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Assessment of ambient benzene and environmental health impacts: A five-year study in Rayong's pollution control Zone, Thailand

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Abstract: This study aimed to assess the temporal variation of ambient benzene concentrations and evaluate the potential health risks associated with long-term exposure in Rayong's Pollution Control Zone, Thailand. Five years (2020–2024) of continuous air quality monitoring data from 11 automated stations were analyzed. Benzene concentrations and associated meteorological and air quality parameters were examined. Exposure assessment was conducted using the U.S. EPA's ExpoFIRST v2.0 to estimate the average daily dose (ADD) and lifetime average daily dose (LADD). Health risks were quantified through lifetime cancer risk (LCR), hazard quotient (HQ), disability-adjusted life-years (DALYs), and environmental burden of disease (EBD). The mean annual benzene concentration was 2.32 μg/m^3. The highest exposure risk was observed among children, with ADD and LADD ranging from 3.27×10^{-4} to 1.06×10^{-3} mg/kg-day. Estimated DALY losses ranged between 0.291 and 0.800 per 100,000 population for benzene concentrations of 1–5.5 μg/m^3. The results highlight significant chronic health risks associated with benzene exposure, particularly in vulnerable populations. These findings support the need for stricter emission controls and continuous monitoring to mitigate long-term public health impacts in industrial regions.
Keywords: *Air pollution, Benzene, Health impact, Pollution control zone, Thailand.*

1. Introduction

Benzene, a volatile organic compound (VOC), has been extensively studied due to its ubiquitous presence in the environment and reported adverse health effects [1]. The International Agency for Research on Cancer (IARC) has classified benzene as a Group 1 carcinogen, meaning there is strong evidence that it can cause cancer in humans, particularly blood cancers like acute myeloid leukemia [2]. Benzene has also been shown to harm the bone marrow, trigger genetic mutations, and damage DNA even when people are exposed to relatively low levels [3]. Chronic inhalation exposure is a major concern for both the public and workers in the petrochemical and gasoline industries [4]. Numerous studies around the world have found that benzene levels in the air of many urban and industrial areas often exceed recommended health guidelines [5, 6]. Occupational groups such as gas station attendants and refinery workers are particularly at risk, with biomonitoring studies reporting a strong association between airborne benzene exposure, its urinary metabolites (e.g., trans-trans-muconic acid, tt-MA), and genetic effects [7, 8]. Collectively, these findings highlight the urgent need to mitigate the effects of environmental and occupational exposure to benzene, which remains a significant public health concern [9]. In Thailand, benzene contamination has been reported in several urban and industrial areas, particularly in Bangkok and Rayong Province, where the petrochemical industry is concentrated [10].

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Rayong Province, part of Thailand's Eastern Economic Corridor (EEC), hosts one of Southeast Asia's largest petrochemical complexes and is recognized as a persistent hotspot for air pollution [11]. Evidence suggests that workers at gas stations and communities living near the Map Ta Phut Industrial Estate are exposed to high levels of benzene, which has been linked to neurological disorders, respiratory symptoms, and other health effects [12]. Additionally, residents in the surrounding area report higher incidences of allergies and respiratory illnesses associated with long-term exposure to volatile organic compounds (VOCs) [13, 14].

Despite growing evidence, comprehensive health risk assessments focused on inhalation exposure to benzene in pollution control zones such as Rayong Province remain scarce. Most existing studies have focused mainly on occupational groups, leaving a significant gap in understanding the cumulative exposure experienced by communities [15]. Bridging this gap is essential to inform effective public health interventions and strengthen regulatory policies. Therefore, this study aimed to address this research gap by conducting a comprehensive 5-year assessment of atmospheric benzene levels and their impact on environmental and health outcomes in the pollution control zone of Rayong Province, Thailand.

1.1. Objectives

The following are the objectives of the proposed work:

- To explore the spatial variation of benzene concentrations at different locations within the Rayong Pollution Control Zone, Rayong Province, Thailand, using data collected from monitoring stations.
- To analyze the temporal differences in benzene levels over the five-year period from 2020 to 2024 using the combined time series data.
- To examine the relationship between benzene concentration and related meteorological parameters.
- To study the relationship between atmospheric benzene concentration and potential health effects in the population within the Rayong Pollution Control Zone, Rayong Province, Thailand.

2. Literature Review

Recent investigations have demonstrated that extensive industrial zones across Southeast Asia, particularly petrochemical complexes, exhibit elevated ambient benzene concentrations, contributing to substantial long-term health risks. These risks are associated with both chronic emissions and episodic releases, commonly arising from the production, storage, and transportation of petroleum and petrochemical products [15]. In Thailand, the Map Ta Phut Industrial Estate, located in Rayong Province, has been repeatedly identified as a significant source of volatile organic compounds (VOCs), notably benzene and 1,3-butadiene. This environmental concern has continued to attract considerable attention in both national and international scientific literature [9].

Spatiotemporal variations and meteorological factors, including temperature, humidity, wind speed, atmospheric pressure, and precipitation, play critical roles in determining the distribution and deposition of benzene. Previous studies in adjacent areas have demonstrated that seasonal patterns and wind dynamics substantially influence VOC dispersion and accumulation, thereby affecting exposure risks among communities surrounding the Rayong Industrial Estate. Empirical evidence indicates that periods characterized by weak winds and limited atmospheric mixing correspond to elevated benzene concentrations and heightened health risks [16]. More recent research has expanded upon these findings through the application of integrated spatiotemporal assessment frameworks and satellite or remote sensing techniques, providing enhanced insights into the sources and spatial distribution of benzene at both community and regional scales [17].

