Research Article

Health Risk Assessment of Gaseous Pollutants in the Ambient Environment of Rayong City, Thailand: The Initiative of the EEC Area

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Abstract

The Eastern Economic Corridor (EEC) project initiative has an adverse impact on the increasing problem of air pollution. This research aims to determine ambient NO_2, O_3, and SO_2 levels in the industrial area (IT) and urban area (UB) in Rayong city as part of a health risk assessment from 2018 to 2020. The average NO_2, O_3, and SO_2 concentrations at IT site were ranged from 23.5–24.7 $\mu g/m^3$, 42.7–56.7 $\mu g/m^3$, and 12.5–14.0 $\mu g/m^3$, while those at UB site were 14.8–20.7 $\mu g/m^3$, 42.5–68.3 $\mu g/m^3$, and 3.2–4.7 $\mu g/m^3$, respectively. Their concentrations in dry season were higher than those in wet season at both IT and UB sites. The days in the IT site exceeded the daily WHO guideline of NO_2 was 34.8–44.0%, while those in the UB site were 10.8–34.5%. The hazard quotient (HQ) values for a non-carcinogenic risk to human health caused by NO_2 exposure indicated a medium hazard (HQ = 1.1–10.0), whereas the HQ values for SO_2 and O_3 indicated a negligible risk (HQ < 1.0). The total non-carcinogenic risk (HI) from air pollutants contamination being exposed concurrently, on the other hand, indicated risk levels that are likely to affect health, particularly children. Therefore, environmental management and protection in Rayong city are important for people who live in industrial and urban areas, especially during dry period.

Keywords: Air pollution, Gaseous pollutants, Health risk assessment, Hazard quotient (HQ), Hazard index (HI)

1 Introduction

Air pollution increases morbidity and mortality from non-communicable cardiovascular and respiratory diseases, which are the leading causes of death worldwide. Over 90% of the world's population lives in an area where the air is too polluted to breathe, resulting in 4.2 million deaths per year (2016 data). Ischemic Heart Disease (IHD) accounted for 38% of all deaths from ambient air pollution, while stroke accounted for 20% and chronic obstructive pulmonary disease (COPD) accounted for 43%. Many gaseous pollutants are major factors in disease in humans. For the long-term effects of ozone (O_3) and nitrogen dioxide (NO_2), only all-cause and cause-specific mortality were evaluated. Short-term effects for O_3, NO_2, and sulfur dioxide (SO_2) were studied for all non-accidental and cause-specific mortality for asthma hospital admissions and emergency room visits [1].

Nitrogen dioxide (NO_2) is produced by burning fuel at high temperatures, typically from the exhaust of Manuscript-anonymized motor vehicles and power plants, and is released into the atmosphere. NO_2 is an important atmospheric trace gaseous. It is an influential factor in determining O_3 concentrations in the troposphere since it is the catalyst for photochemical O_3 synthesis. Fuel is burned at high temperatures, primarily from the exhaust of motor vehicles and power plants to produce the nitric oxides (NO_X) gaseous, which is released into the ambient air [2]. Studies have shown that NO_2 exposure was associated with asthma, respiratory health, ocular symptoms, fatigue, breathing difficulties, and the risk of lung cancer [2]–[5].

Tropospheric O_3 is a secondary air pollutant formed by the photochemical reaction of volatile organic compounds (VOCs) and NO_2. It has the potential to harm both human health and the environment [6]. According to Kumar *et al.* [7], O_3 levels are higher in an industrial town than in a non-industrial town, and living in an industrial town is linked to increased chronic respiratory symptoms, such as cough, phlegm, dyspnea, or wheezing, as well as lung function defect. Essentially, the pattern is almost always initiated by the reaction of various VOCs with the hydroxyl radical ($HO^{\bullet}$) to form organic peroxy radicals ($RO_2^{\bullet}$), which react easily with NO to form NO_2 as shown in Equation (1) and (2). Moreover, the reactions of NO with either the hydroperoxy radical ($HO_2^{\bullet}$) to produce NO_2 [Equation (3)] and $HO^{\bullet}$ can react with NO_2 to produce nitric acid (HNO_3), as presented in Equation (4). Equations (5) and (6) presented that NO_2 is photolyzed to generate oxygen radicals ($O^{\bullet}$), which are combined with O_2 to create O_3 [8]. Therefore, the reaction of NO with O_3 generates NO_2 and O_2 at nighttime as shown in Equation (7).

$$\mathrm{VOCs} + HO^{\bullet} \xrightarrow{[O_2]} RO_2^{\bullet} + H_2O \tag{1}$$

$$RO_2^{\bullet} + NO \xrightarrow{[O_2]} \text{secondary VOCs} + HO_2^{\bullet} + NO_2 \tag{2}$$

$$HO_2^{\bullet} + NO \rightarrow HO^{\bullet} + NO_2 \tag{3}$$

$$HO^{\bullet} + NO_2 \rightarrow HNO_3 \tag{4}$$

$$NO_2 + h\upsilon \rightarrow NO + O^{\bullet} \tag{5}$$

$$O^{\bullet} + O_2 + M \rightarrow O_3 + M \tag{6}$$

$$O_3 + NO \rightarrow NO_2 + O_2 \tag{7}$$

Sulfur dioxide (SO_2) is a significant source of air pollution in many parts of the world, caused by the combustion of sulfur-containing fossil fuels. The creation of sulfurous and sulfuric acids results from the oxidation of sulfur dioxide, particularly at the surface of particles in the presence of metallic catalysts. The most serious problems have occurred in urban areas when coal has been utilized for home heating or in industrial estates with poorly controlled combustion. At increased SO_2 levels, lung diseases such as asthma, chronic bronchitis, and emphysema will have more serious effects. Moreover, SO_2 and NO_X impact the environment when they react with other chemicals in the atmosphere to form acid rain [Equations (11), (13) and (14)] [1].

