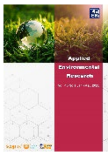
App. Envi. Res. 47(1) (2025): 005

Applied Environmental Research

- RESEARCH FOR SUSTAINABLE PLANET -



Research Article

Investigation and Health Risk Assessment of Indoor and Outdoor Nitrogen Dioxide at Preschools in Haze Areas of Lampang Province and Industrial Areas of Rayong Province, Thailand

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Abstract

Nitrogen dioxide (NO_2) is a major indoor air pollutant and a significant ambient air contaminant associated with health effects, especially for students and teachers who attend schools in the areas of traffic, roads and industry. This study aims to assess the impacts of NO_2 exposure on the health of students in haze and industrial areas from November 2023 to March 2024. Researchers utilized tube-type passive samplers to collect indoor and outdoor NO_2 samples, which were subsequently analyzed via spectrophotometry. The results revealed that the weekly mean indoor and outdoor NO_2 concentrations in the haze areas (HA1–HA5) ranged between 4.4–29.0 and 4.0–37.9 μg m^{-3}, respectively. The ranges of indoor and outdoor NO_2 in industrial areas (ID1–ID5) were 4.9–34.7 and 5.0–37.9 μg m^{-3}, respectively. The indoor levels of NO_2 were lower than the World Health Organization (WHO) standard of 40 μg m^{-3}, whereas the outdoor levels were above the WHO recommended limit of 10 μg m^{-3}, approximately 84–89%. The highest levels of NO_2 in haze and industrial areas were influenced by the haze episode in Thailand. NO_2 and $PM_{2.5}$ levels in haze ($r = 0.441–0.475$) and industrial areas ($r = 0.667–0.734$) were significantly correlated. The noncarcinogenic risk for chronic exposure to NO_2, both indoors and outdoors ($HQ>1.0$), indicates that exposure significantly affects children and that long-term exposure could result in the accumulation of effects in adults, especially in industrial areas.

ARTICLE HISTORY

Received: 5 Oct. 2024
Accepted: 11 Feb. 2025
Published: 27 Feb. 2025

KEYWORDS

Hazard quotient (HQ);
Indoor air pollution;
Nitrogen dioxide;
Outdoor air pollution;
Passive sampler;
Preschool

Introduction

Nitrogen dioxide (NO_2) is a gaseous pollutant that is the most hazardous category of nitrogen oxide (NO_X) [1–4]. Nitrogen dioxide is linked to combustion sources, including traffic, industrial emissions, biomass burning, cooking stoves and heaters [5–8]. The mean NO_2 concentration in buildings devoid of combustion activities is fifty percent of that found outdoors; however, when gas stoves and heaters are utilized, indoor levels frequently exceed outdoor levels [5]. Indoor NO_2 concentrations are influenced by both outdoor and indoor sources; thus, elevated outdoor levels from combustion or local traffic can affect indoor concentrations. The distance from buildings to roadways significantly affects indoor NO_2 levels [7]. Furthermore, the exchange of air between the outdoors and indoors influences NO_2 concentrations within buildings. The major indoor sources of NO_2 include smoking and appliances that burn wood, gas, oil, coal, and kerosene, such as stoves, space heaters, ovens, water heaters and fireplaces [6]. Ground-level NO_2 hotspots have been detected in commercially and industrially relevant coastal cities globally, with elevated

https://doi.org/10.35762/AER.2025005

levels prevalent in autumn and winter. Vehicle exhaust emits a major gaseous contaminant known as NO_2 [2]. Passive samplers for NO_2 have been regularly used for air quality monitoring and epidemiological studies [9]. Passive sampling presents many significant advantages, including simplicity, light weight, low cost, no power requirements, unattended operation, no need for expensive and sometimes complicated equipment, and the ability to produce accurate results [9–10]. Using passive samplers, researchers in Thailand reported that the indoor and outdoor NO_2 concentrations at primary schools in urban-industrial areas in Rayong city ranged from 4.6 to 19.4 μg m^{-3} and from 6.1 to 24.4 μg m^{-3}, respectively, due to traffic [1]. The indoor levels of NO_2 in the schools of downtown children with asthma determined via the use of passive samplers ranged from 4.3 to 29.7 ppb (mean 11.1 ppb), which was related to increased airflow obstruction in children with asthma. Outdoor-generated NO_2 from local traffic-related gases is the main source of indoor NO_2 at schools [3]. Olufemi et al. [4] used passive samplers to monitor NO_2 concentrations inside and outside schools located near a coal mine in South Africa. The reported levels of NO_2 indoors ranged from 19 to 28 μg m^{-3}, whereas outdoors, they ranged from 9.9 to 27 μg m^{-3}. Most studies reported that outdoor NO_2 concentrations were higher than indoor NO_2 concentrations, potentially because of traffic and industrial sources.

Nitrogen dioxide influences children's health worldwide, especially in areas with high traffic density in urban and industrial environments. Compared with adults, children are more vulnerable and have a longer life duration to the numerous harmful health impacts of NO_2. Exposure to NO_2 in children is associated with allergic skin diseases, increased body weight, wheezing, asthma symptoms, lung function, and the respiratory system [11–15]. Several investigations revealed strong connections between exposure to NO_2 and negative health impacts on children. Gillespie-Bennett et al. [16] reported that the mean indoor NO_2 level of 11.4 μg m^{-3} was related to the lower and upper respiratory tract symptoms of children with asthma, including more frequent coughs and wheezing. One study examined the relationship between ambient NO_2 levels and neurodevelopmental delays in children by analyzing functional connectivity (FC) across a 2-year period. A study by Cotter et al. [17] revealed a link between ambient NO_2 levels and changes in the development of brain network connections over time. Epidemiological studies have identified links between NO_2 exposure in urban schools and obese children. They reported that for every 10 ppb increase in NO_2, there was an effect on obesity in children [11]. Chen et al. [18] reported that high levels of NO_2 may increase the risk of obesity in 2-year-olds and accelerate growth from birth to 2 years of age. Norbäck et al. [19] reported that the mean indoor NO_2 value was 23 μg m^{-3}, which was associated with ocular discomfort and fatigue in children who experienced greater NO_2 exposure than adults did. High levels of NO_2 inside primary schools in Thailand may significantly risk individuals' health, causing symptoms such as ocular irritation, runny nose, sore throat, trouble breathing, and cough, which are commonly observed in students [1]. Previous studies reported that short-term exposure to NO_2 primarily causes ocular discomfort, runny nose, sore throat, and cough, whereas long-term exposure is associated with asthma and respiratory irritation [1, 3–4, 11, 19]. Moreover, Lertxundi et al. [20] reported that exposure to $PM_{2.5}$ and NO_2 during pregnancy may negatively influence the motor and cognitive development of infants. This adverse impact may be stronger near metal processing industries. Fu et al. [21] investigated $PM_{2.5}$ responses to other air pollutants and meteorological factors across multiple temporal scales. The results revealed that the responses of $PM_{2.5}$ to various pollutants and meteorological factors varied at different temporal scales and that the temporal trend of NO_2 coincided with that of $PM_{2.5}$.