Within the broader air quality context, benzene frequently co-occurs with other atmospheric pollutants such as $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and various specific VOCs originating from both combustion and industrial activities. Several studies conducted in Thailand have characterized VOC emission profiles and explored urban–rural dynamics, revealing their influence on both direct health risks and the formation of secondary pollutants such as ozone and particulate matter. These findings underscore the importance of concurrently evaluating multiple air quality indicators when assessing the environmental and health impacts of benzene [18].

From a health perspective, benzene is mechanistically classified as a human carcinogen (IARC Group 1), with substantial evidence linking chronic exposure to various forms of leukemia, even at relatively low exposure levels over prolonged periods. Recent epidemiological investigations have further indicated elevated cancer risks associated with long-term environmental exposure to benzene, as well as hematological and neurological effects observed in certain occupational settings [19]. For toxicological reference and regulatory benchmarking, authoritative sources such as the U.S. EPA's Integrated Risk Information System (IRIS) and California's Office of Environmental Health Hazard Assessment (OEHHA) are commonly utilized to establish health-based risk parameters and reference concentration levels in numerous risk assessment studies [5].

In the context of exposure and risk assessment, recent advancements in inhalation-based VOC risk evaluation, including that of benzene, have increasingly incorporated quantitative metrics such as the Average Daily Dose (ADD) and Lifetime Average Daily Dose (LADD) to estimate both cancer risk (Lifetime Cancer Risk; LCR) and non-cancer risk (Hazard Quotient; HQ). These approaches are typically grounded in the U.S. EPA's Risk Assessment Guidance for Superfund (RAGS) framework and operationalized through tools such as the EPA's ExpoFIRST v2.0, which facilitates transparent and reproducible scenario-based exposure estimation. Case studies, including those conducted in developing regions, have demonstrated the application of ExpoFIRST to annual and multi-year environmental monitoring datasets to quantify human health risks. Emerging research is further integrating these assessments with broader disease burden indicators such as Disability-Adjusted Life Years (DALYs) and Environmental Burden of Disease (EBD) to enhance policy relevance and improve risk communication [20].

3. Methodology

3.1. Study Area and Setting

This study focuses on the Map Ta Phut Industrial Estate in Rayong Province, Thailand, which has been designated as a pollution control zone by the Thai government since 2009 [21]. It currently comprises five main industrial estates: Map Ta Phut, Hemaraj Eastern Seaboard, Asia, Pha Daeng, and Rayong Industrial Estate (RIL), along with one deep-sea port, as shown in Figure 1. Industrial activities in the region can be broadly divided into upstream and midstream processes, primarily based on petrochemical production. The area also contains a diverse range of industrial operations, including petrochemical plants, coal-fired power plants, iron and steel industries, natural gas power plants, gas separation plants, and oil refineries, which are major sources of volatile organic compounds (VOCs) released into the atmosphere at both local and regional scales. In addition, diffuse VOC emissions may originate from non-industrial sources, such as transportation activities within the area. Therefore, the ongoing release of VOCs into the atmosphere represents a persistent public health concern for surrounding communities.

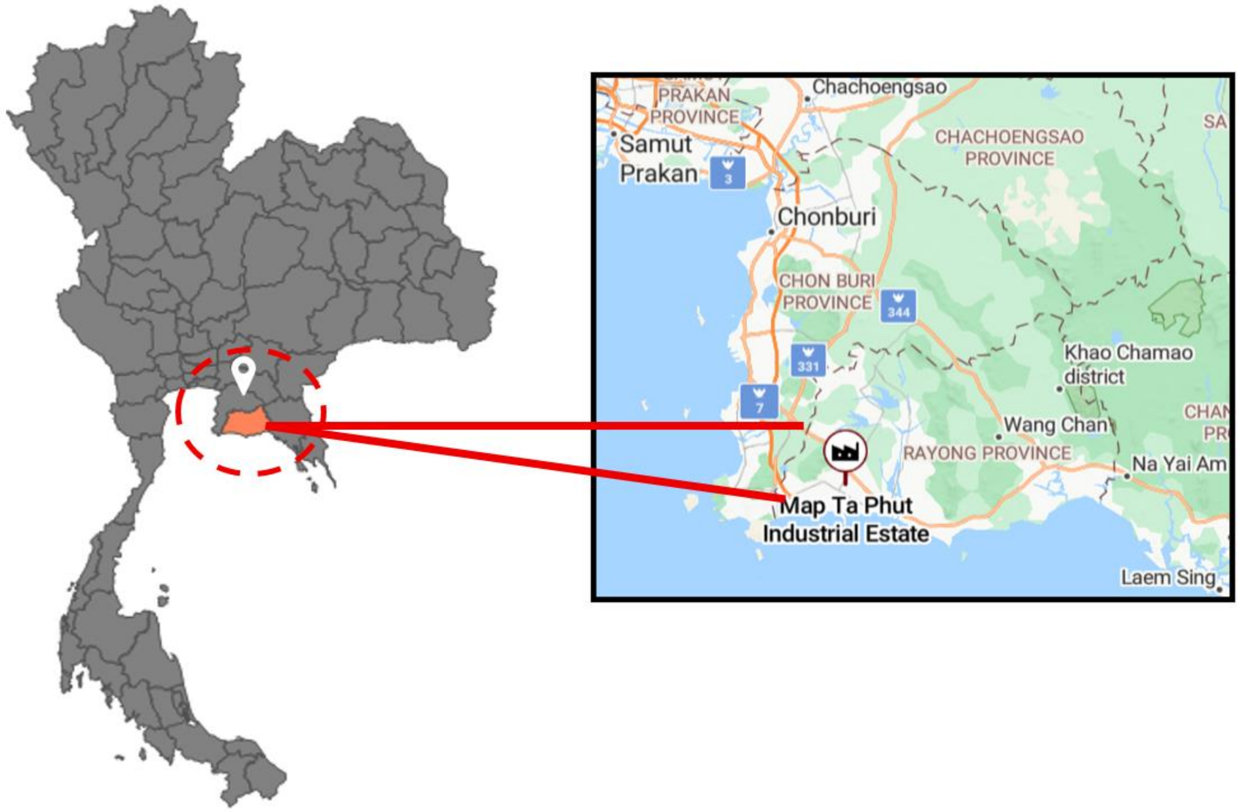

Figure 1.
Location of the study area, emission sources, and air quality monitoring stations.