$$NO_2 + O_3 \rightarrow {}^{\bullet}NO_3 + O_2 \tag{8}$$

$${}^{\bullet}NO_3 + SO_2 \rightarrow NO_2 + SO_3 \tag{9}$$

$$N_2O_5 + SO_2 \rightarrow SO_3 + 2NO_2 \tag{10}$$

$$SO_3 + H_2O \rightarrow H_2SO_4 \tag{11}$$

$$NO_2 + SO_2 \rightarrow (SO_3)_2N_2O_{3\,(s)} \tag{12}$$

Wilson Jr *et al.* [9] revealed that the associations of NO_2, O_3, and SO_2 reactions in the atmosphere are represented by Equations (8)–(12). Furthermore, it may relate to particulate matter in ambient air shown in Equation (12). During the night, the NO_3 radical is combined with NO_2 to generate N_2O_5. In ambient air, the probable loss pathways for NO_3 radical and N_2O_5 with water to produce HNO_3 at nighttime [Equations (13)–(15)]. This should result in NO_2 formation during the daytime [Equation (16)] [10].

$${}^{\bullet}NO_3 + NO_2 \rightleftharpoons N_2O_5 \tag{13}$$

$$N_2O_5 + H_2O \rightarrow 2HNO_3 \tag{14}$$

$${}^{\bullet}NO_3 + H_2O \rightarrow HNO_3 (\text{+ other products}) \tag{15}$$

$${}^{\bullet}NO_3 + h\upsilon \rightarrow NO_2 + O^{\bullet} \tag{16}$$

Furthermore, previous research has revealed a link between NO_2, O_3, and SO_2 in ambient air. NO_2 and SO_2 concentrations in ambient air were negatively associated with O_3, but NO_2 values were positively correlated with SO_2 [11]–[13]. Several researchers studied the investigation of NO_2, O_3 and SO_2 in industrial area, urban and mining areas. Olufemi *et al.* [14] reported a concentration of NO_2, O_3, and SO_2 in schools emitted from a coal mine in South Africa. They found that the concentration of NO_2, O_3, and SO_2 in ambient air in descending order were O_3 (66–110 $\mu g/m^3$) > SO_2 (14–84 $\mu g/m^3$) > NO_2 (9.9–27 $\mu g/m^3$). According to an investigation of the average NO_2, SO_2, and O_3 concentrations in Al Khafji city, Saudi Arabia, they were found to be approximately 11.3, 3.1, and 85.0 $\mu g/m^3$ in residential areas, 33.8, 56.8, and 95.8 $\mu g/m^3$ in industrial areas, and 14.3, 53.1, and 101.4 $\mu g/m^3$ in the terminal heliport, respectively [13].

The hazard quotient (HQ) has been widely used in non-carcinogenic risk assessment to describe exposure to air pollutants in the environment. Several studies have determined the HQ values for assessing the risk of heavy metals to human health in particulate matters (PM) from traffic and road dust, construction dust, and biomass burning [15]–[17]. Similar to this, the non-carcinogenic risk assessment of gaseous pollutants such as CO, CO_2, NO_2, O_3, and SO_2 exposure in ambient air was analyzed [12], [13]. However, the non-carcinogenic risk for NO_2, O_3, and SO_2 exposure was calculated using the hazard quotient (HQ), which showed negligible risk (HQ<1.0). Researchers in China studied the concentrations of NO_2, O_3, and SO_2 in the Shanghai municipality from 2015 to 2018. The average NO_2, O_3, and SO_2 concentrations in cities were 44–48 $\mu g/m^3$, 43–47 $\mu g/m^3$ and 8–13 $\mu g/m^3$, respectively. The primary source of pollutants was coal combustion and traffic-related emission [12]. From 2007 to 2016, Cichowicz and Stelegowski [18] reported gaseous pollutants emitted from power plants in Poland in both urban and rural areas. The average NO_2, O_3, and SO_2 concentrations in urban areas were 18.3, 52.8, and 9.9 $\mu g/m^3$, while the mean values in rural areas were 13.4, 55.8, and 8.6 $\mu g/m^3$, respectively. They observed that as a result of the analysis, SO_2 concentrations have decreased by 75% in urban regions and 59% in rural areas. The changes in NO_2 and O_3 were only about –8% to 12%. It was estimated that NO_2 and O_3 concentrations above standard values in subsequent years may expose vegetation and people living in these locations to adverse NO_2 and O_3 impacts. Epidemiology studies of scientific literature confirmed that NO_2, O_3, and SO_2 induced pulmonary irritants and respiratory system, but the genetic and related effects induced by gaseous exposures were not investigated [19]. Previous research has revealed that abnormal immune system regulation and chronic inflammation are key mechanistic features of obstructive pulmonary disorders that increase the risk of lung cancer [11], [19]–[21].

The Eastern Economic Corridor (EEC) is a strategic plan derived from the royal Thai government's 20-year strategy to achieve high-income status by 2036, named “Thailand 4.0”. The goals are to encourage investment in Thailand's industrial sector, increasing the country's competitiveness and allowing for long-term growth. Chonburi, Rayong, and Cha-Cheng-Sao are the three Eastern provinces targeted, each with over 13,000 km^2. The EEC area will be a hub for automation and robotics, aviation and logistics, biofuel and biochemicals, and digital. Under the management system for the years 2017–2021, this will strengthen Thailand's position as the ASEAN economic hub [21].

Poor air quality has a significant impact on people's health, which is a major concern. Furthermore, there have not been many studies on gaseous pollutants for health risk assessment in Rayong province, which is the initiative of the EEC area. As a result, the main objective of this research is to precisely measure gaseous pollutant concentrations (NO_2, O_3, and SO_2) in various locations near industrial zones in Rayong city to evaluate air quality and potential health risks under the EEC model.

