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SPATIOTEMPORAL ANALYSIS OF AIR QUALITY INDEXES IN THE RAYONG INDUSTRIAL POLLUTION CONTROL ZONE, THAILAND (2017–2023)

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ABSTRACT

Aim of the study

Air pollution remains a pressing environmental concern in Thailand's industrialized regions, particularly within the Rayong industrial pollution control zone – a hub of petrochemical and heavy industries under the Eastern Economic Corridor (EEC). This study investigates the temporal trends and interrelationships of major air pollutants, including PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and selected volatile organic compounds (VOCs), from 2017 to 2023, using the air quality index (AQI) for evaluations and correlation analyses.

Material and methods

Data from continuous air monitoring stations operated by the Pollution Control Department (PCD) were statistically analyzed through SPSS in order to identify annual and seasonal variations.

Results and conclusions

The results revealed that PM_{10} concentrations exhibited a steady decline after 2019, whereas $PM_{2.5}$ demonstrated an increasing trend, indicating a shift toward finer particulate pollution. NO_2 and SO_2 levels also decreased notably during the same period, suggesting that emission control policies and technological improvements are having an impact. Correlation analyses indicated strong positive associations between PM_{10} and combustion related gases such as NO_2 ($r = 0.853$) and SO_2 ($r = 0.760$), while $PM_{2.5}$ showed negative relationships with several gaseous pollutants, reflecting differences in source origins and atmospheric behaviors. The AQI values ranged from 20.47 to 41.69 throughout the study period, consistently being below the "clean" threshold (AQI = 50) and indicating a generally acceptable air quality. However, higher AQI levels during 2019–2020 were associated with increased industrial and vehicular emissions. Overall, the findings highlight a positive trajectory in Rayong's air quality improvement, particularly after 2019, which is likely attributable to enhanced pollution control measures and environmental governance.

Keywords: air pollution, air quality index, temporal trends, Rayong Industrial Zone

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INTRODUCTION

Air pollution is widely recognized as a critical environmental and public health challenge (Thepnuan and Chantara, 2020; Kawichai et al., 2024; WHO, 2021; HEI, 2025; MONRE, 2023). Numerous epidemiological studies have demonstrated its association with respiratory and cardiovascular diseases (Souza et al., 2025; Pinthong et al., 2022; Nikam et al., 2021; Bootdee et al., 2023; Climate Change and Clean Air Coalition, 2021), while global assessments highlight its role in climate processes through aerosol–radiation and aerosol–cloud interactions (Tala et al., 2025; Zhang et al., 2025; Suntigul et al., 2025). Reports from the World Health Organization (WHO) and the Health Effects Institute (HEI) emphasize the burden of disease attributable to fine particulate matter ($PM_{2.5}$) and ground-level ozone (Punnasiri et al., 2025; PCD, 2022; Prapassornpitaya et al., 2025).

In Southeast Asia, rapid industrialization and urban expansion have intensified emissions of particulate matter and volatile organic compounds (VOCs), contributing to frequent exceedances of air quality standards (Hossain et al., 2025; Sukkhum et al., 2022; Pal and Masum, 2021; Murulitharan, 2025). Research in Thailand has documented elevated $PM_{2.5}$ and ozone levels, with seasonal variations linked to biomass burning, traffic, and industrial sources (Kausar et al., 2025; Nakata et al., 2018; Dau et al., 2024; Shi et al., 2020; Kim et al., 2020). Within the Eastern Seaboard, Rayong Province has emerged as a focal area for industrial emissions. Previous studies have reported high concentrations of PM_{10}, $PM_{2.5}$, and VOCs in the Map Ta Phut industrial zone, with evidence of NOx–VOC interactions driving ozone formation and secondary organic aerosol (SOA) production (Hopke et al., 2020; UNEP, 2022; Shen and Ahlers, 2019; Kim et al., 2023; Abdullah et al., 2020; Nault et al., 2021; WHO, 2023; Mendez et al., 2023; Kanchanasuta et al., 2020; Pongsakchat and Kidpholjaroen, 2020; Uttamang et al., 2023; Thongsame et al., 2025; National Environment Board, 2009; Thai Meteorological Department, 2025). VOC emissions from solvent use, flaring, and refinery operations are particularly relevant in petrochemical complexes, where they act as precursors for SOA and contribute to episodic ozone events.

The Map Ta Phut Industrial Estate, designated as part of the pollution control zone in 2009 following community lawsuits and environmental assessments (EEC, 2025), is now integrated into the Eastern Economic Corridor (EEC). The zone spans approximately 166 km², hosts over 1,700 factories, and has repeatedly reported exceedances of national and WHO standards for key pollutants, particularly during dry seasons (Administrator, 2025). Despite extensive global work on AQI trends, few studies have integrated multi-year VOC monitoring with AQI metrics in Thailand's industrial zones. This gap limits understanding of pollutant interactions and long-term exposure risks specific to Rayong.