Haze, particularly $PM_{2.5}$, has become a public problem, especially in northern Thailand. It has had a serious impact on the economy and public health over the last half-decade. In 2020, the air pollutant levels in Thailand exceeded the standard for more than 70 days, especially in northern provinces [22]. In addition, haze pollution in northern Thailand is a regional problem that occurs annually during the dry season (January–April) due to agricultural open burning and an increase in natural forest fires [22]. Natural forest fires and anthropogenic burning activities, particularly the open burning of agricultural residues, emit large quantities of atmospheric pollutants during the dry season in northern Thailand. Consequently, many residents suffer from breathing ailments during this period.

In their study, Song et al. [23] reported a correlation between NO_2 and short-term occurrence of eye and adnexa disorders (EADs). They reported that a 10 μg m^{-3} increase in NO_2 in the present day is associated with an increase in daily outpatients with EADs. Favarato et al. [24] reported a correlation between the incidence of asthma in children and the release of ambient NO_2 from traffic pollution. Therefore, a previous study revealed that NO_2 emitted by traffic can be used as a useful bioindicator to evaluate the hazardous impacts of air pollution caused by traffic [25].

The increased focus on human health concerns related to air pollution emphasizes the necessity of assessing the correlation between exposure and adverse health effects. The United States Environmental Protection Agency (US-EPA) human health risk assessment framework is an effective instrument utilized to evaluate the potential human health risks associated with exposure to specific pollutants. Research has indicated that health risk assessment is effective for estimating the incidence of adverse health effects in both children and adults due to the direct inhalation of atmospheric particulates [26].

Considering the information submitted, the researcher initially measured the levels of NO_2 both indoors and outdoors and conducted a noncarcinogenic risk assessment in targeted preschools located in urban areas during periods of haze and in industrial areas. Furthermore, the health risks to the students related to NO_2 inhalation were assessed. The results of this study should be useful for school administrators and relevant agencies in implementing appropriate actions to mitigate exposure to indoor and outdoor air pollutants, thereby reducing their impact on human health, especially in young children.

Materials and methods

1) Sampling sites

Researchers randomly studied and selected sampling sites in two areas of Thailand. Researchers have randomly collected air quality samples from indoor and outdoor environments at preschools in Lampang and Rayong Provinces, with a focus on community ambient air, urban areas, and industrial estates. The preschools accommodate kindergarten children aged 2 to 4 years. The samples were continuously exposed for a duration of one week, covering November 2023 to April 2024, which was correlated with the dry season. The sample site categories are listed below (Figure 1).

1.1) Haze area (HA): Lampang Province is located in the northern part of Thailand at latitude 18° 17' 24" N and longitude 99° 28' 48" E. This site played a crucial role during the haze period in Thailand. It was influenced by the haze generated from biomass burning. Furthermore, five preschools were selected to represent the urban area in Lampang Province. Variables such as roadside locations, residential and commercial structures, government offices, transportation networks, areas with high traffic intensity, and locations with significant human activity guided the selection of sampling sites. The symbols of the sampling sites in this area are HA1–5.

1.2) Industrial area (ID): Rayong Province's industrial estate lies on the eastern coast of the Gulf of Thailand. It is located at latitude 12° 40' 48" N and longitude 101° 16' 48" E. The city plays a crucial role in Thailand's industry. The Map Ta Phut industrial estate, as depicted in Figure 1, covers 8,012.39 acres in Rayong Province and is the main industrial estate. Five preschools in the Map Ta Phut Town municipality provided data on sampling locations for the Map Ta Phut industrial estate. Petrochemical and chemical manufacturing facilities, steel and metal industries, machinery and equipment production, coal-powered electricity plants, oil refineries, residential districts, and transportation infrastructure dominate the region [27]. ID1–5 represent the sampling sites in the industrial area.

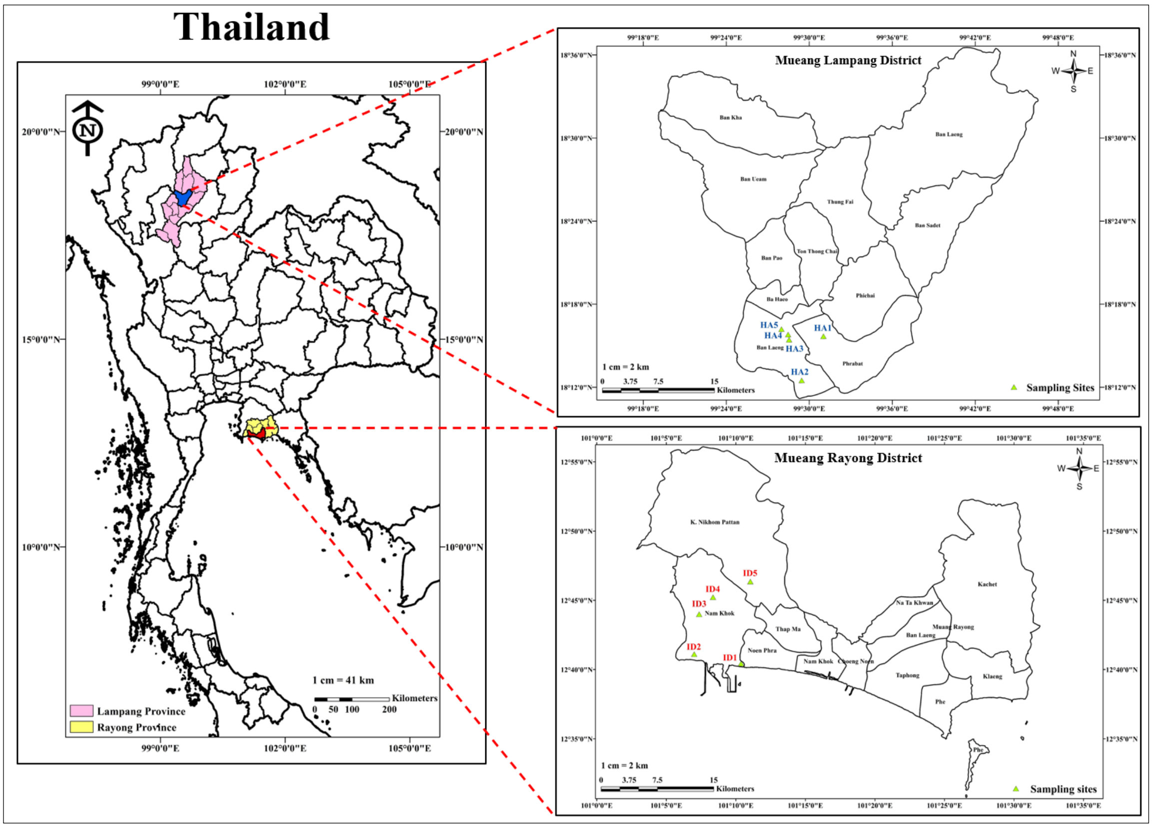


Figure 1 Sampling sites in Lampang and Rayong Provinces.

