind speeds contribute to the increased distribution and constant concentration of pollutants (Yang *et al*., 2020). Similarly, in the main railroad area of Atlanta, Georgia, changing wind conditions can increase CO concentrations by 1.1–1.2 (Brantley *et al*., 2019). Implementing roadside vegetation or urban woods can help mitigate air pollution levels. In California, USA, roadside vegetation has potentially reduced the average downwind pollutant concentrations by up to 50% (Deshmukh *et al*., 2018).

Measurement of CO and $PM_{2.5}$ *level*

Direct measurements were made all day, starting in the morning, and it was discovered that the concentrations of CO and $PM_{2.5}$ varied at each point. The spatial distributions are shown in Fig. 3, while Tables 1, and 2 highlight the differences in terms of CO and $PM_{2.5}$ concentrations between South Tangerang and other nations. This study found that the average concentrations of CO and $PM_{2.5}$ in the examined area were higher than the WHO air quality recommendation (AQG). For short-term (24-hour average) and long-term (annual average) exposures, the WHO-AQGs for CO, and PM $_{2.5}$ are 15 µg/m^3 and 5 µg/m^3, respectively (WHO, 2021). The concentration levels of CO and $PM_{2.5}$ found in the investigation were below Indonesian air quality standards but exceeded the WHO AQG levels (Government Regulations, 2021). The highest CO and $PM_{2.5}$ were found in the southeastern portion of the industrial area, specifically in Serua Indah, Ciputat district, with levels of 6729 µg/m^3 and 116 µg/m^3, respectively. This area is primarily occupied by traders who own businesses along the streets and is situated on a flat alluvial plain. The distribution of CO and $PM_{2.5}$ from various vehicles and small-scale industrial activities may have contributed to the increased levels of these pollutants in homes and some schools in the community. Tables 1 and 2 show the concentration differences of CO and $PM_{2.5}$ between South Tangerang and other nations. The adults' population faced the highest HQ risk for CO and PM2.5 with scores of 22,589 and 1.7, respectively. The highest and lowest THQ risks were measured at 8.992, and 1.386.

The highest and lowest risks of HQ for children with CO were 3.013 and 0.614, respectively. The highest HQ level of $PM_{2.5}$ was 0.180. In addition, the highest value of target hazard quotient (THQ) for CO of children was 7.370, whereas the lowest was 1.522 unit less. The highest level of THQ of PM 2.5 was 0.311 and the lowest was 0.037 unit less, respectively. According

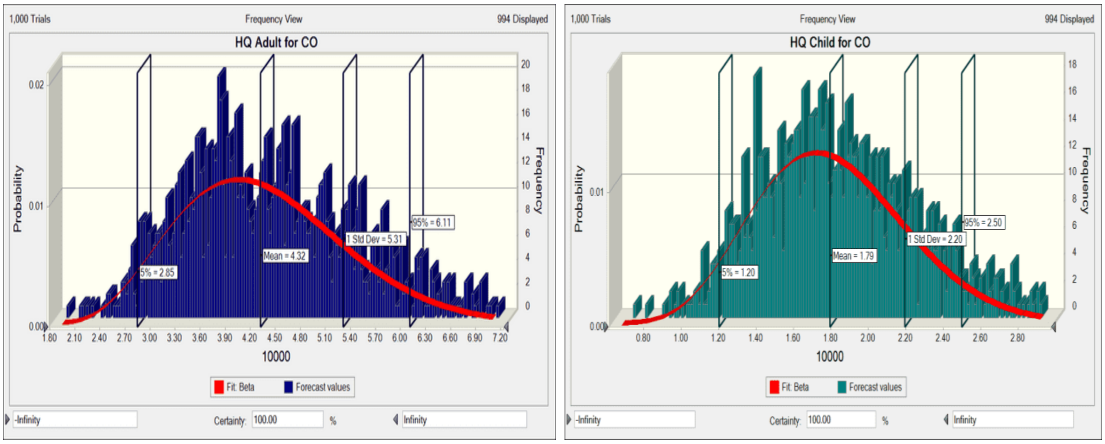

Fig. 3: The HQ adults and children for CO risk exposure

Table 1: Pollutant concentration, HQ, and THQ in adults in South Tangerang city, Indonesia