2 Materials and Methods

2.1 *Sampling site and gaseous pollutants concentration*

Rayong province is one of the industrial estates in Thailand. The Maptaphut Industrial Estate is the main industrial estate in Rayong province, which was developed and began operations in 1989 and covers an area of 2,746.64 acres. At present, the estate consists of 706 industrial plants, which include 6 coal-fired power plants, 142 petrochemical and chemical product plants, 9 petroleum plants, 2 oil refineries, 89 steel and metal factories, 47 food industries, and 42 rubber processing plants [22]. Rayong province

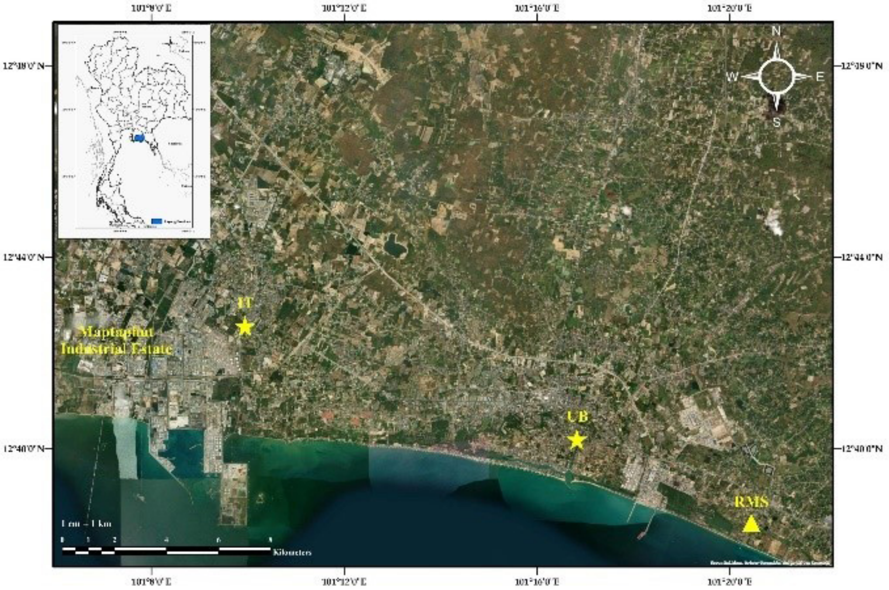


Figure 1: The sampling sites in Rayong city.

has been selected to prepare construction areas in the EEC innovation platform industry in the future. The establishment of industrial estates are developed next- generation automotive, intelligent electronics, advanced agriculture and biotechnology, food for the future, high-value and medical tourism, automation and robotics, aviation, and logistics, and digital [23]. As a consequence, sustainable natural resource management and a well-conserved environmental system are critical in the EEC area.

The Air Quality Monitoring Station (AQM), Pollution Control Department (PCD), Thailand provided secondary data for this investigation. In Rayong city, NO_2, SO_2, and O_3 concentrations were continually recorded at 2 AQMs. The industrial area (IT), which is located at 12o 42' 30.9924 and 101o 9' 57.6288, was represented by the Maptaphut AQM (29t). The industrial area is situated close to oil refineries, petrochemical and chemical product plants and coal-fired power plants. Rayong provincial Agriculture Office AQM (30t) in downtown Rayong city (12° 40' 17.7312 and 101° 16' 33.3408) provided the urban area (UB). It is located at the center of Rayong city, nearby residential area, commercial activities, and government offices.

The methods of pollutant monitoring are based on ultraviolet fluorescence for SO_2 and chemiluminescence for NO_2 and O_3. This study lasted from 1 January 2018 to 31 December 2020. The sample data began at 9.00 a.m. and ended at 9.00 a.m. (the next day). Each month, approximately 720 data were recorded. Figure 1 illustrates the sampling locations. The meteorological parameter was received from Rayong Meteorological Station (RMS), the Thai Meteorological Department. Sunshine duration (SS), relative humidity (RH), wind speed (WS), rainfall (RF), and temperature (T) are all daily meteorological parameters.

2.2 *Non-carcinogenic risk assessment*

This study used the HQ to calculate a health risk assessment for non-carcinogenic NO_2, O_3, and SO_2 exposure. The hazard quotient (HQ) is a numerical ratio of a single substance exposure level during a particular time period to a reference dose for that substance derived from a similar exposure period [24]. Long-term non-carcinogenic effects in organisms caused by causes other than cancer. The health risk assessment of NO_2, O_3, and SO_2 exposure pathways was linked to the exposure factor described by Prasertsin and Nathapindhu [25]. The HQ was computed from the ratio of the average daily dosage (ADD) to the reference dose (RfD) of each pollutant using the following Equation (17).

$$\mathrm{HQ} = \frac{\mathrm{ADD}}{\mathrm{RfD}} \tag{17}$$

When the HQ < 0.1 indicate no hazard exists, HQ = 0.1–1.0, there is a low hazard or only negligible risks, HQ = 1.1–10 implies moderate hazard, and the HQ > 10 indicates a high hazard [26], [27]. Equation (18) can be used to compute the ADD through inhalation.

$$\mathrm{ADD} = \frac{\mathrm{C} \times \mathrm{Inh\,R} \times \mathrm{ET} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \tag{18}$$

Where ADD is the ADD of pollutants [24]; C is the concentration of ambient air pollutants (µg/m^3); InhR is the inhalation rate (m^3/hour); ET is the exposure time (hours/day); EF is the exposure frequency (days/year); ED is the exposure duration (years); BW is the body weight of the exposed group (kg) and AT is the average time (days). The values of these parameters were shown in Table 1

Table 1: Parameters of the average daily dose (ADD) for NO_2, SO_2, and O_3 [25]