3.2. Data Collection

This dataset covers the period 2020–2024 and was used to study the relationship between atmospheric benzene concentrations and health outcomes within the study area. Secondary data were obtained from three main sources: air quality records, meteorological records, and health outcome records maintained by relevant national agencies.

1. Air Quality Data: Ambient benzene concentration data were obtained from the Air and Noise Quality Management Office, Pollution Control Department, Ministry of Natural Resources and Environment, Thailand, covering the period 2020-2024 [22]. Measurements were conducted at 11 monitoring stations in the study area (ST1-ST11). These data provided the basis for assessing the temporal patterns of benzene levels and their potential impacts on the environment and public health.

2. Health Data: Comprehensive health outcome data, focusing on the incidence of respiratory and hematological diseases, were collected from the Health Data Center (HDC), Ministry of Public Health, Thailand, for the period 2020–2024 [23]. These datasets provide an essential baseline for assessing potential links between variations in air quality and adverse health outcomes in the study area.

3. Climate and Meteorological Data: Air quality data are continuously monitored through 11 automated stations (ST1–ST11) located in designated pollution control zones of Rayong Province, Thailand. The dataset covering the period from 2020 to 2024 was obtained from the Meteorological Department, Ministry of Digital Economy and Society, Thailand [24]. These data provide a comprehensive basis for examining the variability of air quality over time and its relationship with climatic and meteorological conditions in each region.

4. Exposure Assessment and Environmental Disease Burden: Air pollution directly impacts on human health disproportionately [25]. To assess exposure and environmental disease burden (EBD) in

the Rayong Pollution Control Zone, Rayong Province, Thailand, we used the U.S. EPA's Exposure Factors Interactive Resource for Scenarios Tool (ExpoFIRST v2.0) [20]. This tool was used to calculate the average daily inhalation dose (ADD, mg/kg-day) and the average lifetime daily dose (LADD) based on airborne exposure to long-term respiratory rate (day), and site/activity and receptor-specific parameters (gender, age group, and subpopulation). Benzene was identified as the target contaminant, with input parameters including concentration and permeability coefficient (0.14 cm/h at 26 °C) [26] and molecular weight (78.11 g/mol). The detailed calculation procedure is described in the ExpoFirst document [20].

ExpoFIRST generates dose estimates based on contaminants and receptor groups, and detailed results are exported to a summary report of key parameters defining ADD and LADD scenarios with corresponding equations available in the supplementary material. Health effects are quantified using three key indicators: lifetime cancer risk (LCR), hazard quotient (HQ), and disability-adjusted life years (DALY).

3.3. Statistical Analysis

The descriptive statistics (mean, standard deviation, and variance) were used to analyze annual air quality parameters for comparison with Air Quality Index (AQI) standards, and the Spearman rank correlation was used to study the relationship between benzene concentration and other air quality parameters.

4. Results and Discussions

4.1. Differences between Various Locations of the Pollution Control Zone, Rayong Province, Thailand

Time series analysis of each monitoring station revealed spatial and temporal variations in benzene concentrations over the five-year period (Table 1). The dataset included annual means, multiyear means, and the minimum and maximum concentrations recorded at each site [27, 28]. At all stations, the annual mean benzene concentration decreased slightly, from 2.71 μg/m^3 in 2020 to 1.81 μg/m^3 in 2024, with a multiyear mean of 2.32 μg/m^3. This continuous downward trend indicates a gradual improvement in ambient air quality concerning benzene exposure over the study period [29].

Spatially, significant differences were observed between stations. Stations ST-3 and ST-11 consistently reported the highest annual average values, reaching peak values of 5.54 μg/m^3 (2021) and 7.80 μg/m^3 (2021), respectively. Notably, ST-11 also recorded the highest observed concentration during the study period (32.00 μg/m^3 in 2021), indicating localized pollution sources or isolated events influencing air quality in that area. In contrast, stations ST-5, ST-6, ST-8, ST-9, and ST-10 consistently displayed lower annual average values, typically below 2.0 μg/m^3 after 2021.

The minimum concentrations at most stations were close to zero, indicating periods of very low benzene levels, possibly resulting from favorable weather conditions or reduced industrial activity. However, the consistently increasing maximum concentrations, particularly at stations ST-3 and ST-11, highlight the influence of episodic emission events and emphasize the need for targeted monitoring and control. This study is consistent with previous research, Sharma et al. [30] and Siddiqua et al. [31], which found that there should be planning and monitoring of air pollutant emissions from industrial sources to nearby residents.

Table 1.
Annual variations in benzene concentration (µg/m³) from 11 monitoring stations in the Rayong Pollution Control Zone, Thailand, during 2020–2024.