2) NO_2 sampling and analysis

The Environmental Chemistry Research Laboratory (ECRL) in the Chemistry Department of Chiang Mai University developed passive diffusion tubes for assessing indoor and outdoor NO_2 levels [9]. The passive NO_2 samples used in this study are presented in Figure 2. The passive sampler consists of 5 sample tubes and 3 blank tubes placed in a shelter (Figure 2(a)). The polypropylene tube is 7.70 cm in length and 1.50 cm in diameter, and it contains a GF/A grade glass fiber filter (Whatman, USA) impregnated with 50 µL of 20% triethanolamine (TEA). The passive samples inside and outside the classrooms of preschools were hung at 1.5–2.0 m above ground level for one week (one sample) from November 2023 to April 2024 (Figure 2(b)). One set of samples was collected from each classroom, and one set of samples was collected outdoors. After sampling, the NO_2 concentration was analyzed colorimetrically and reported as nitrite ions (NO_2^-). The samples were placed in a tube containing 2 mL of deionized water and swirled for 15 minutes to dissolve the nitrite ions. One milliliter of the nitrite solution was combined with 2 mL of the Saltzmann reagent. A spectrophotometer (Thermo Scientific GENESYS 150, USA) was used to measure the absorbance at a wavelength of 540 nm after extraction. The NO_2 concentration in the sample was calculated from the standard curve of the NO_2 solution. Details of the chemical preparation and extraction are explained in Bootdee et al. [9].

3) $PM_{2.5}$ concentrations

The Air Quality Monitoring Station (AQM), Pollution Control Department (PCD), Thailand, provided data on the $PM_{2.5}$ concentrations in Lampang and Rayong Provinces. The Phra Bat AQM (37t) represented the $PM_{2.5}$ concentrations around five preschools in Lampang Province (HA1–5), whereas the Map Ta Phut AQM (29t) represented Rayong Province (ID1–5). The distance from the 37t station to the five preschools in Lampang is approximately 2–8 km, whereas the distance from the 29t station to the five preschools in Rayong is approximately 4–8 km. The hourly mean $PM_{2.5}$ concentrations from November 2023 to April 2024 at the 37t and 29t stations obtained from the Federal Reference Method (FRM), US-EPA standard, were used to calculate the weekly mean $PM_{2.5}$ concentrations, which were used to assess the correlation between the $PM_{2.5}$ and NO_2 concentrations.

4) Data analysis

The concentrations of NO_2 and $PM_{2.5}$ followed a normal distribution. One-way analysis of variance (ANOVA) was performed in this study to analyze the mean differences between the indoor and outdoor NO_2 concentrations, while various sampling periods and groups of sampling sites were considered within the same period. Pearson's correlation coefficients (r) were calculated to measure the relationships between indoor and outdoor NO_2 concentrations and $PM_{2.5}$ concentrations. All the statistical analyses were performed in IBM SPSS (IBM Corp., IBM SPSS Statistics for Windows, Version 29.0, Armonk, New York, NY, USA).

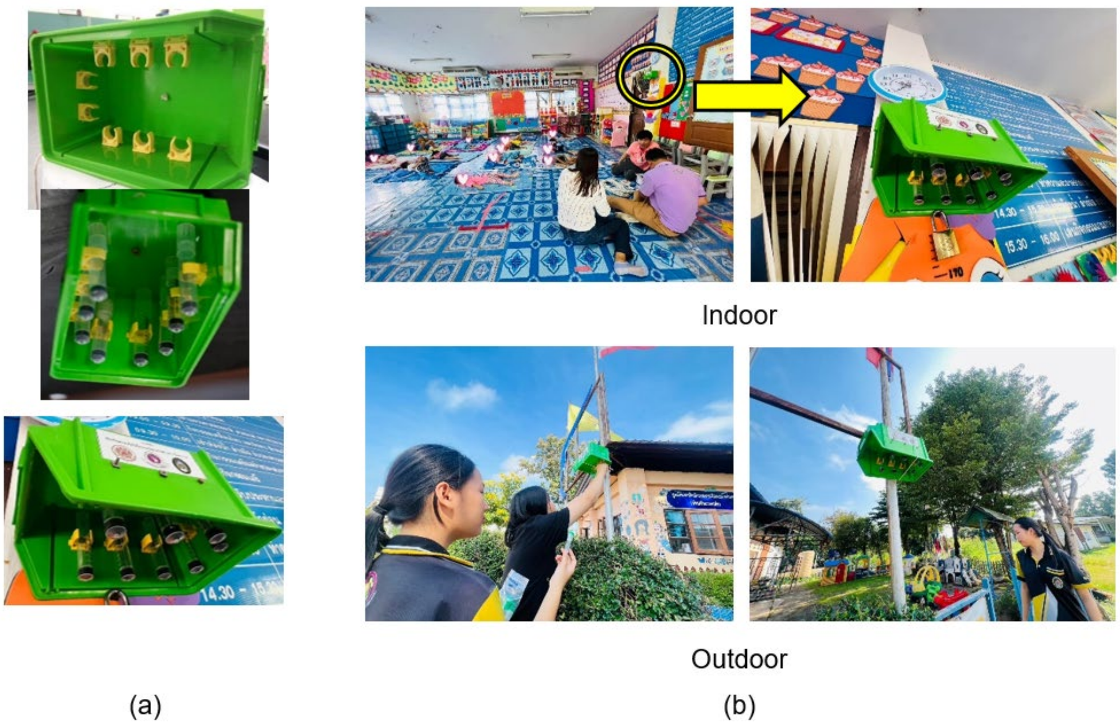


Figure 2 Passive NO_2 sampling; (a) a set of passive samplers and (b) indoor and outdoor NO_2 sampling.