Parameters	**Exposed Group**		
	Children (6–11 years)	**Teenagers (12–19 years)**	**Adult (≥20 years)**
Inhalation rate (InhR)	0.46 m^3/h (11.0 m^3/day)	0.58 m^3/h (14 m^3/day)	0.54 m^3/h (13 m^3/day)
Exposure frequency (EF)	350 days/year	350 days/year	350 days/year
Exposure duration (ED)	5 years	7 years	30 years
Exposure time (ET)	24 hours/day	24 hours/day	24 hours/day
Averaging time (AT) AT = ED × 365 days	1,095 days	1,277.5 days	8,760 days
Bodyweight (BW)	29 Kg	52 Kg	65 Kg

The reference dose (RfD) for human exposure to NO_2, O_3, and SO_2 is based on the World Health Organization (WHO) air quality guideline, as indicated in Table 2. RfC is the reference concentrations of ambient air pollutants (µg/m^3); IR is the inhalation rate of 0.83 m^3/h; ET is the exposure time of 24 h/day; EF is the exposure frequency of 350 days/year); ED is the exposure duration of 70 years; BW is the body weight of the exposed group of 70 kg and AT is the average time of 70 years × 365 days/year [28] [Equation (19)].

$$\mathrm{RfD} = \frac{\mathrm{RfC} \times \mathrm{IR} \times \mathrm{ET} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \tag{19}$$

Table 2: The reference concentrations (RfC) and the reference dose (RfD) of ambient air pollutants [1]

Pollutants	**Annual Mean Concentrations of WHO Air Quality Guideline (µg/m^3)**	**RfD (µg/kg-day)**
NO_2	25	6.82
SO_2	40	10.9
O_3	100	27.3

The hazard index (HI) was also used to determine the total non-carcinogenic risk from many contaminants being exposed at the same time. The HI value is the sum of the HQ of the gaseous pollutants in a mixture. It was calculated by Equation (20).

$$\mathrm{HI} = \sum \mathrm{HQ} = \mathrm{HQ}_{NO_2} + \mathrm{HQ}_{SO_2} + \mathrm{HQ}_{O_3} \tag{20}$$

HI values less than 1.0 suggest that the pollutant under evaluation is probable to suffer health impact, while HI values greater than 1.0 indicate risk levels that are likely to affect health [29], [30].

2.3 *Data analysis*

The concentrations of gaseous pollutants were distributed normally. The mean difference between gaseous pollutants and year in Rayong city was determined statistically using One-way ANOVA. The T-test was used to compare average NO_2, O_3, and SO_2 concentrations between sampling sites. Pearson's correlation analysis was used to assess the relations between meteorological parameters and gaseous pollutant concentrations.

3 Results and Discussion

3.1 *Concentrations of NO_2, O_3, and SO_2*

Concentrations of NO_2, O_3, and SO_2 were analyzed at both IT and UB sites in the city of Rayong from 2018 to 2020. The results are shown in Figure 2. The average NO_2, O_3, and SO_2 concentrations at IT site in descending order were 42.7 ± 7.8 to 56.7 ± 11.8 µg/m^3 (O_3) >