Monitoring Station	**Annual Average** (µg/m³)					**Multiannual Average** (µg/m³)	**Minimum** (µg/m³)					**Maximum** (µg/m³)				
Year	**2020**	**2021**	**2022**	**2023**	**2024**		**2020**	**2021**	**2022**	**2023**	**2024**	**2020**	**2021**	**2022**	**2023**	**2024**
ST-1	3.42	2.89	1.92	1.86	1.38	2.29	1.60	1.20	0.00	0.65	0.00	5.20	4.40	3.32	3.70	3.10
ST-2	2.43	2.99	2.34	2.48	1.23	2.29	1.30	0.81	0.00	0.43	0.20	4.50	9.20	8.40	5.10	2.20
ST-3	4.88	5.54	2.64	4.66	3.58	4.26	1.90	1.50	0.00	0.86	0.90	13.00	21.00	7.30	15.00	13.00
ST-4	3.23	2.87	1.98	1.26	2.36	2.34	1.40	1.60	0.00	0.22	0.73	7.60	5.50	4.60	4.10	3.70
ST-5	1.97	1.34	0.81	1.05	1.70	1.37	0.68	0.23	0.00	0.24	0.20	3.10	2.43	2.43	1.70	3.70
ST-6	2.26	2.12	0.81	1.05	1.74	1.60	0.41	0.16	0.00	0.24	0.20	6.20	3.93	2.43	1.70	4.00
ST-7	2.65	2.37	1.67	1.70	2.09	2.10	0.42	1.00	0.00	0.46	0.80	6.00	5.00	3.20	2.90	4.30
ST-8	2.15	1.42	1.24	1.10	0.97	1.38	0.64	0.73	0.00	0.52	0.20	6.60	3.19	3.19	2.00	1.80
ST-9	1.68	2.57	2.05	1.48	1.50	1.86	0.63	1.30	0.00	0.49	0.70	2.90	5.81	5.81	3.10	2.50
ST-10	1.66	1.62	1.29	1.05	1.10	1.34	0.41	1.00	0.00	0.39	0.24	3.20	2.30	2.65	2.80	2.20
ST-11	3.48	7.80	5.45	4.21	2.28	4.64	0.69	1.90	0.00	0.37	0.20	9.30	32.00	19.00	10.0	5.30
Average	2.71	3.05	2.02	1.99	1.81	2.32	0.92	1.04	0.00	0.44	0.40	6.15	8.61	5.67	4.74	4.16

4.2. Year-to-Year Differences Analyzed from Aggregated Time Series (2020–2024)

To better understand the overall trend of benzene pollution in the study area, the monthly averages from all 11 monitoring stations were combined into a single time series. Figure 2 shows the dynamics of benzene concentrations in the Pollution Control Zone, Rayong Province, Thailand, during 2020–2024, alongside the annual average.

Data show monthly average benzene concentrations in the Pollution Control Zone, Rayong Province, Thailand, from 2020 to 2024. The figure represents the monthly average concentration (µg/m³) of all monitoring stations for each year (2020-2024), along with the multi-year monthly average (dashed line). The results show significant seasonal variation and interannual fluctuations, with clear mid-year peaks and occasional spikes towards the end of the year [32, 33]. These results show that benzene concentrations fluctuate throughout the year, underscoring the need for continuous monitoring and proactive air quality management strategies to reduce potential health risks [34]. This study is consistent with previous research, Sanda et al. [29] and Sillapapiromsuk et al. [35], which found that there should be monitoring every season of air pollutant emissions from industrial sources.

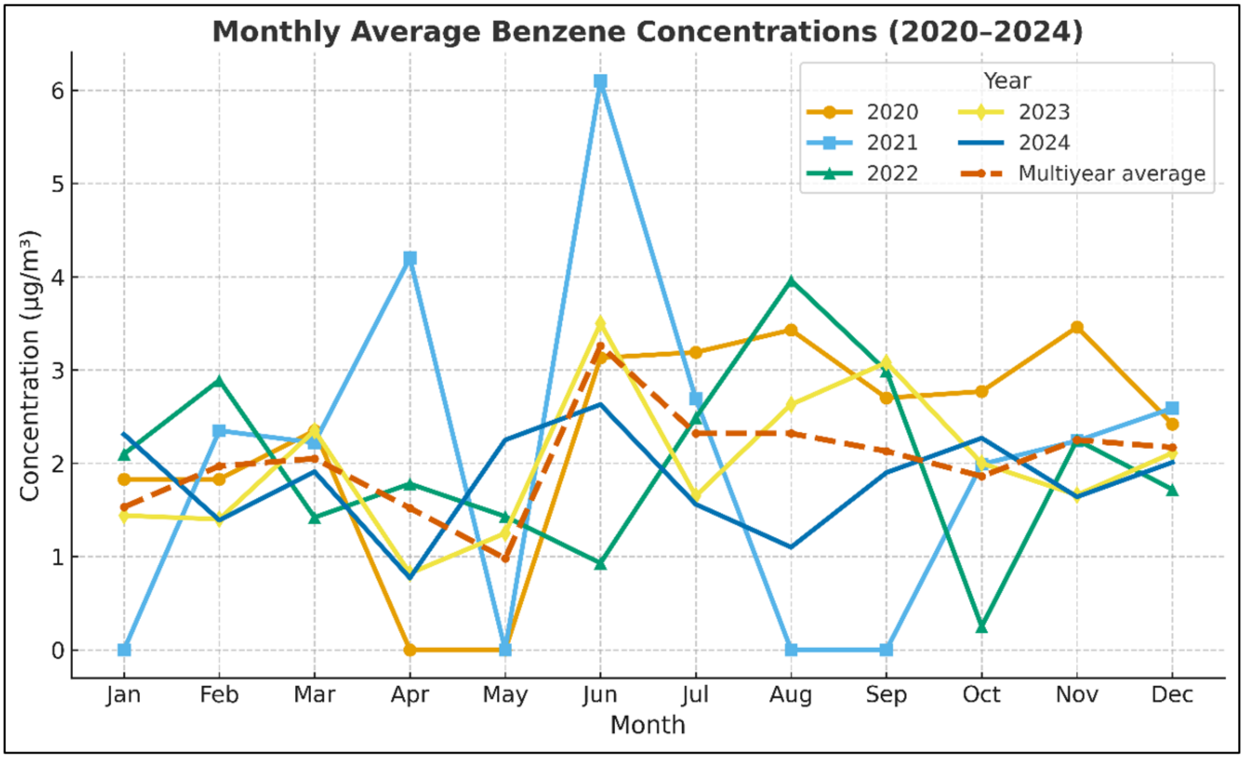

Figure 2.
Monthly average benzene concentration in pollution control zones, Rayong Province, Thailand (2020–2024) Multi-year average.