5) Health risk assessment

Assessment of noncancer risk associated with NO_2 exposure by the hazard quotient (HQ). It is expected that concentrations of NO_2 could be increased in children and adults during inhalation [26]. The estimation of HQ in this study includes both acute (short-term) and chronic (long-term) exposure to the weekly mean NO_2 concentrations. The HQs of indoor and outdoor NO_2 levels were used to evaluate acute and chronic exposure for noncarcinogenic risk in children aged 2 to <3 years, children aged 3 to <6 years, and adults aged 19–75 years. For NO_2 inhalation, the acute exposure period is 8 hours, and the chronic exposure period (worst case) is annual NO_2 exposure. The noncarcinogenic assessment ratio for NO_2 exposure, HQ, is calculated by the average daily dose (ADD) and RfD via Eq. 1 [26, 28].

$$HQ = \frac{ADD}{RfD} \quad \text{(Eq. 1)}$$

When HQ>1.0, exposure significantly affects noncarcinogenic risk, and when HQ<1.0, noncarcinogenic risk does not occur. The acute and chronic exposure assessment is calculated via Eq. 2.

$$ADD = \frac{C \times IR \times ET \times EF \times ED}{BW \times AT} \quad \text{(Eq. 2)}$$

where ADD is the average daily dose of NO_2 inhalation (µg kg^{-1} day^{-1}); C is the concentration of NO_2 (µg m^{-3}); ED is the exposure duration (days); EF is the exposure frequency (days $year^{-1}$); ET is the exposure time (hour day^{-1}); ED is the exposure duration (year); BW is the body weight of the exposed group (kg); AT is the average time (days); and IR is the inhalation rate (m^3 $hour^{-1}$). Table 1 presents the parameters for assessing ADD [26, 29].

The reference concentrations (RfC) of NO_2 inhalation are based on the World Health Organization (WHO) and the Office of Environmental Health Hazard Assessment (OEHHA) guidelines [6, 30–31], as shown in Table 2. The reference dose (RfD) of indoor and outdoor NO_2 for both acute exposure and chronic exposure can be calculated from the RfC via Eq. 3 [32].

$$RfD = \frac{RfC \times 20\ m^3\ day^{-1}}{70\ kg} \quad \text{(Eq. 3)}$$

where the value of 20 m^3 day^{-1} is an assumed human inhalation rate and 70 kg is an assumed human body weight [32].

Table 1 Age category parameters of the NO_2 inhalation pathway for health risk assessment

Parameters	Acute exposure			Chronic exposure			Ref.
	Children (2 to <3 years)	Children (3 to <6 years)	Adults (19–75 years)	Children (2 to <3 years)	Children (3 to <6 years)	Adults (19–75 years)	
Exposure frequency (EF; days $year^{-1}$)	350	350	350	350	350	350	[26]
Exposure time (ET; hour day^{-1})	1	1	3	24	24	24	[26]
Exposure duration (ED; year)	1	3	30	1	3	30	[26, 29]
Inhalation rate (IR; m^3 $hour^{-1}$)	1.2	1.2	1.2	13.5	13.5	13.3	[26]
Averaging time (AT); AT = ED × 365 days (day) for acute exposure AT = 70 years × 365 days (day) for chronic exposure	365	1,095	10,950	25,550	25,550	25,550	[26, 29]
Body weight (BW; kg)	13.8	18.6	71.8	13.8	18.6	71.8	[26, 29]

Table 2 Reference dose (RfD) and reference concentration (RfC) for indoor and outdoor NO_2

Parameters	RfC for NO_2 guideline (µg m^{-3})		RfD for NO_2 (µg kg^{-1} day^{-1})	
	Indoor	Outdoor[c]	Indoor	Outdoor
Acute exposure	470[a]	25	134	7
Chronic exposure	40[b]	10	11	3

Remark: Values for a, b, and c were obtained from [30], [6], and [31], respectively.

Results and discussion

1) NO_2 concentrations

The weekly mean indoor and outdoor NO_2 concentrations were determined via diffusive sampling at each preschool in Lampang and Rayong Provinces from November 2023 to March 2024. Figure 3 displays the results. Measurements taken over a 5-month period were used to determine the NO_2 concentrations both indoors and outdoors at 5 sampling sites in Lampang Province (HA1–5) and 5 sampling sites in Rayong Province (ID1–5). The indoor NO_2 concentrations in Lampang Province ranged from 4.4±1.5 to 29.0±7.7 μg m^{-3}, whereas the outdoor concentrations ranged from 4.0±0.6 to 37.9±2.6 μg m^{-3}. In comparison, the indoor NO_2 concentrations in Rayong Province ranged from 4.9±2.0 to 34.7±3.0 μg m^{-3}, and the outdoor concentrations ranged from 5.0±0.2 to 37.9±3.3 μg m^{-3}. The mean values of indoor and outdoor NO_2 in Lampang were 14.7±6.1 and 17.4±7.1 μg m^{-3}, respectively, whereas those in Rayong were 18.0±6.3 and 20.4±7.7 μg m^{-3}, respectively. Notably, there was little variation between Lampang and Rayong Provinces in terms of indoor and outdoor NO_2 levels. Most values of indoor NO_2 were lower than those of outdoor NO_2, while all the indoor and outdoor NO_2 levels at the Rayong sites were almost higher than those at the Lampang sites. The highest levels of indoor and outdoor NO_2 in Lampang and Rayong Provinces were HA5 and ID2, respectively. Both sites were situated near major intersections with significant vehicle traffic. In a previous study published by Kaewrat et al. [33], the indoor NO_2 levels in an open window in the classroom of Nakhon Si Thammarat's primary school in Thailand were measured. The results of their study revealed that the indoor NO_2 concentrations ranged between 46.4 and 77.8 μg m^{-3}, which were higher than the values reported in the present study in Lampang and Rayong Provinces (4.4–29.0 and 4.9–34.7 μg m^{-3}, respectively). In the Mpumalanga Province of South Africa, Olufemi et al. [4] reported the indoor and outdoor NO_2 levels in five schools near coal mines and coal-powered plants. The levels of NO_2 within the classrooms ranged from 19 to 28 μg m^{-3}, whereas the values obtained outside the classroom ranged between 9.9 and 27 μg m^{-3}. Villanueva et al. [34] studied the indoor and outdoor NO_2 levels in primary schools located in industrial areas in the city of Ciudad in Spain. The results revealed that the indoor NO_2 levels ranged from 9.8 to 15.8 μg m^{-3} (mean 13.4±2.5 μg m^{-3}), whereas the outdoor NO_2 levels ranged from 3.7 to 9.2 μg m^{-3} (mean 6.0±2.2 μg m^{-3}). The mean indoor NO_2 concentration in Lampang Province reported in this study (14.7±6.1 μg m^{-3}) was similar to that reported in primary schools in Spain, whereas the level reported in Rayong Province (18.0±6.3 μg m^{-3}) was slightly higher than the indoor NO_2 level reported in Spain. The mean outdoor NO_2 levels in the present study (17.4±7.1 and 20.4±7.7 μg m^{-3}) were approximately 3 times higher than those recorded in Spain. Salonen et al. [35] investigated human exposure to NO_2 in the indoor environments of schools and offices. The outdoor NO_2 concentrations are generally higher than those observed during the summer. The indoor NO_2 levels in school and office environments are statistically significantly correlated with a variety of building and indoor environment characteristics, including the type of ventilation, air exchange rates, airtightness of the envelope, furnishing and surface characteristics of the building, location of the building (urban versus sub-urban and proximity to traffic routes), and occupant behavior (such as opening windows) [35]. Consequently, our investigation indicates that indoor NO_2 concentrations in the classroom are influenced by an outdoor source.