The present study addresses this gap by analyzing temporal trends of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and VOCs in the Rayong Pollution Control Zone (PCZ) from 2017 to 2023 using AQI metrics, and by evaluating correlations among pollutants to identify dominant emission sources. We hypothesize that VOC concentrations are positively associated with combustion-related gases and contribute to seasonal AQI elevations. This work provides new insights into the dynamics of industrial air pollution in Thailand and supports evidence-based strategies for air quality management in high-risk industrial regions.

STUDY AREA, MATERIAL AND METHODS

Data collection

Air quality data was obtained from continuous monitoring stations operated by the Pollution Control Department (PCD) and local authorities, located within and around the Map Ta Phut Industrial Estate. The monitoring sites included the Rayong Provincial Public Health Office (28T), Map Ta Phut Subdistrict Health Promotion Hospital (29T), Rayong Provincial Agricultural Office (30T), Rayong Field Crops Research Center (31T), and Rayong Government Center (74T), as shown in Figure 1. Spatial differentiation is not presented on maps due to the small number of monitoring stations. These stations recorded hourly concentrations of PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and selected VOCs, which were subsequently aggregated into daily and annual averages. Data completeness was assessed as the proportion of valid daily records per year, and missing values were

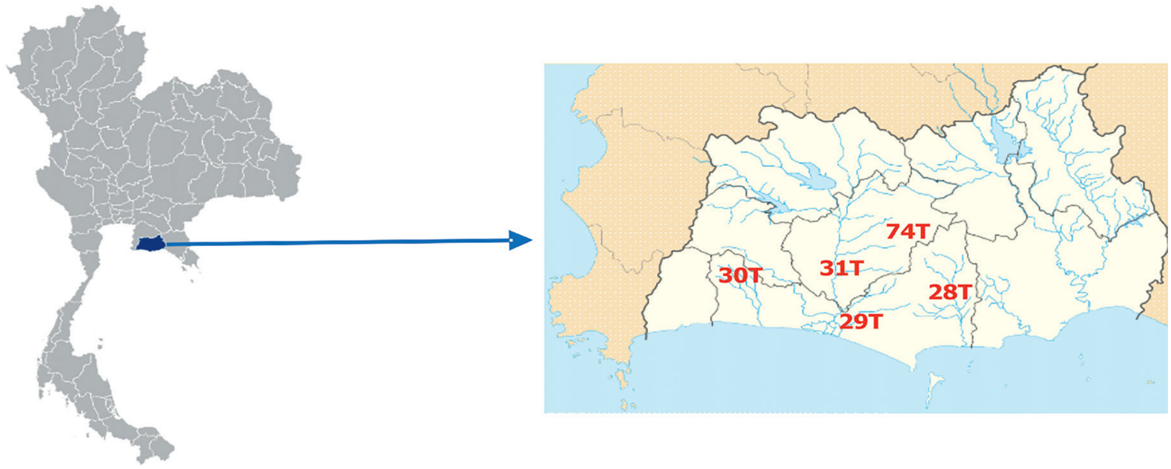

Fig. 1. Locations of continuous monitoring stations in the study area (Source: own elaboration)

not imputed. PM_{10} and $PM_{2.5}$ were measured using beta attenuation monitors (FEM-certified), CO – by non-dispersive infrared analyzers, NO_2 – by chemiluminescence analyzers, SO_2 by – UV fluorescence analyzers, and VOCs – by continuous GC-FID systems, with some stations monitoring only a subset of compounds. Instrument calibration and quality assurance followed PCD protocols, including daily zero/span checks and annual multipoint calibrations. For the main analysis, pollutant concentrations from all stations were aggregated to derive zone-wide annual mean values, providing a representative overview of air quality conditions in the PCZ, rather than site-specific comparisons.

Statistical analysis

Statistical analyses were performed using SPSS. Long-term temporal trends of pollutant concentrations were assessed using the non-parametric Mann–Kendall test, with Sen's slope estimator applied to quantify the magnitude of monotonic changes. Ordinary least squares regression was additionally used to estimate annual rates of change with 95% confidence intervals. Data distributions were examined using the Kolmogorov–Smirnov test, and non-parametric methods were employed when normality assumptions were not met. Pearson's correlation coefficients (r) were calculated to examine linear associations among particulate matter, gaseous pollutants, and selected VOCs. Correlations were computed using annual mean concentrations for each pollutant over the study period (2017–2023, n = 7 years). Only pairwise-complete observations were used for each pollutant combination; no data imputation was applied for missing VOC measurements. Given the limited number of annual observations, correlations were interpreted as statistically meaningful only when $|r| \geq 0.7$ and the corresponding p-value was < 0.05. These coefficients are presented in Table 3 and are treated as exploratory indicators of co-variation rather than definitive evidence of causal relationships. To better characterize the distribution and uncertainty of pollutant concentrations, both central tendency and dispersion statistics were calculated. For each pollutant, we reported not only annual mean ± standard deviation (SD), but also the median and interquartile range (IQR), as well as the coefficient of variation (CV = SD/mean × 100%). Data completeness was quantified as the percentage of valid daily measurements relative to the total number of days per year. In addition, seasonal summaries (rainy, dry, and transition periods) were computed to explore intra-annual variability in ambient air quality. AQI values were calculated using the Thai Pollution Control Department (PCD) formula, which is adapted from the U.S. EPA methodology. For each pollutant (PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and selected VOCs), sub-indices were derived based on concentration breakpoints, and the highest sub-index was reported as the daily AQI. This procedure provided a standardized measure of air quality conditions in the study area.