4.3. The Relationships Between Benzene Concentrations and Relevant Meteorological Parameters

Figure 3 illustrates the variation in benzene concentrations across important meteorological parameters. Figure 3a Benzene vs Temperature, this subgraph shows the relationship between the monthly average benzene concentration and ambient temperature from 2020 to 2024. The results indicate that during certain periods with higher temperatures, benzene concentrations also tend to increase. This pattern suggests that higher temperatures may promote chemical reactions and evaporation processes, which may increase benzene emissions [36, 37]. However, this relationship is not strictly linear, suggesting that other meteorological factors such as wind speed, humidity, and air pressure also play important roles in shaping the distribution and accumulation of benzene.

Figure 3b Benzene vs Wind Speed, this subgraph highlights the inverse relationship between benzene concentration and wind speed. When wind speeds are below approximately 2 m/s, benzene tends to accumulate, resulting in higher atmospheric concentrations. Conversely, wind speeds above 3 m/s favor horizontal and vertical air mixing, promoting dispersion and dilution of the pollutant, which significantly reduces benzene levels. These results underscore the critical role of atmospheric dynamics, particularly wind patterns, in regulating air pollutant levels.

Figure 3c Benzene vs Ventilation Index, the ventilation index, calculated as the product of wind speed and a constant (1000), provides an estimate of the dispersing capacity of a pollutant in the atmosphere. This subgraph shows that lower ventilation values are associated with higher benzene concentrations, reflecting poor atmospheric mixing and limited dispersion of the pollutant. In contrast, higher ventilation indexes are associated with lower benzene levels, consistent with the theoretical principle that effective ventilation is the key to preventing pollutant accumulation.

Figure 3d Benzene vs Relative Humidity and Precipitation, this subgraph illustrates the interaction between benzene concentration, relative humidity, and rainfall. Benzene levels tend to rise during periods of high relative humidity and low rainfall, indicating stagnant atmospheric conditions that promote pollutant accumulation. In contrast, heavy rainfall events effectively reduce benzene concentrations through wet precipitation processes, effectively removing airborne pollutants. These findings highlight the crucial role of rainfall in regulating natural air pollution.

Figure 3e Monthly Mean Benzene: This bar chart summarizes the monthly average benzene concentrations over the study period (2020–2024). The data show significant seasonal variation, with peaks seen in the middle and late parts of the year. These fluctuations likely reflect both the influence of anthropogenic activities, such as fuel combustion and industrial emissions, and seasonal meteorological factors that affect the movement, dispersal, and removal of pollutants.

Figure 3f Benzene vs Air Pressure, this final subgraph examines the relationship between benzene concentration and atmospheric pressure. The results indicate that periods of relatively low air pressure correspond to higher benzene levels, suggesting that low-pressure systems or still atmospheric conditions can enhance pollutant accumulation. This finding shows that large-scale weather patterns play an important role in how atmospheric benzene levels vary.