All the values of indoor NO_2 at the Lampang and Rayong sites were in accordance with the suggested standard of guidelines established by the WHO, which states that the annual mean indoor NO_2 level should be below 40 μg m^{-3} [6]. The outdoor NO_2 concentration in this study did not exceed the mean annual limit for NO_2 outdoor air quality stan-dards created by the National Ambient Air Quality Standard (NAAQS) (100 μg m^{-3}) [36] and the PCD, Thailand (57 μg m^{-3}) [37]. However, the level of outdoor NO_2 in this study exceeded the WHO air quality recommendation level [31], which lists 10 μg m^{-3} as the mean annual limit for NO_2 in outdoor air. The mean outdoor NO_2 concentration in Lampang Province exceeded the WHO standard by approximately 84% (88 samples), whereas in Rayong Province, the value was approximately 89% (89 samples).

Table 3 shows the monthly mean NO_2 concentrations measured indoors and outdoors in Lampang and Rayong Provinces from November 2023 to March 2024. In November 2023, the mean NO_2 concentrations in Lampang and Rayong Provinces were lowest at 11.15±2.24 and 15.22±5.33 μg m^{-3}, respectively, which was attributed to indoor sources. The highest mean NO_2 concentrations were recorded in outdoor sources in Lampang (20.97±6.11 μg m^{-3}) and Rayong (28.43±5.58 μg m^{-3}) Provinces in February 2024 and January 2024, respectively. The highest levels of NO_2 in Lampang in February 2024 may be influenced by the smoke haze episode in upper northern Thailand, which is characterized by high particulate matter during the first quarter of every year [38–39]. The highest NO_2 levels in Rayong in January 2024 may be attributed to the haze periods in Bangkok, Thailand, which significantly increased particulate matter concentrations, especially from January to February [40–41]. Bangkok is the capital and most populous city of Thailand. It is not far from Rayong Province and is approximately 140 km long. Nitrogen dioxide and meteorological factors had different effects on $PM_{2.5}$ at different time scales, and their trends over time were very similar to those of NO_2 [21]. In the outside environment, $PM_{2.5}$ is strongly correlated with soot, which is also highly related to NO_2 [42]. There was a correlation between $PM_{2.5}$ and NO_2.

In February 2024, the mean $PM_{2.5}$ concentration recorded at the Phra Bat AQM station (37t) in Lampang Province was 67.9 µg m^{-3} (21.7–100.1 µg m^{-3}), whereas in January 2024, the Map Ta Phut AQM station (29t) in Rayong Province presented a mean of 38.9 µg m^{-3} (26.2–60.0 µg m^{-3}) (Figure 3). Most of the mean levels of outdoor NO_2 in Lampang and Rayong Provinces were slightly higher than those of indoor NO_2, but there was no significant difference among their mean levels in each province during the same period ($p > 0.05$). Furthermore, this study revealed that both indoor and outdoor NO_2 levels in Lampang and Rayong Provinces significantly differed among the 5-month sampling periods. The indoor and outdoor NO_2 values in Lampang city significantly differed between November–December 2023 and January–March 2024 ($p<0.05$), whereas those in Rayong in January 2024 significantly differed from those in the other months ($p<0.05$).