Sampling site	Measured concentration (µg/m^3)		HQ		THQ		Coordinates	
	CO	PM$_{2.5}$	CO	PM$_{2.5}$	CO	PM$_{2.5}$	Latitude	Longitude
1	4010	31	8.481	0.151	5.359	0.093	106° 40' 26,015" E	6° 14' 40,078" S
2	2979	10	1.498	0.012	3.981	0.030	106° 39' 33,268" E	6° 14' 14,446" S
3	3093	11	2.038	0.017	4.133	0.033	106° 38' 58,610" E	6° 14' 51,864" S
4	2406	12	7.107	0.082	3.215	0.036	106° 39' 10,541" E	6° 15' 58,356" S
5	4563	55	6.780	0.188	6.098	0.165	106° 39' 16,027" E	6° 16' 58,282" S
6	2510	60	4.442	0.244	3.354	0.180	106° 39' 22,417" E	6° 16' 57,972" S
7	4557	38	5.508	0.106	6.090	0.114	106° 40' 38,600" E	6° 17' 19,064" S
8	1078	27	0.795	0.046	1.441	0.081	106° 41' 15,216" E	6° 18' 19,757" S
9	3594	38	4.756	0.116	4.803	0.114	106° 42' 52,344" E	6° 16' 26,155" S
10	5020	74	22.589	1.718	6.708	0.348	106° 43' 23,862" E	6° 16' 34,828" S
11	4663	32	3.835	0.061	6.231	0.096	106° 43' 34,277" E	6° 16' 17,810" S
12	3780	27	2.530	0.042	5.051	0.081	106° 44' 29,717" E	6° 16' 16,943" S
13	3551	22	3.527	0.050	4.745	0.066	106° 44' 52,359" E	6° 16' 14,914" S
14	4764	37	3.959	0.071	6.366	0.111	106° 44' 40,499" E	6° 16' 31,296" S
15	1089	22.8	1.196	0.056	1.455	0.068	106° 44' 2,076" E	6° 17' 27,917" S
16	2154	27	3.824	0.110	2.878	0.081	106° 45' 54,180" E	6° 17' 50,925" S
17	3666	19	3.852	1.046	4.899	0.057	106° 45' 33,739" E	6° 17' 48,095" S
18	3208	22	3.253	0.051	4.287	0.066	106° 45' 24,343" E	6° 18' 17,338" S
19	1834	34	1.270	0.054	2.451	0.102	106° 45' 57,366" E	6° 20' 15,133" S
20	1360	92	0.844	0.131	1.817	0.276	106° 44' 47,274" E	6° 19' 21,068" S
21	1922	96	2.857	0.328	2.568	0.288	106° 44' 16,213" E	6° 19' 4,116" S
22	6729	166	12.546	0.317	8.992	0.222	106° 43' 38,474" E	6° 18' 42,264" S
23	3551	26	2.425	0.041	4.745	0.078	106° 43' 5,405" E	6° 18' 33,610" S
24	1037	17	3.018	0.114	1.386	0.051	106° 43' 5,956" E	6° 18' 10,534" S
25	4552	38	14.396	0.276	6.083	0.114	106° 42' 13,036" E	6° 18' 56,419" S
26	2458	27	1.892	0.048	3.285	0.081	106° 42' 31,828" E	6° 19' 25,831" S
27	3817	29	1.622	0.028	5.101	0.087	106° 43' 58,008" E	6° 20' 36,582" S
28	2347	18	5.782	0.102	3.136	0.054	106° 42' 45,072" E	6° 20' 39,959" S
29	2510	60	4.604	0.253	3.354	0.180	106° 41' 45,467" E	6° 20' 49,078" S
30	1278	35	0.554	0.035	1.708	0.105	106° 40' 57,230" E	6° 21' 16,067" S
31	1468	98	1.224	0.188	1.962	0.294	106° 40' 16,241" E	6° 20' 49,056" S
32	4383	68	4.294	0.153	5.857	0.204	106° 39' 24,332" E	6° 20' 56,328" S
WHO, 2021 Standard	4000	15	1.0	1.0	1.0	1.0		

to a prior study, this region has the greatest total suspended particulate linked to metals (Rauf *et al.*, 2021; Rauf *et al.*, 2022). Furthermore, anthropogenic activities, weather, soil resuspension from roads, and other factors impact PM$_{2.5}$ pollution (Hua *et al.*, 2020; Shahri *et al.*, 2019; Sun *et al.*, 2019; Zhang *et al.*, 2022).