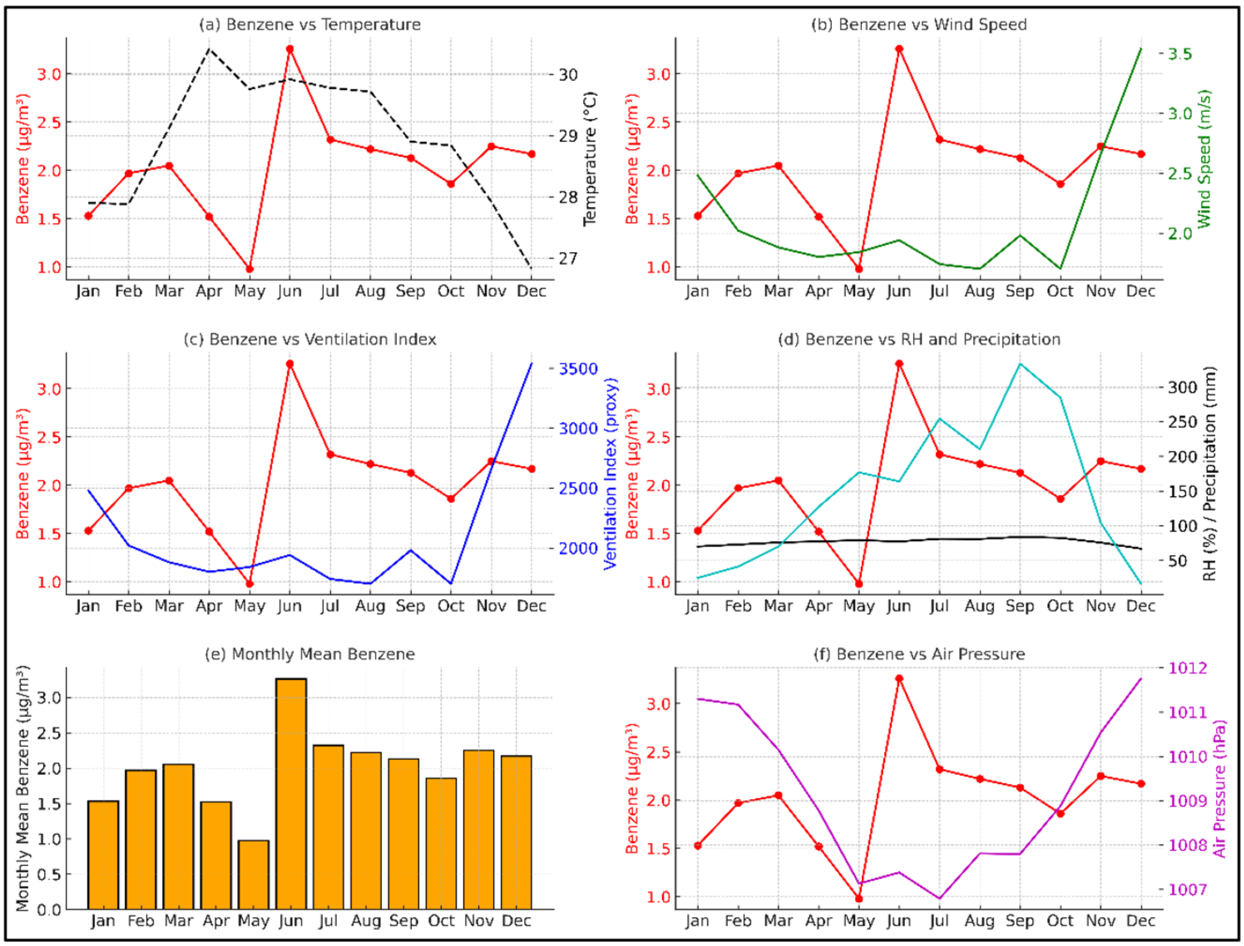

Figure 3.
The relationship between benzene concentration and important meteorological parameters.

The heat maps display the strength and direction of the relationships (Spearman's ρ) between benzene and various environmental variables, including temperature, wind speed, relative humidity, rainfall, air pressure, NO_2, CO, SO_2, vinyl chloride ($H_2C=CHCl$), 1,3-butadiene, PM_{10}, and $PM_{2.5}$. Warm

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colors indicate positive correlations, while cool colors represent negative correlations. The size and intensity of the ellipses reflect the magnitude of the correlation coefficients. Asterisks denote levels of statistical significance ($p < 0.05$; $p < 0.01$). This analysis emphasizes the meteorological and atmospheric conditions most strongly associated with atmospheric benzene concentrations, as illustrated in Figure 4.

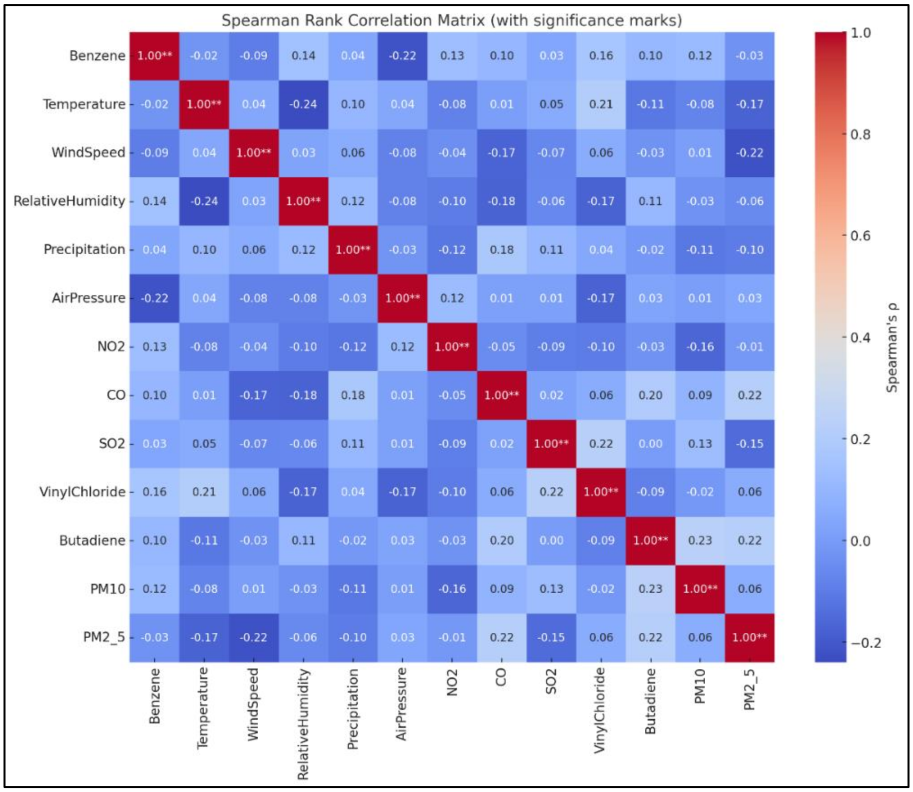

Figure 4.
Spearman rank correlation matrix between monthly benzene concentrations and important meteorological and air quality parameters.

4.4. Ambient Benzene Levels and Associated Health Impacts in the Pollution Control Zone, Rayong Province, Thailand

Using the ExpoFIRST tool, we calculated the average daily dose (ADD) and lifetime average daily dose (LADD) (mg/kg-day) for three potential exposure scenarios to assess the health risk from airborne particles.

Scenario 1 – Baseline multi-year average: The first scenario represents a long-term average concentration of 2.32 $\mu g/m^3$, reflecting the multi-year average observed during the study period. To ensure comparability, 11 age groups were analyzed using the instrument's default exposure parameters and assuming 100 exposure days per year as the reference standard.

Scenario 2 – High atmospheric concentrations in Rayong Province, Thailand: The second scenario uses a higher concentration of 5.54 $\mu g/m^3$ based on values measured at Station ST-3 in the Pollution Control Area, Rayong Province, Thailand, in 2021. As with Scenario 1, the analysis uses a default exposure setting and assumes 100 exposure days per year, allowing for a direct comparison of results between normal and high pollution levels.