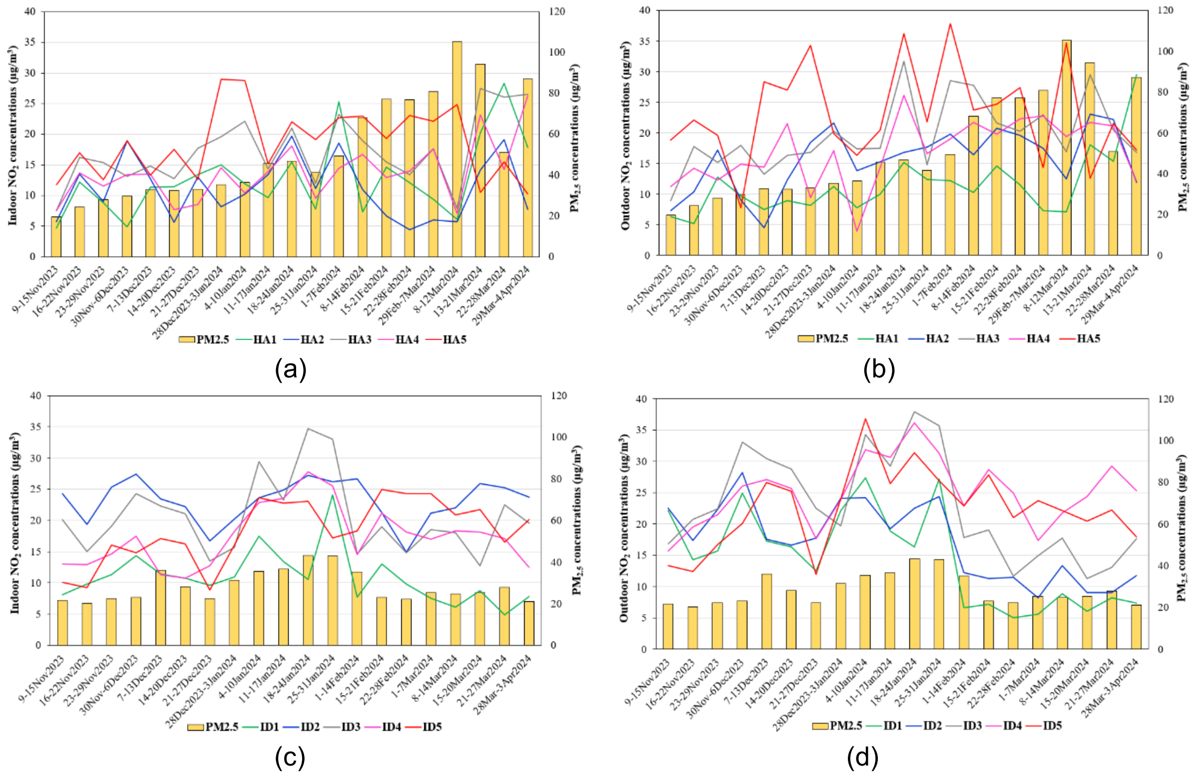


Figure 3 Concentrations of indoor NO_2, outdoor NO_2 and $PM_{2.5}$ in Lampang Province ((a)–(b)) and Rayong Province ((c)–(d)).

Table 3 Monthly mean indoor and outdoor NO_2 concentrations in Lampang and Rayong Provinces from November 2023 to March 2024

Month		NO_2 concentrations (µg m^{-3})					
		Lampang Province			Rayong Province		
		Indoor	Outdoor	I/O ratio	Indoor	Outdoor	I/O ratio
Nov. 2023	Minimum	8.6	8.1		9.7	14.1	
	Maximum	13.8	20.2		23.0	20.7	
	Mean±SD	11.1±2.2$^{a, A}$	13.3±4.4$^{a, AB}$	0.84	15.2±5.3$^{a, AB}$	18.2±2.6$^{a, B}$	0.84
Dec. 2023	Minimum	11.2	9.1		11.4	18.6	
	Maximum	18.3	23.5		22.0	26.9	
	Mean±SD	13.7±3.1$^{ab, A}$	15.6±5.3$^{ab, A}$	0.88	16.3±4.3$^{a, AB}$	22.4±3.2$^{ab, B}$	0.73
Jan. 2024	Minimum	11.2	11.3		16.4	22.4	
	Maximum	21.3	23.7		30.1	34.3	
	Mean±SD	15.3±4.0$^{b, A}$	17.3+4.8$^{b, A}$	0.89	23.7±5.1$^{b, B}$	28.4±5.6$^{b, B}$	0.83
Feb. 2024	Minimum	10.2	12.1		10.2	6.2	
	Maximum	22.0	28.4		22.5	25.5	
	Mean±SD	15.9+4.4$^{b, A}$	21.0±6.1$^{c, A}$	0.76	17.5±4.8$^{a, A}$	16.7±8.1$^{a, A}$	1.01
Mar. 2024	Minimum	10.6	15.5		7.0	7.2	
	Maximum	21.1	21.3		23.6	23.6	
	Mean±SD	16.5±3.8$^{b, A}$	18.7±2.3$^{bc, A}$	0.88	17.2±6.3$^{a, A}$	15.5±7.0$^{a, A}$	1.11

Remark: $^{a, b, c}$ = Groups of sampling periods were significantly different ($p < 0.05$, vertical direction).
$^{A, B}$ = Groups of sampling sites (indoor/outdoor) within the same period were significantly different ($p < 0.05$, horizontal direction).

The data on the indoor/outdoor (I/O) ratios of NO_2 concentrations from November 2023–March 2024 are presented in Table 3. In this study, the NO_2 I/O ratio ranged from 0.73 to 1.11, which is typically less than 1, indicating that NO_2 exposure can be greater outside than indoors. Most of the I/O ratios of Rayong (0.73–0.84) and Lampang (0.76–0.89) Provinces are also less than 1. This could be because most school classrooms have closed systems with air conditioning. Therefore, indoor NO_2 levels may be slightly affected by outdoor NO_2 levels. A study by Kaewrat et al. [33] reported the I/O ratios of a primary school in Nakhon Si Thammarat Province, Thailand. The I/O ratios ranged from 0.69 to 0.90, with a mean value of 0.79±0.06, which were similar to those obtained in this study. It was suggested that outdoor NO_2 could significantly contribute to indoor NO_2 in the room [33]. However, some schools are located close to roads, construction sites and industrial zones, resulting in high NO_2 concentrations. The I/O ratios of Rayong Province from February–March 2024 (1.01–1.11) were slightly greater than 1 because of the peak tourist season and increased traffic. In the natural ventilation of residential buildings, indoor levels from inside sources are influenced by the operation of windows, which is correlated with weather conditions. In the absence of inside NO_2 sources, an increased ventilation rate led to significant contributions from outside NO_2 to indoor NO_2 concentrations, resulting in the I/O ratio approaching 1 [43].

2) Correlation between indoor and outdoor NO_2 concentrations and $PM_{2.5}$ levels

The Pearson correlations of the NO_2 values and $PM_{2.5}$ levels in Lampang and Rayong Provinces are listed in Table 4. The outdoor NO_2 levels of HA1 were significantly correlated with the $PM_{2.5}$ levels (r = 0.441) because HA1 is situated near a narrow and curved road, resulting in reduced vehicle speed and NO_2 accumulation. The positive correlations between the indoor and outdoor NO_2 levels of HA4 and the $PM_{2.5}$ concentrations were stronger (r = 0.475). HA4 is located in the area of the municipality, where it causes a significant amount of vehicle traffic. The indoor NO_2 concentrations of ID1–ID4 and the $PM_{2.5}$ concentrations were well correlated (r = 0.473–0.707). The outdoor NO_2 levels of ID3–ID5 were strongly correlated with the $PM_{2.5}$ values (r = 0.667–0.734). The NO_2 values in Rayong Province were more strongly correlated with $PM_{2.5}$ than those in Lampang Province were. Rayong city is an industrial estate in Thailand that displays higher levels of air pollutants than Lampang Province does. Pollutants, including SO_2 and NO_2, are important precursors in the formation of $PM_{2.5}$, showing patterns equivalent to those of $PM_{2.5}$ [21].