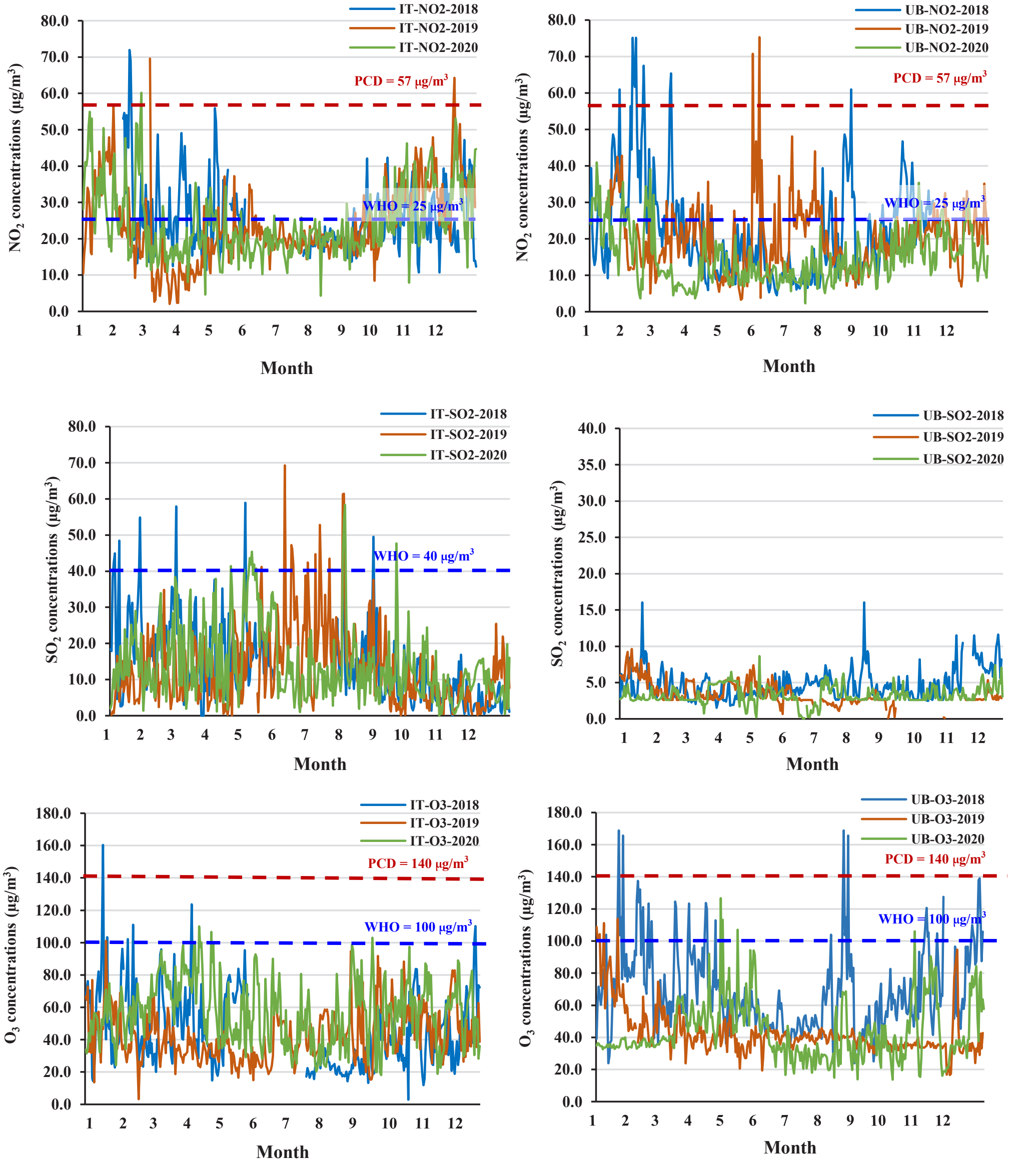


Figure 2: Concentrations of NO_2, SO_2, and O_3 at UB and IT of Rayong city in 2018–2020.

23.5 ± 8.4 to 24.7 ± 4.1 μg/m^3 (NO_2) > 12.5 ± 3.3 to 14.0 ± 6.5 μg/m^3 (SO_2), while those at the UB location were 42.5 ± 11.4 to 68.3 ± 16.4 μg/m^3 (O_3), 14.8 ± 5.2 to 20.7 ± 11.4 μg/m^3 (NO_2) and 3.2 ± 1.5 to 4.7 ± 1.4 μg/m^3 (SO_2). Compared with the previous studies, it was found that the concentration of NO_2, O_3, and SO_2 in ambient air in descending order were O_3 (66–110 μg/m^3) > SO_2 (14–84 μg/m^3) > NO_2 (9.9–27 μg/m^3) emitted from coal mine and combustion in South Africa [14]. Moreover, the average concentration of NO_2, O_3, and SO_2 was higher than the values released from urban areas (18.3, 52.8 and 9.9 μg/m^3) and rural areas (13.4, 55.8 and 8.6 μg/m^3) emitted from the vicinities of the power plant in Poland [18]. Chen *et al.* [12] studied the NO_2, O_3 and SO_2 values released from coal combustion and traffic-related emission in Shanghai, China from 2015 to 2018, which were 44–48, 43–47, and 8–13 μg/m^3, respectively. However, it was found that the NO_2 and SO_2 values were higher than the value of industrial areas, while O_3 values were lower than in this study. This study of industrial area (23.5–24.7 µg/m^3 for NO_2, 42.7–56.7 µg/m^3 for O_3, and 12.5–14.0 µg/m^3 for SO_2) showed lower than ambient NO_2, O_3, and SO_2 concentrations in Bangladesh, which were measured to be 15.2–79.0 µg/m^3, 7.85–13.7 µg/m^3, and 4.97–22.0 µg/m^3 and in Al Khafji city, Saudi Arabia, where the values were 2.82–193 µg/m^3, 22.0–363 µg/m^3, and 16.7–313 µg/m^3, respectively [31].

Most of NO_2, O_3, and SO_2 concentrations collected in the dry season (January–April and November–December) were significantly higher than those in the wet season (May–October) both IT and UB sites from 2018 to 2020 as illustrated in Figure 2. The average NO_2, O_3, and SO_2 concentrations at IT site obtained in dry season were in a range of 23.5–26.6, 42.7–56.7, and 12.5–14.0 µg/m^3 respectively, while those in wet season were in a range of 20.8–22.8, 33.7–52.0, and 11.9–16.7 µg/m^3 respectively. The average NO_2, O_3, and SO_2 concentrations at UB site obtained in dry season were in a range of 14.8–23.4, 42.5–68.3, and 3.3–4.7 µg/m^3 respectively, while those in wet season were in a range of 12.6–19.1, 38.1–55.4, and 2.8–4.4 µg/m^3 respectively. It can be seen that their concentrations in dry season were approximately 1 time higher than those in wet season.

During the period 2018–2020, the percentage of days in the IT site that exceeded the daily WHO guideline (25 µg/m^3) of NO_2 was 43.0% (117 days in 2018), 34.8% (126 days in 2019), and 36.9% (134 days in 2020), while the percentage of days in the UB site was 34.5% (108 days in 2018), 25.3% (88 days in 2019), and 10.8% (10 days in 2020). (38 days in 2020). Furthermore, the annual NO_2 percentage for PCD standard (57 µg/m^3) was lower than the WHO value, which was 0.3–0.7% in IT site and 0.6–2.9% in UB site during the year 2018–2020. However, the SO_2 and O_3 levels at the IT and UB sites were well below the daily WHO guideline and PCD standard.