CO and PM2.5 concentration due to transportation mobile

Generally, from Monday to Friday, the concentrations of both CO and PM$_{2.5}$ pollutants are quite high as compared to Saturday and Sunday. In this study, the highest concentrations of CO pollutants were recorded at points 22, 14, and 11, with readings of 6729, 4764, and 4663 μg/m^3, respectively. This was attributed to the increased traffic flow because workers and students used the same road, thereby leading to traffic congestion and, consequently, high concentrations of CO gas and PM$_{2.5}$. However, the lowest concentrations were recorded at points 24, 8, and 15, with readings of 1037, 1078, and 1089 μg/m^3, respectively, which was attributed to fewer vehicles on the road and less crowded areas. The highest concentrations for PM$_{2.5}$ were at stations 22, 31, and 21, with concentrations of 166, 98, and 96

Table 2: Pollutant concentration, HQ, and THQ in children in South Tangerang city, Indonesia

Sampling site (Not all site collected)	Measured concentration (µg/m^3)		HQ		THQ		Coordinate	
	CO	$PM_{2.5}$	CO	$PM_{2.5}$	CO	$PM_{2.5}$	Latitude	Longitude
3	3093	11	2.096	0.017	4.541	0.037	106° 38' 58,610" E	6° 14' 51,864" S
4	2406	12	1.167	0.013	3.532	0.041	106° 39' 10,541" E	6° 15' 58,356" S
6	2510	60	1.917	0.105	3.685	0.203	106° 39' 22,417" E	6° 16' 57,972" S
9	3594	38	2.646	0.064	7.370	0.128	106° 42' 52,344" E	6° 16' 26,155" S
13	3551	22	2.405	0.034	5.213	0.074	106° 44' 52,359" E	6° 16' 14,914" S
16	2154	27	1.837	0.053	3.162	0.091	106° 45' 54,180" E	6° 17' 50,925" S
18	3208	22	3.013	0.048	4.710	0.074	106° 45' 24,343" E	6° 18' 17,338" S
20	1360	92	1.160	0.180	1.997	0.311	106° 44' 47,274" E	6° 19' 21,068" S
21	1922	96	1.302	0.150	2.822	0.324	106° 44' 16,213" E	6° 19' 4,116" S
24	1037	17	0.614	0.023	1.522	0.057	106° 43' 5,956" E	6° 18' 10,534" S
25	4552	38	2.741	0.053	6.683	0.128	106° 42' 13,036" E	6° 18' 56,419" S
28	2347	18	2.349	0.041	3.446	0.061	106° 42' 45,072" E	6° 20' 39,959" S
29	2510	60	1.944	0.107	3.685	0.203	106° 41' 45,467" E	6° 20' 49,078" S
30	1278	35	0.879	0.055	1.876	0.118	106° 40' 57,230" E	6° 21' 16,067" S

µg/m^3, respectively, while the lowest were recorded at three stations, namely, 2, 3, and 4 with 10, 11, and 12 µg/m^3. During school hours and lunch breaks, as well as due to parked cars reducing road capacity on both sides of the road, the concentration of CO, and $PM_{2.5}$ pollutants are noted to be elevated from Monday through Friday, specifically during the day. Private cars are the primary vehicles parked in the area, often used for picking up school children and for dining purposes, as there are several eateries nearby. This congestion leads to increased emissions of CO and $PM_{2.5}$ from moving vehicles. Additionally, on weekdays, and school days in the afternoon, the concentration of CO, and $PM2_{.5}$ increases due to the higher traffic volume during after-work hours. Ambient air measurements show high levels of CO and $PM_{2.5}$ pollutants in the air, caused by multiple sources of pollution. The data indicate that traffic-related sources are the sole cause of the high levels of CO pollution. However, the accuracy of the calculations can be affected by various factors such as data collection, wind direction, and speed, humidity level, and atmospheric stability. In certain circumstances, these factors may not align with the area's conditions, resulting in higher calculated results. For example, when wind speed measurements are taken during low wind speeds, this may cause an increase in the concentration of CO and $PM_{2.5.}$