Table 5 shows the correlation between indoor and outdoor NO_2 levels in Lampang and Rayong Provinces. The positive correlations between the indoor and outdoor NO_2 levels of HA1 and HA3 were 0.517–0.602. HA1 is located near a narrow and curved road, whereas HA3 is situated close to the school and temple. The burning of incense during religious ceremonies in temples emits many gaseous and particulate pollutants. Bootdee and Chantara [44] reported that NO_2 and $PM_{2.5}$ concentrations were moderately correlated (r = 0.580–0.779) on all occasions. Pollutant emissions significantly depend on the amount of incense burned. Indoor NO_2 levels in schools were significantly associated with outside concentrations at Rayong sites, with the exception of ID2, which had values between 0.714 and 0.808. ID1 is located near the refinery, which is one of the emission sources contributing to the yearly NO_2 concentration recorded by Khamyingkert and Thepanondh [8]. Their analysis focused on five types of industrial emission sources in the Maptaphut industrial area of Rayong Province, Thailand: gas separation plants, metals, petrochemical industries, power plants, and oil refineries. The studies revealed that the primary sources of NO_2 emissions were petrochemicals (67.23%), power plants (28.23%), and refineries (2.99%). The establishment of a new industry, marked by an abundance of trucks, has been identified as the main source of pollution in ID3. ID4 is situated near the daily evening market and the tapioca flour mill, serving as a distribution source for NO_2 emissions, mainly from vehicular traffic. The accumulation of NO_2 from community intensity and transportation networks was the main cause of the pollution affecting ID5.

Table 4 Pearson's correlation coefficients of NO_2 concentrations and $PM_{2.5}$ levels in Lampang and Rayong Provinces

Lampang Province/Parameters		$PM_{2.5}$	Rayong Province/Parameters		$PM_{2.5}$
$PM_{2.5}$		1	$PM_{2.5}$		1
Indoor NO_2 concentrations (n = 105)	HA1	0.177	Indoor NO_2 concentrations (n = 100)	ID1	**0.513***
	HA2	-0.283		ID2	**0.473***
	HA3	0.235		ID3	**0.707****
	HA4	**0.475***		ID4	**0.621****
	HA5	0.103		ID5	0.298

Table 4 Pearson's correlation coefficients of NO_2 concentrations and $PM_{2.5}$ levels in Lampang and Rayong Provinces (*continued*)

Lampang Province/Parameters		$PM_{2.5}$	Rayong Province/Parameters		$PM_{2.5}$
$PM_{2.5}$		1	$PM_{2.5}$		1
Outdoor NO_2 concentrations (n = 105)	HA1	**0.441***	Outdoor NO_2 concentrations (n = 100)	ID1	0.435
	HA2	0.366		ID2	0.339
	HA3	0.433		ID3	**0.667****
	HA4	**0.475***		ID4	**0.713****
	HA5	0.038		ID5	**0.734****

Remark: * The correlation is significant at the 0.05 level (2-tailed).
** The correlation is significant at the 0.01 level (2-tailed).

Table 5 Pearson's correlation coefficients of indoor and outdoor NO_2 concentrations in Lampang and Rayong Provinces

Lampang Province (n = 21)	Correlation (r)	Rayong Province (n = 20)	Correlation (r)
HA1	**0.517***	ID1	**0.716****
HA2	0.102	ID2	0.285
HA3	**0.602****	ID3	**0.808****
HA4	0.289	ID4	**0.714****
HA5	0.183	ID5	**0.714****

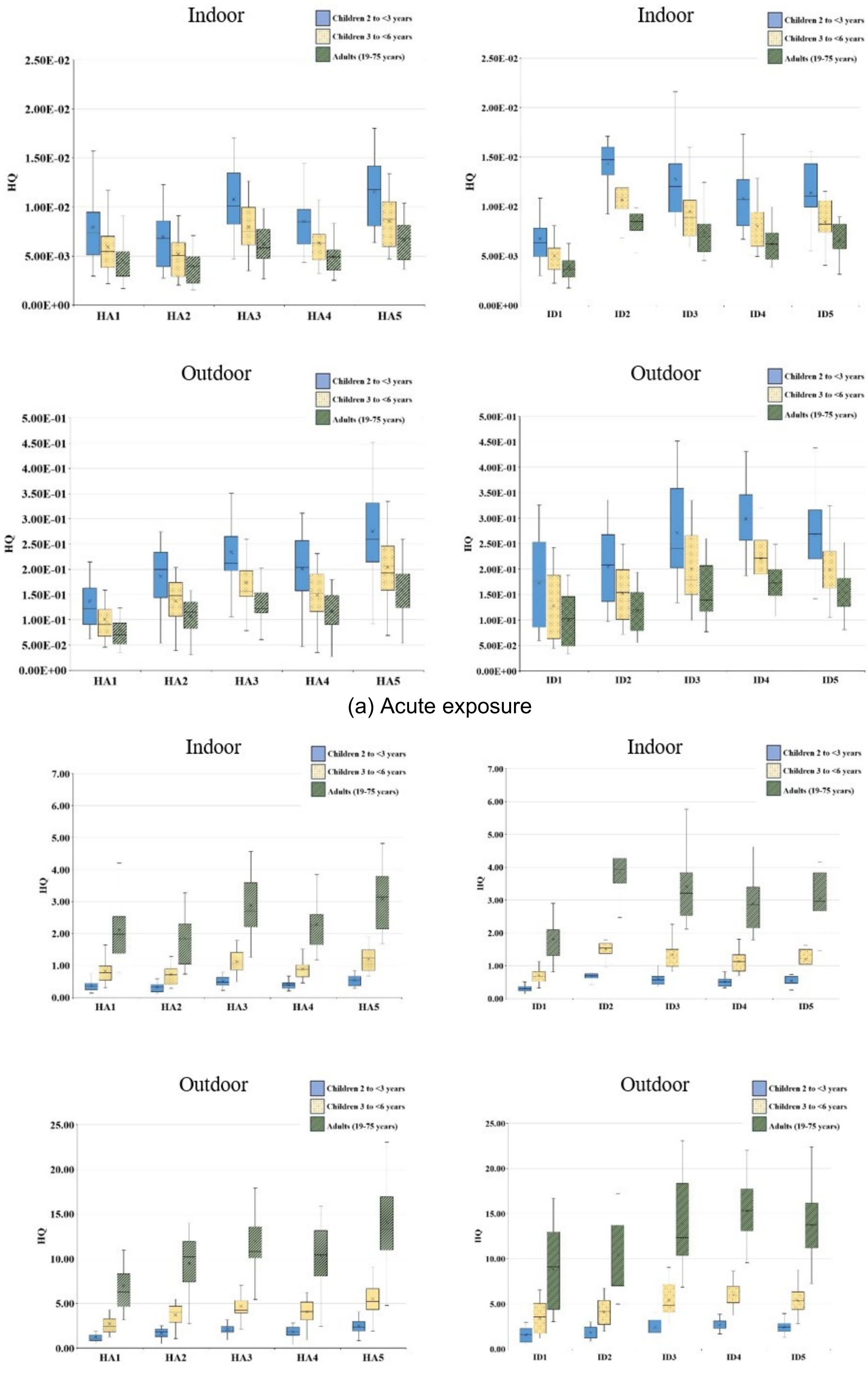
Remark: * The correlation is significant at the 0.05 level (2-tailed).
** The correlation is significant at the 0.01 level (2-tailed).