Scenario 3 – Daily short-term outdoor exposure: The third scenario focuses on short-term outdoor exposure and models exposure for 3 hours (180 minutes) per day for all age groups. For example, in the adult category (aged 21–70 years), the initial daily exposure time is 283 minutes. This 3-hour value is

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derived from the current average outdoor time estimate, calculated as: (2 hours × non-workdays) + (3.5 hours × workdays) / 7, averaged over both summer and winter. For the LADD calculation, a 365-day exposure frequency was used to represent the year-round lifetime exposure.

Table 2.
ADD (mg/kg-day) for three 100-day exposure scenarios by age group and LADD (mg/kg-day) for the lifetime (0–70 years, frequency 356 days).

Indicator	**ADD (mg/kg·Day)**			**LADD (mg/kg·Day)**		
Simulation	**Scenario 1 ExpoFIRST Default Exposure (2.32 µg/ m³)**	**Scenario 2 ExpoFIRST Default Exposure (5.54 µg/ m³)**	**Scenario 3 (3 h Outdoor Exposure, Daily) (6 µg/ m³)**	**Scenario 1 ExpoFIRST Default Exposure (2.32 µg/ m³)**	**Scenario 2 ExpoFIRST Default Exposure (5.54 µg/ m³)**	**Scenario 3 (3 h Outdoor Exposure, Daily) (6 µg/ m³)**
Birth to <1 month	4.99×10^{-4}	4.28×10^{-4}	8.99×10^{-4}	8.99×10^{-4}	-	-
1 month to <3 months	3.16×10^{-5}	5.42×10^{-5}	7.11×10^{-4}	7.11×10^{-4}	-	-
3 months to <6 months	9.99×10^{-5}	1.64×10^{-4}	5.11×10^{-4}	5.11×10^{-4}	-	-
6 months to <1 year	5.43×10^{-4}	9.31×10^{-4}	7.04×10^{-4}	7.04×10^{-4}	-	-
1 year to <2 years	1.68×10^{-4}	1.60×10^{-4}	7.65×10^{-4}	7.65×10^{-4}	-	-
2 years to <3 years	3.26×10^{-4}	5.63×10^{-4}	7.73×10^{-4}	7.73×10^{-4}	-	-
3 years to <6 years	3.87×10^{-4}	6.50×10^{-4}	8.93×10^{-4}	8.93×10^{-4}	-	-
6 years to <11 years	3.32×10^{-4}	5.69×10^{-4}	4.52×10^{-4}	4.52×10^{-4}	-	-
11 years to <16 years	1.87×10^{-4}	3.20×10^{-4}	2.54×10^{-4}	2.54×10^{-4}	-	-
16 years to <21 years	1.55×10^{-4}	2.67×10^{-4}	2.23×10^{-4}	2.23×10^{-4}	-	-
21 years to <70 years	1.53×10^{-4}	2.62×10^{-4}	2.29×10^{-4}	2.29×10^{-4}	-	-
Birth to <70 years	3.27×10^{-4}	5.60×10^{-4}	4.04×10^{-4}	3.95×10^{-4}	1.06×10^{-3}	6.76×10^{-4}

Table 2 presents the average daily dose (ADD) and lifetime average daily dose (LADD) of airborne particulate matter calculated under three scenarios using the ExpoFIRST model. Scenario 1 indicates an initial exposure level of 2.32 μg/m³. Scenario 2 reflects a higher initial exposure level of 5.54 μg/m³. Scenario 3 involves a daily 3-hour outdoor exposure level of 6 μg/m³.

Pollutant exposure concentrations depended on age. Infants, particularly newborns under 1 month of age, received the highest mean daily dose (ADD) in all scenarios, reaching 8.99×10^{-4} mg/kg/day in scenario 3. With increasing age, the ADD decreased steadily, remaining stable at approximately 1.5×10^{-4} mg/kg/day in adults aged 21–70 years. This trend suggests that the early stage of life is significantly more susceptible to pollutant exposure, even though exposure levels are similar [38].

Scenario comparison: Scenario 2 consistently had ADD values 1.5–2 times higher than Scenario 1 across all age groups. Scenario 3, despite slightly higher concentrations (6 μg/m³), had similar or only slightly higher ADD values than Scenario 2, and only in younger age groups, primarily reflecting the shorter exposure time of 3 hours, which reduced the total dose despite the higher concentrations.

Over the lifetime, considering lifetime exposure from birth to 70 years at 356 days per year, LADD would be as high as 1.06×10^{-3} mg/kg^{-1} day^{-1} in Scenario 1 and 6.76×10^{-4} mg/kg^{-1} day^{-1} in Scenario 3. These results clearly show that chronic, long-term exposure leads to a higher cumulative lifetime health risk than short-term outdoor exposure, even when particle concentrations are slightly higher.

Overall, the findings reveal that early-life exposure to pollutants determines short-term endogenous pollutant load, while long-term chronic exposure determines lifelong health burden [39, 40]. This highlights the need for preventative measures targeted at infants and young children, such as improving indoor air quality, limiting outdoor pollutant exposure, and implementing sustainable air quality management strategies to reduce lifelong health risks for all age groups [41].

These insights underscore the need for both short-term and long-term interventions to protect at-risk populations and reduce the cumulative health impacts of airborne particulate matter [42]. Table 3 summarizes the simulation results for nine annual mean benzene concentrations: 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, and 5.5 μg/m³. These levels represent concentrations recorded during the study period and were used to assess three key health impact indicators: environmental disease burden (EBD), population attributable fraction (PAF), and disability-adjusted life-years ($DALY_{EBD}$).