For statistical analysis, the observed NO_2, O_3, and SO_2 values were normal distribution. T-test was used to compare the average NO_2, O_3, and SO_2 concentrations between the IT and UB site and One-Way ANOVA was used to compare the average NO_2, O_3, and SO_2 concentrations over time. It was found that the concentrations of NO_2 and SO_2 measured in the IT site were significantly higher difference than in the UB site ($p < 0.05$), while O_3 values in both sites were not significantly different ($p > 0.05$). The NO_2, O_3, and SO_2 concentrations measured in both IT and UB sites were significantly different ($p < 0.05$). The O_3 values in both sites were the highest of gaseous pollutants. Because of accumulated NO_2, O_3, and SO_2 from surrounding coal-fired power plants, petrochemical and chemical product infrastructure, and traffic congestion, gaseous pollution levels at the IT sites were reported to be greater than at the UB site. According to Khamyingkert and Thepanondh [32], annual mean NO_2 values emitted from the petrochemical industry and power plant (Coal combustion) group in Maptaput industrial estates were 67.23% and 28.23%, respectively, while annual mean SO_2 values emitted from the petrochemical industry, power plant and refinery plant group were 89.64%, 4.97%, and 3.94%, respectively. According to Nwosisi *et al.* [33], NO_2 emissions from gas flaring stations in Nigeria ranged between 29 to 36 µg/m^3. Local NO_X emissions, generally in the form of NO from combustion sources, and VOCs emissions trigger photochemistry that leads to high O_3 levels. The formation of secondary radicals (ROX) from the decomposition of VOCs due to interactions with OH lengthens the radical and NO_X reaction chains that generate O_3 in industrial areas [34]. Furthermore, gas pollutant concentrations measured at the UB site in 2018 were statistically higher than those observed in 2019 and 2020 ($p < 0.05$), while gaseous pollutants values at the IT site were not significantly different from those measured each year. The result of the UB site could be related to the economic and transportation activity that has been significantly reduced because of the lockdown response to COVID-19 [35], [36]. However, Wetchayut [36] reported that during the COVID-19 lockdown in Bangkok, all pollutants tended to decline, except for NO_2 and SO_2 levels, which were caused by logistic transportation, industrial activity, and increasing energy use, resulting in electric power plants for work from home. As can be seen, while comparing the emitted gaseous pollutants in ambient air from both sites, the IT site emits no gaseous pollution that was significantly different from those measured each year.

The Pearson's rank correlation of daily gaseous pollutants and meteorological parameters is shown in Table 3. NO_2 concentrations were significantly positively correlated ($p < 0.01$) with SO_2 ($r = 0.201$)

and O_3 (r = 0.187–0.340). According to Khamyingkert and Thepanondh [32], the industrial area in Rayong city emitted NO_2 and SO_2 concentrations in the atmosphere and their correlation. Moreover, O_3 is well known to be dependent on photochemical interactions of gaseous precursors composed of nitrogen oxides (NO_X) and VOCs [34]. Therefore, the correlation between O_3 levels and sunshine duration (SS) was significantly positive (r = 0.094 to 0142, $p < 0.01$) and relative humidity (RH) was significantly negative (r = –0.113 to –0.158). In general, long periods of sunshine and low relative humidity play a significant role and have a direct effect on chemical kinetic rates and the mechanistic pathways of O_3 [37]. The significant inverse relationship between NO_2 and O_3 levels and temperature (T), with higher temperatures promoting photochemical reactions and increasing O_3 abundance [37]. In contrast, the previous research revealed a significant positive correlation between O_3 and temperature. The reason for this study is the reaction of NO_2 and O_3 to NO_3 radicals at night [10]. It is removed to nitric acid (HNO_3) after reaching the peak concentration of NO_2 [9]. Moreover, it was found that NO_2 values were found positively and significantly correlated with SS (r = 0.094 to 0.164, $p < 0.01$). The photochemical reaction in the industrial area converted VOCs to NO_2. However, it was dependent on local emission of NO_X and VOCs may be significantly limited as shown in Equations (1)–(3) [27]. Negative correlations between gas pollutants and rainfall (r = –0.037 to –0.113) and significantly correlated in SO_2 indicate that these air pollutants are diluted by precipitation. Furthermore, wind speed (WS) had significant negative correlations with NO_2 (r = –0.128 to –0.158). Pollutant accumulation and chemical reaction are assisted by calm wind, cloudy weather, and weak sunshine duration [38]

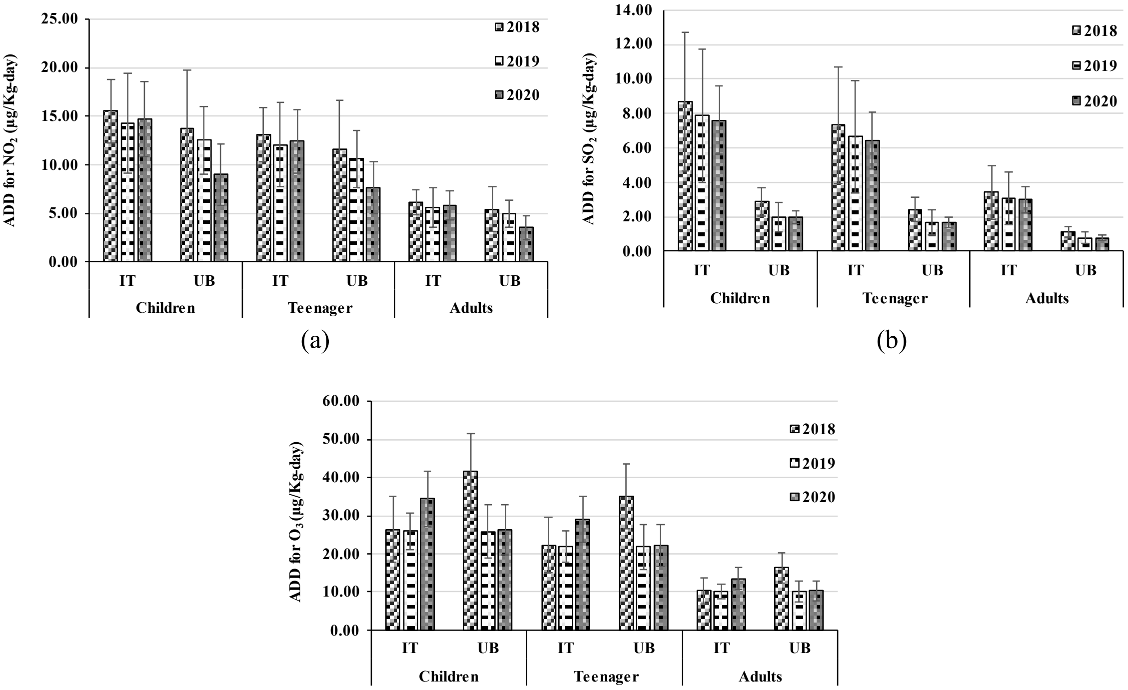
3.2 *Health risk assessment for NO_2, SO_2, and O_3*