3) Noncarcinogenic risk assessment for indoor and outdoor NO_2 exposure

Noncarcinogenic risks refer to adverse health effects in an organism resulting from environmental exposures that do not involve cancer. In an epidemiological study of the noncarcinogenic risk of indoor and outdoor NO_2 exposure, the hazard quotient (HQ) was used to evaluate preschools in urban and industrial areas. As a result, (Figure 4), all HQ values for indoor and outdoor NO_2 exposure for children aged 2 to <3 years, children aged 3 to <6 years, and adults aged 19–75 years during acute exposure were less than 1.0, implying no evidence of risk in either urban or industrial areas. Chronic exposure predominantly revealed that HQ values for both children and adults suggested possible noncarcinogenic effects (HQ>1.0).

Figure 4(a) shows that the HQ values for this study revealed that acute exposure to NO_2 was greater in children aged 2 to <3 years and children aged 3 to <6 years than in adults. Children may be more sensitive to corrosive chemicals than adults because the intrarespiratory tract has a significantly smaller diameter [45]. Children could be especially vulnerable because of their comparatively higher minute ventilation per kilogram of body weight and their inability to immediately flee an area when exposed [45]. Moreover, Phantu and Bootdee [1] and Norbäck et al. [19] reported acute exposure to NO_2 and reported a correlation between indoor NO_2 and classroom symptoms, including ocular symptoms, runny nose, sore throat, wheezing, coughing, and fatigue. Belanger et al. [46] revealed that the inhalation of indoor NO_2 at values less than the annual outdoor standard of the US-EPA (100 µg m^{-3} or 53 ppb) correlates with respiratory symptoms in asthmatic children. Therefore, this research revealed that HQ values for chronic exposure to NO_2 indoors and outdoors were greater than 1.0, which suggests that NO_2 may pose a health risk (Figure 4(b)). Therefore, indoor and outdoor NO_2 exposure had a greater impact on children.

In a long-term study of HQ for NO_2 exposure, the noncancer risk of indoor and outdoor NO_2 exposure during chronic exposure in preschools in urban and industrial areas of Thailand was greater than 1.0. This study also revealed that indoor and outdoor NO_2 levels in HQs were higher for adults than for children, as shown in Figure 4(b). Chronic exposure is not associated with cancer, but long-term exposure may lead to the accumulation of acute effects. Subchronic and chronic exposures (weeks to months) to low concentrations of NO_2 have various effects, such as alterations in lung metabolism, structure and function; inflammation; and increased susceptibility to pulmonary infections [47]. This is possible if specific short-term impacts have a significant influence on life expectancy [48]. Research by Heinrich et al. [49] revealed that a 16 µg m^{-3} rise in NO_2 exposure was linked to death from any cause and heart disease in a group of women. Epidemiological research indicates that chronic exposure to NO_2 from traffic-related air pollution is correlated with an increased risk of all-cause cardiovascular and respiratory mortality [50]. In humans, NO_2 reacts with antioxidants in the epithelial lining fluid (ELF) of the lungs when it is breathed. This creates reactive oxygen species (ROS), such as superoxide (O_2^-) and hydrogen peroxide (H_2O_2). These ROS cause oxidative stress, leading to inflammation and damage to the airways and alveoli. Chronic exposure to NO_2 can worsen respiratory conditions such as asthma and contribute to chronic lung diseases by impairing lung function [45]. Consequently, chronic exposure to NO_2 could present potential health hazards.



(a) Acute exposure

(b) Chronic exposure

Figure 4 HQs for indoor and outdoor NO_2 exposure for (a) acute exposure and (b) chronic exposure.

Conclusions

This study revealed that the indoor and outdoor NO_2 levels in preschools located in urban (Lampang) and industrial (Rayong) areas during the haze period were caused mainly by emissions from biomass burning, traffic, and industry. The indoor NO_2 levels were below the WHO limit of 40 μg m^{-3}. The outdoor NO_2 concentration was lower than the mean annual concentration recommended for NO_2 outdoor air quality standards created by the NAAQS (100 μg m^{-3}) and the PCD, Thailand (57 μg m^{-3}). However, outdoor NO_2 levels were above the WHO air quality limit of 10 μg m^{-3}, approximately 84–89%. Most of the I/O ratios of Rayong and Lampang Provinces are also less than 1 (0.73-0.89). These findings suggest that indoor NO_2 levels may be slightly affected by outdoor NO_2 levels. Owing to the Thai smoke haze episode, NO_2 levels in Lampang and Rayong Provinces were highest in February and January 2024. Furthermore, the correlation between NO_2 and $PM_{2.5}$ concentrations in Lampang and Rayong Provinces was strong, indicating that NO_2 is a significant precursor to the formation of $PM_{2.5}$. However, traffic and industrial emissions were the primary sources of data used in this study. The health risk assessment revealed that the HQ value for chronic exposure to indoor and outdoor NO_2 was greater for adults than for children. The indoor and outdoor NO_2 concentrations in the schools strongly affected both children and adults (HQ>1.0). Long-term exposure could contribute to the accumulation of effects in adults. Moreover, HQ is directly proportional to the pollutant concentration and the duration and duration of exposure.

Limitations of the study

1) In this study, NO_2 was collected via passive sampling. Passive sampling has several limitations that may sometimes be difficult to overcome, most likely the most important of which is the possible effect of environmental conditions (such as temperature, air movement, and humidity) on analyte uptake.

2) The sampling period of this study was the dry season, so the meteorological factors had a slight correlation with the NO_2 concentration, especially rainfall.

3) There is no evidence quantifying NO_2 emissions from power plants in Lampang Province, which may affect NO_2 concentrations in this study. This issue may be investigated further in the future.

4) The US-EPA guidelines provide most of the values for the health risk assessment in this study. Therefore, the values for the health risk assessment guidelines in Thailand are subject to further investigation.

Acknowledgments

The authors are grateful to the Faculty of Science, Energy, and Environment, King Mongkut's University of Technology North Bangkok. This research was funded by King Mongkut's University of Technology North Bangkok, Contract no. KMUTNB-67-BASIC-14. The authors would like to thank all the teachers at the selected preschools in Lampang and Rayong Provinces. We are also grateful to Thailand's Pollution Control Department (PCD) for providing the $PM_{2.5}$ data.

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