The estimated EBD values, reflecting the excess deaths attributable to benzene-associated leukemia, range from 0.04 to 0.11 at these concentrations. Similarly, the health burden, expressed as DALYs lost to leukemia per 100,000 population, steadily increased with increasing benzene concentrations. Specifically, DALYs were 0.291 at 1.0 - 2.0 μg/m³, 0.364 at 2.5 μg/m³, 0.437 at 3.0 μg/m³, 0.509 at 3.5 μg/m³, 0.582 at 4.0 μg/m³, 0.727 at 5.0 μg/m³, and 0.800 at 5.5 μg/m³ in the Rayong Pollution Control Zone, Thailand. This continued upward trend clearly demonstrates that as benzene levels increase, the health risks and associated disease burden increase proportionally [43, 44]. Figure 5 clearly illustrates this relationship, highlighting the increasing health effects across a range of concentrations.

Table 3.
Environmental burden of disease from exposure to benzene at annual concentrations in the pollution control zone, Rayong Province, Thailand (26 leukemia deaths*, 100,000 population, DALYs: 520).

Annual Average Benzene Concentration (μg/m³)	EBD (Number of Excess Deaths)	PAF (Population Attributable Fraction)	$DALY_{EBD}$	$DALY_{EBD}$ per 100,000 Inhabitants
1.0	0.04	0.00138	0.524	0.291
1.5	0.04	0.00138	0.524	0.291
2.0	0.04	0.00138	0.524	0.291
2.5	0.05	0.00172	0.655	0.364
3.0	0.06	0.00207	0.786	0.437
3.5	0.07	0.00242	0.917	0.509
4.0	0.08	0.00276	1.048	0.582
5.0	0.10	0.00345	1.310	0.727
5.5	0.11	0.00380	1.441	0.800

Note: *Remark: Health Information System Development Office (HISO), Ministry of Public Health [45].

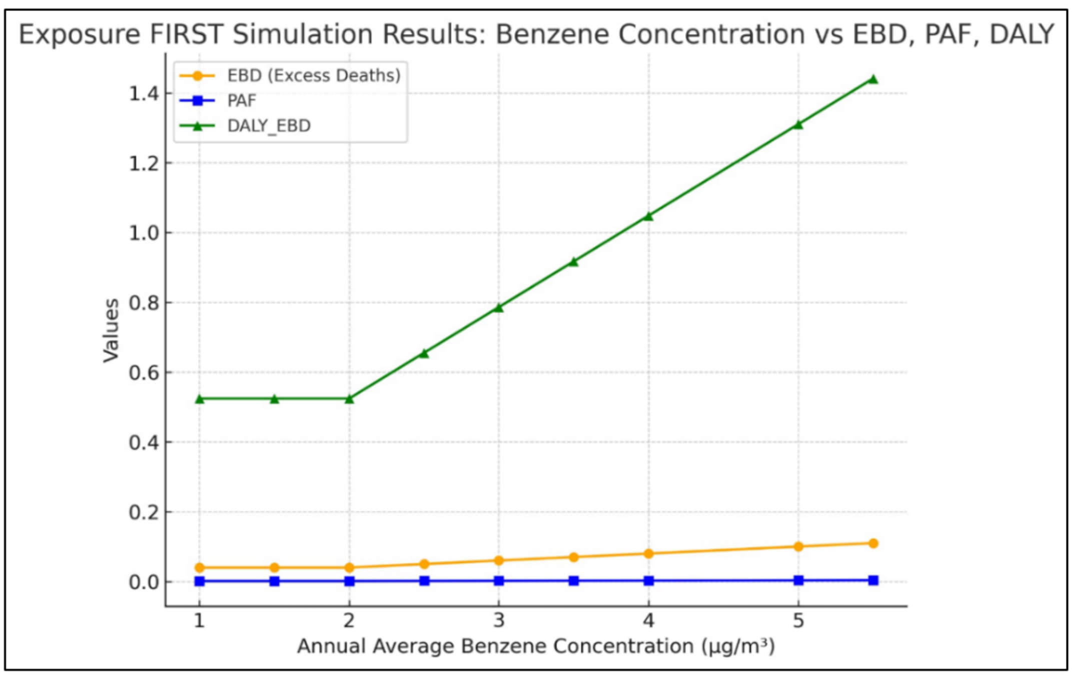

Figure 5.
Benzene Concentration vs EBD, PAF, and $DALY_{EBD}$.

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5. Conclusion

This study is the first to provide a clear, data-driven picture of how benzene exposure impacts public health in the industrial hub of Rayong Province, Thailand. Using the Exposure FIRST model, we examined a range of benzene concentrations (1.0–5.5 μg/m^3) and found a simple but powerful pattern: as benzene levels rise, so do the health risks. The results show that even at low concentrations, benzene exposure leads to measurable harm, including increased excess deaths (EBD), higher population attributable fractions (PAF), and more years of healthy life lost (DALYs). By the time concentrations reach the upper end of the scenarios we modeled, the health burden nearly triples compared to the lowest exposure levels.

These findings serve as an important reminder for policymakers: there is no safe level of benzene exposure, and the increased health burden is preventable. Thailand, particularly in heavily industrialized areas like Rayong, needs stricter air quality standards, ongoing monitoring, and community health surveillance to protect workers and residents alike. Beyond Thailand, the impacts are global. Industrialized regions across Southeast Asia and other rapidly developing economies face similar challenges. Our research demonstrates that tools like Exposure FIRST can guide evidence-based decision-making, even in low- and middle-income countries where detailed health data are often insufficient. In short, cutting benzene emissions is not merely an environmental objective but a public health necessity. Reducing exposure today can prevent avoidable illnesses and deaths in the future, safeguarding communities and supporting sustainable economic growth.

Institutional Review Board Statement:

This study was approved by the Research Ethics Review Committee, Rajamangala University of Technology Tawan-ok (RMUTTO REC Reference No. 033/2024), on July 15, 2024, in accordance with the ethical principles stated in the Declaration of Helsinki and Good Clinical Practice Guidelines (ICH-GCP). No personal data was collected, and all patient-identifying information was fully anonymized. The analysis was performed using aggregated data.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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