In Rayong city, the health risk assessment for ambient NO_2, SO_2, and O_3 in 2018–2020 is concerned with the health impact of exposure to gaseous pollutants. Hazard quotient (HQ) values were used to calculate the non-carcinogenic risk of NO_2, SO_2, and O_3 exposure. Non-carcinogenic risk refers to all adverse health effects in an organism caused by environmental factors other than cancer. Based on the calculated average daily dosage (ADD) and taking the reference values or RfD doses into account. Figure 3 depicted the ADD values for children, adolescents, and adults at UB and IT in Rayong City. ADD values from NO_2

Table 3: Pearson's correlation coefficients of different variables for gas pollutants and meteorological parameters in Rayong city

Parameters	NO_2	SO_2	O_3	SS (h)	RH (%)	WS (m/s)	RF (mm)	T (°C)
UB (n = 884)								
NO_2	1.000							
SO_2	0.201**	1.000						
O_3	0.340**	0.329**	1.000					
SS	0.094**	–0.005	0.094**	1.000				
RH	0.034	–0.019	–0.113**	–0.429**	1.000			
WS	–0.128**	–0.014	–0.044	–0.245*	0.025	1.000		
RF	–0.064	–0.113**	–0.061	–0.268**	0.270**	0.108**	1.000	
T	–0.285**	0.046	–0.104**	0.121**	–0.038	0.107**	–0.073*	1.000
IT (n = 925)								
NO_2	1.000							
SO_2	–0.017	1.000						
O_3	0.187**	–0.154**	1.000					
SS	0.164**	0.067**	0.142**	1.000				
RH	–0.064	–0.022	–0.158**	–0.418**	1.000			
WS	–0.158**	0.214**	–0.123**	–0.236**	0.031	1.000		
RF	0.037	–0.107*	0.096	–0.062	0.141*	0.043	1.000	
T	–0.487**	0.304**	–0.179**	0.106**	–0.037	0.071*	-0.043	1.000

**Correlation is significant at the 0.01 level (2-tailed).; *Correlation is significant at the 0.05 level (2-tailed).



(a) (b)

(c)

Figure 3: The ADD values for (a) NO_2, (b) SO_2 and (c) O_3 at Rayong city in 2018–2020.

and SO_2 exposure at IT in Rayong were higher than UB, while ADD values from O_3 exposure at UB were higher than IT.

The results of the estimation of non-carcinogenic risks from NO_2, SO_2 and O_3 exposure are shown in Figure 4. It was observed that the HQ values for children, teenagers, and adults from inhalation NO_2 exposure at IT ranged from 2.10–2.28, 1.77–1.92 and 0.82–0.89, while HQ levels at UB were 1.32–2.20, 1.11–1.99 and 0.52–1.00, respectively. However, the HQ values for NO_2 exposure in children and teenagers at IT and UB were 1.1–10.0, indicating a moderate hazard risk [Figure 4(a)]. While HQ values for SO_2 in children, teenagers, and adults were less than 1.0, this indicates a low hazard risk [Figure 4(b)]. Children at UB had HQ values for O_3 [Figure 4(c) that were 1.1–10.0. Furthermore, the hazard index (HI) for all age groups in IT and UB was 1.48–4.12 and 0.97–3.79, respectively, explaining risk levels that are likely to have an impact on health Figure 4(d)]. In descending order, the HI values of exposure to inhalation of gaseous pollutants obtained from both sampling sites were children > teenagers > adults. The result was the same as Morakinyo *et al.* [39], the HQ values for normal and worst-case chronic exposure to NO_2 and SO_2 exposure in an urban-industrial area in South Africa were found to be greater than 1.0 for all age groups, with children appearing to be more likely to be affected than adults. HQ levels for O_3 were shown a negligible risk ($HQ<1.0$). Olufemi *et al.* [14] reported that HQ values for inhalation of NO_2, SO_2 and O_3 in outdoor schools in the vicinities of a coal mine were 0.0007–0.0019, 0.0018–0.0090, and 0.0073–0.012, respectively. However, it was less than 1.0, indicating a safe since health risk. Moreover, Tarassoli *et al.* [40] observed that the HQ values for NO_2 and SO_2 exposure in residential-industrial areas in Iran was lower than 1.0 for up to 6 years (0.02 and 0.02), 6–12 years (0.03 and 0.03) and >12 years (0.01 and 0.02), which HQ values for NO_2 and SO_2 are considered to have negligible hazard. The HQ values for NO_2 exposure per day in children and teenagers in the industrial area (IT) of Rayong city were higher than those for individuals in Rayong city's urban areas (UB). The HQ