Health risk assessment of CO and $PM_{2.5}$ using HQ and THQ

The information provided pertains to quantifying health risks and potential health impacts resulting from reduced air pollution quality. This is accomplished by formulating a health risks assessment using the HQ and THQ indicators, as shown in Tables 1 and 2. The HQ and THQ values indicate the risks magnitude whether it is greater or less than 1, indicating a risk, or no risk.. It should be noted that this differs from the relative risk values obtained through a systematic review and meta-analysis of large, international epidemiological studies (Di Vaio *et al.*, 2018; Manisalidis *et al.*, 2020; Rajagopalan *et al.*, 2018; Turner *et al.*, 2020). This study evaluated the relationship between CO and $PM_{2.5}$ and the potential health risks. The toxicological risk was quantified by calculating the risk quotient for individuals who received an average dosage of CO and $PM_{2.5}$. Figs. 3 and 4 show the results of the health risk analysis conducted using the 5th and 95th percentiles. The findings indicated that children were at a higher health risk (HQ = 0.171) as compared to adults (HQ = 0.011) in South Tangerang. However, the health risk presented by exposure to CO and $PM_{2.5}$ in the ambient air was found to be lower than the USEPA limits, where HQ >1. Exposure to toxic chemicals associated with CO and $PM_{2.5}$

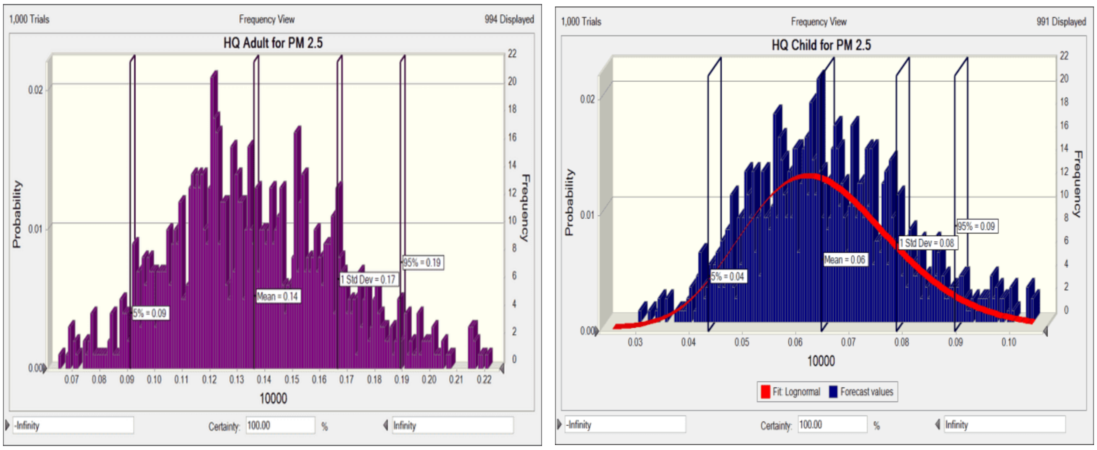

Fig. 4: The HQ adults and children for $PM_{2.5}$ risk exposure

could lead to health problems in both the short term and long term. Children's regular activities may make them more vulnerable to certain health issues than adults, such as an increase in the incidence (number new cases) of some diseases, such as; children malignancies, asthma, birth defects, neuro-developmental disorders and obesity has been observed. (De Oliveira *et al.,* 2012; Mallongi *et al.,* 2020). The production of pollutants such as CO and $PM_{2.5}$ is noted to be greater in regions with high levels of metal and gas air pollution (Rauf *et al.*, 2021; Rauf *et al.,* 2022). Several factors, such as anthropogenic activities, weather, and soil resuspension from roads, may contribute to CO, and $PM2_{.5}$ pollution (Nkhama *et al.,* 2017; Shahri *et al.,* 2019).

Health risks assessment using Monte Carlo simulation

The MCS can be performed using the Crystal Ball software environment, assuming the model's behavior appears "reasonable." It is crucial to specify the number of simulation steps when commencing the simulation. The number of simulation steps was set to 10,000 in the analyzed company, meaning 10,000 values were generated within the simulation for each risk factor and criterion quantity (Iqbal *et al.,* 2020; Mallongi *et al.,* 2023). According to preliminary studies, Monte Carlo is a mathematical-statistical theory used in estimating HQ to account for the probabilities of uncertainties. In estimating the variation of HQ across various age groups, a probabilistic approach is adopted through the Monte Carlo technique, using 10,000 repetitions in addition to point estimation. The exposed group to pollutant emissions resulting from traffic exposure is the subject of the HQ estimation. The air pollutant concentration is significantly influenced by traffic density, mode of transportation, and trip distance (Guimaraes *et al.*, 2018; Han *et al.*, 2023; Laskowski *et al.,* 2018). MCS yields a frequency histogram of the criteria variable and automatically normalizes the probability distribution, which allows for the calculation of various statistical information. The number/probability distribution provides an overview of potential values and their likelihood, which is deemed significant for risk analysis. During the simulation, Crystal Ball calculates the sensitivity by determining the rank correlation coefficients between assumptions and forecasts (Wu *et al.*, 2021). Correlation coefficients serve as a valuable metric for quantifying the degree to which projections and assumptions fluctuate concurrently. A strong correlation coefficient between a forecast and an assumption indicates that the assumption has a significant impact on the forecast, both due to its uncertainty and its model sensitivity. Positive coefficients suggest that the assumption and forecast are positively related, while negative coefficients imply the opposite. This means that negative coefficients can result in more accurate risk assessments by reducing uncertainties and increasing precision in concentration measurements. Therefore, among all relevant factors, reducing the number of vehicles appears to be the most effective strategy to mitigate health risks among children and adults (Fallahzadeh and Ghadirian, 2018).

Uncertainty analysis using Monte Carlo simulation

Uncertainty analysis in this study was carried out using the Monte Carlo method for both CO and $PM_{2.5}$ risks. MCS model is known to be a sophisticated, advanced, and dependable method that generates an accurate and precise point estimate of risk. It calculates the likelihood of a health or ecological effect based on the relationship between exposure frequency and health or ecological impact, taking into account the level of exposure observed, and it also describes the element of uncertainty associated with the predicted risk. MCS was utilized in this investigation as a probability distribution to estimate risk or exposure and to ensure the assessment of elements linked to the uncertainty surrounding the anticipated risk. Oracle software, specifically Crystal Ball version 11.1.2, was employed in Microsoft Excel 2019 to conduct the simulation study.

HQ and sensitivity level of CO and $PM_{2.5}$ for adults and children

MCS results revealed that the probability of cancer risk occurrence at the 5th and 95th percentiles among adults were 2.85 and 6.11 for CO, indicating a medium risk. Meanwhile, the probability for $PM_{2.5}$ was 0.09 and 0.19, indicating low risks. The percentiles for children were 1.20 and 2.50 for CO as well as 0.04 and 0.09 for $PM_{2.5}$, respectively, thereby indicating a low probability of non-cancer risks. This is because children spend less time outside and more time inside their school rooms than adults. These results suggest that the South Tangerang regency population is at a medium risk of non-cancer health issues due to CO exposure in adults, whereas children have a lower probability of being at risk for both CO and $PM_{2.5}$. The greater the CO value, the greater the potential health risk for both adults and children.

According to Figs. 5 and 6, the sensitivity chart for adults shows that exposure frequency (fE) has the highest impact on health problems (20.8%), followed by CO concentration (C) (16.5%), time exposure (tE) (21.6%), duration time (Dt) (20.9%), and inhalation rate (20.2%). For children, CO concentration (C) is determined as the most significant factor (19.6%), followed by R (15.8%), Fe, Dt, and tE with 18.8, 21.8, and 21.1%. This indicates that reducing exposure time and monitoring vehicle emissions near residential areas are important to minimize the negative effects of CO pollution. In addition, exposure frequency (fE) is the primary contributor to $PM_{2.5}$ risks for adults (23%), followed by C, tE, Dt, and R with percentages of 18.8, 16.6, 21.4, and 20.3%, respectively. The information presented shows that as the frequency of discrete exposure occurrences increases, the risk of inhabitants being affected by air pollution also rises. Therefore, to