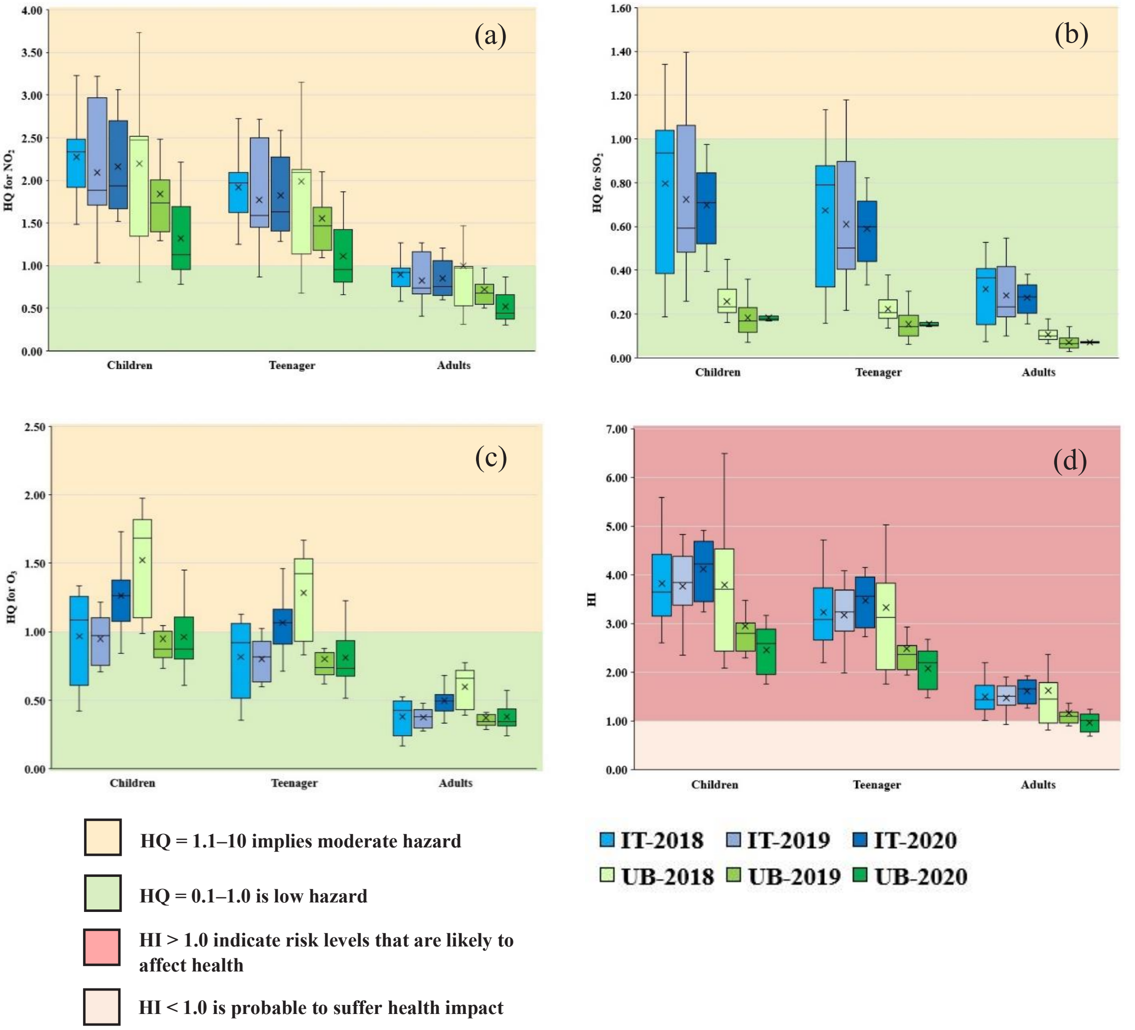


Figure 4: The HQ and HI values for children, teenagers, and adults in Rayong city (a) HQ values for NO_2, (b) HQ values for SO_2, (c) HQ values for O_3, and (d) HI values.

values in relation to a non-carcinogenic risk to human health deriving from NO_2 exposure have indicated the existence of a medium hazard (HQ = 1.1–10.0). As a consequence, under EEC policy, the non-carcinogenic risk of NO_2 exposure may be associated with a health risk for children and teenagers in Rayong. Previous health risk studies found that exposure to low NO_2 levels was associated with increasing risks of chronic obstructive pulmonary disease (COPD), asthma, decreased lung function, hospital admissions, and an increased mortality [3], [41]–[43]. Especially, children are concerned about the health risks of inhaling gaseous pollutants in the urban-industrial area. U.S.-EPA [44] concluded that children's higher inhalation rate per body weight or pulmonary surface area compared to adults may result in higher pollutant exposures.

4 Conclusions

The development of the Eastern Economic Corridor (EEC) is the main to Thailand 4.0. In Rayong province, the establishment of industrial estates is developed next-generation automotive, intelligent electronics, advanced agriculture and biotechnology, food for the future, high-value and medical tourism, automation and robotics, aviation, digital and logistics. The development of EEC policy may have had an impact on local air pollution, posing a health risk. The concentrations of NO_2, SO_2, and O_3 were measured in an urban-industrial area in Rayong city. The percentage of days in the IT site that exceeded the daily WHO guideline (25 $\mu g/m^3$) of NO_2 in 2018–2020 was 34.8–44.0%, while the percentage of days in the UB site was 10.8–34.5%. Furthermore, the annual NO_2 percentage for the PCD standard (57 $\mu g/m^3$) in the IT site was 0.3–0.7% and 0.6–2.9% in the UB. However, SO_2 and O_3 levels at the IT and UB sites were significantly lower than the daily WHO guideline and PCD standard. The HQ values for a non-carcinogenic risk to human health resulting from NO_2 exposure indicated a medium hazard (HQ = 1.1–10.0), whereas HQ values for SO_2 and O_3 indicated a negligible risk (HQ < 1.0). The total non-carcinogenic risk (HI) from air pollutants contamination being exposed at the same time, on the other hand, indicated risk levels that are likely to affect health, particularly in children. Therefore, the findings of health risk assessment and gaseous concentrations in the ambient environment of Rayong are important for environmental management and protection in the city, especially during dry season (January-April and November-December).

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Author Contributions

S.K., S.S., and S.B.: conceptualization, investigation, reviewing and editing; S.B.: investigation, methodology, writing an original draft; S.K. and S.S.: research design, data analysis; S.B.: conceptualization, data curation, writing—reviewing and editing, funding acquisition, project administration. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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