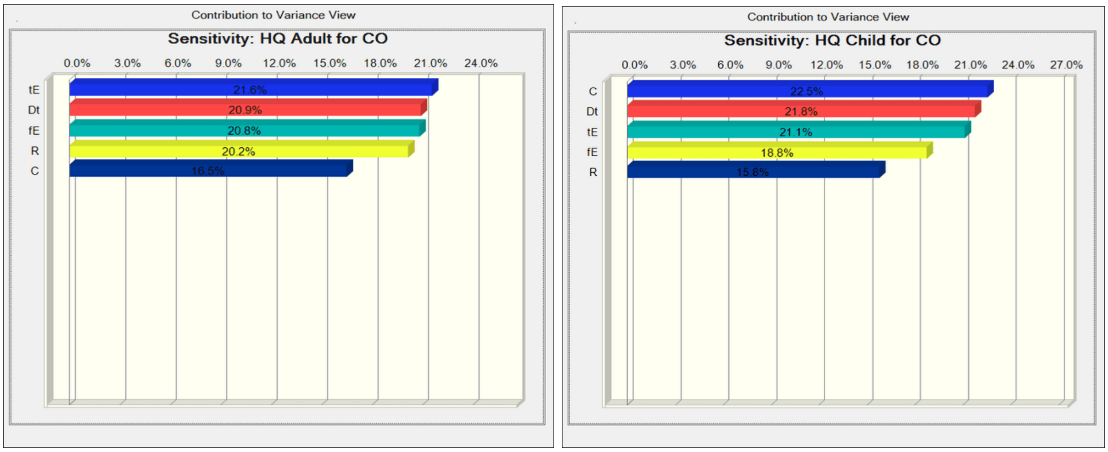

Fig. 5: The analysis of sensitivity percentage of HQ adults and children for CO

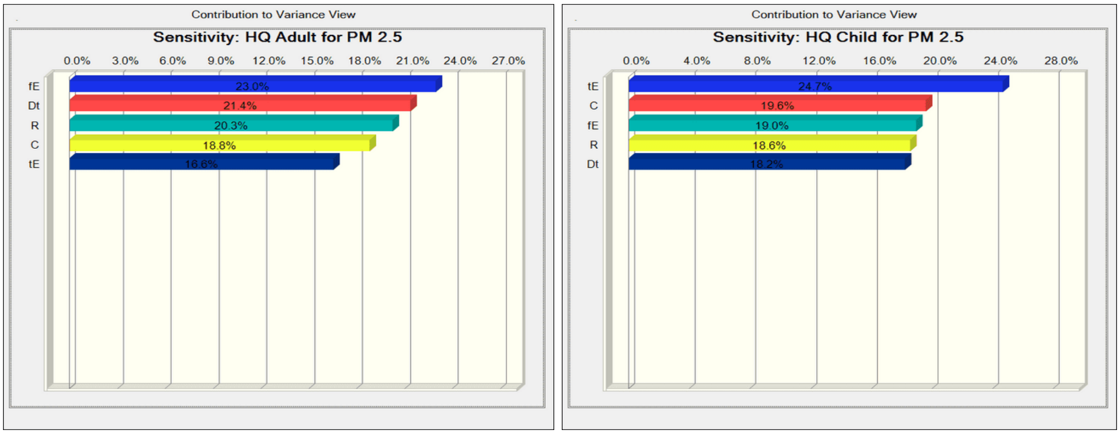

Fig. 6: Sensitivity percentage of HQ adults and children for $PM_{2.5}$

lessen their exposure to air pollution containing dangerous compounds, both kids, and adults should limit their activities and utilize safety gear. Sensitivity analysis also revealed that body weight (BW) made a negligible contribution, suggesting that it could be disregarded as a significant factor in this context. Similar to the results of Guimaraes research to reduce activities and shorten trips. Use protective equipment when using transportation in the Rio de Janeiro metropolitan area (Guimaraes *et al.*, 2018).

CONCLUSION

In conclusion, of these 32 stations, the level of CO concentration exceeded the WHO standard of 4000 µg/m^3 in 9 stations. However, only three stations had $PM_{2.5}$ concentration lower than WHO standard (15 µg/m^3), which means that there is high $PM_{2.5}$ pollutant concentration in the 32 stations. A significant percentage of the calculation values of HQ risk for CO of adults exceeded the standard or >1 state at risk, with only three lower than 1 and still safe. Most HQ values for PM2.5 were lower than 1, indicating safety, while all other 29 stations exceeded the WHO standard and were at risk. These findings were consistent with THQ calculation results for both CO and $PM_{2.5}$ at the 32 stations.

In adults, the likelihood of cancer risk incidence at the 5th and 95th percentiles was 2.85 and 6.11 for CO, indicating medium risks. The corresponding values for $PM_{2.5}$ were 0.09 and 0.19, indicating moderate risks. In contrast, for children, the percentiles for CO were 1.20 and 2.50, whereas for $PM_{2.5}$, the percentiles were 0.04 and 0.09, respectively, indicating a minimal likelihood for non-cancer risk occurrence. This may be due to the fact that children spend more time indoors, such as in classrooms, resulting in shorter exposure times as compared to adults. The exposure frequency (fE), concentration (C) of CO (with 16.5%), time exposure (tE) (with 21.6%), duration time (Dt) (with 20.9), and inhaling rate (with 20.2%) were also found to be important factors in the adults' increased health problems. However, in children, the most significant factor was CO concentration at 19.6%, followed by R at 15.8%, Fe, Dt, and tE at 18.8%, 21.8%, and 21.1%, respectively. This suggested that the concentration of CO pollution had the greatest impact on the prevalence of harmful health effects in both adults and children. The risk to occupants increases as exposure events occur more frequently. Therefore, both adults and children should limit their activities and utilize safety gear to reduce their exposure to air pollution containing hazardous compounds such as CO and $PM_{2.5}$.

AUTHOR CONTRIBUTIONS

E. Ernyasih performed the literature review, methodology, and experimental design, analyzed and interpreted the data, and prepared the manuscript text and manuscript edition. A. Mallongi performed the simulation model, experiments, and literature review, compiled the data, and helped in manuscript preparation. A. Daud helped in the literature review, compiled the data, and helped in manuscript preparation. S. Palutturi performed some of the remaining experiments and managed data curation and validation. R. Thaha reviewed the draft and interpreted the results and the model simulation. E. Ibrahim made a presentation draft review and data curation. W. Al-Moudhun helped in the literature review and manuscript preparation.

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CONFLICT OF INTEREST

The authors declare no conflict of interests regarding the publication of this manuscript. In addition, the 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.

OPEN ACCESS

PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
°C	Degree Celcius
$\mu g/m^3$	Microgram per cubic meter
µg/kg/day	Microgram per kilogram/day
ADDinh	Acceptable daily dose inhalation
AT	Averaging time
BW	Body weight
C	Concentration
CI	Confidence interval
CO	Carbon monoxide
COHb	Carboxyhemoglobin
Dt	Duration time
dpl	above sea level
ED	Exposure duration
EDI	Estimated daily intake
EF	Exposure frequency
Eq	Equation
ET	Exposure time
fE	Frequency of exposure
FINS	Fasting Insulins
Fig.	Figure
FIR	Food ingestion rate (300 grams/ person/day)
HI	Hazard index
HOMA-B	Homeostatic model assessment of beta cell function
HOMA-IR	Homeostatic model assessment insulin resistance
HQ	Hazard quotient
Inhrate	Inhalation rate
IR	Intake rate

MCS	Monte Carlo simulations
mg/m^3	Miligram per cubic meter
m/s	meters per second
NO_2	Nitrogen dioxide
$PM_{2.5}$	Particulate matter 2.5
PM10	Particulate matter 10
THQ	Target hazard quotients
TSP	Total Suspended Particulate
tE	Time exposure
USEPA	United States Environmental Protection Agency
R	Rate
RfC	Reference concentration
VOC	Volatile organics compound
WHO	World Health Organization
YLL	Years of life lost

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