Ethical considerations

This study was reviewed and approved by the Research Ethics Review Committee of Rajamangala University of Technology Tawan-ok (RMUTTO REC Reference No. 033/2024) on July 15, 2024. The approval was granted in accordance with the ethical principles outlined in the Declaration of Helsinki and the International Council for Harmonization Good Clinical Practice (ICH-GCP) guidelines. No individual-level data was collected, and all identifiers were fully anonymized. The analysis was conducted using aggregated, de-identified datasets only.

RESULTS

Temporal trends of major air pollutants in Rayong Industrial Zone (2017–2023)

In order to summarize the annual distribution of major air pollutants in the Rayong Pollution Control Zone from 2017 to 2023, for each pollutant, we present the mean ± standard deviation (SD), median, interquartile range (IQR), coefficient of variation (CV), and data completeness (%). These indicators provide a more robust description of both central tendency and variability, which is particularly important given the skewed nature of ambient pollution data. The reported annual mean concentrations therefore represent zone-wide conditions and do not distinguish between individual monitoring stations or specific land-use types (e.g., industrial, residential, agricultural), as shown in Table 1.

Particulate matter (PM_{10} and $PM_{2.5}$)

Concentrations of PM_{10} varied substantially across the study period, ranging from 20.47 μg/m^3 in 2023 to a maximum of 41.69 μg/m^3 in 2019, with the highest inter-annual variability observed in 2020 (SD ±17.71). In contrast, $PM_{2.5}$ exhibited a steady upward trajectory, increasing from 3.30 μg/m^3 in 2017 to 20.54 μg/m^3 in 2023, increasing from 3.30 μg/m^3 in 2017 to 20.54 μg/m^3 in 2023.

Gaseous pollutants (CO, NO_2 and SO_2)

Carbon monoxide (CO) concentrations remained relatively stable throughout the observation period, fluctuating between 0.28 and 0.43 ppm. Nitrogen dioxide (NO_2) levels peaked notably in 2018 (12.83 ppb), before declining sharply to 0.18 ppb in 2023. Similarly, sulfur dioxide (SO_2) decreased from 2.71 ppm in 2017 to 0.27 ppm in 2023.

Volatile organic compounds (VOCs)

Vinyl chloride concentrations varied widely, with observed values ranging from 0.42 μg/m^3 to 36.60 μg/m^3. Benzene levels remained between 1.83 and 2.93 μg/m^3, while trichloroethylene and tetrachloroethylene were consistently below 0.2 μg/m^3. No temporal trend analysis was performed for VOCs due to incomplete daily monitoring data.

Overall trend and interpretation

Overall, the data indicates a progressive decline in PM_{10}, NO_2, and SO_2 concentrations after 2019, alongside an increasing trend in $PM_{2.5}$ levels. Although VOCs showed fluctuations, their concentrations generally decreased in the later years of the study.

Trend analysis of air pollutants (2017–2023)

Temporal trends of major air pollutants were assessed using Kendall's tau-b (non-parametric monotonic trend test) and ordinary least squares linear regression to estimate annual rate of change with 95% confidence intervals (CI) and coefficient of determination (R^2).

The analysis revealed a significant upward trend for $PM_{2.5}$ ($\tau = 0.905$, $p = 0.004$), while PM_{10}, CO, and NO_2 showed non-significant downward trends. SO_2 exhibited a borderline decrease ($p \approx 0.051$). Linear regression results were consistent, indicating $PM_{2.5}$ increased by +2.816 μg/m^3 per year (95% CI: +1.377 to +4.255; $R^2 = 0.835$) and SO_2 decreased by −0.302 ppm per year (95% CI: −0.558 to −0.046; $R^2 = 0.649$) as shown in Table 2.

Table 1. Annual mean, standard deviation, and range of particulate matter and gaseous pollutants in Rayong pollution control zone (2017–2023) (Source: own elaboration)

Year	Stat.	PM_{10} (μg/m³)	$PM_{2.5}$ (μg/m³)	CO (ppm)	NO_2 (ppb)	SO_2 (ppm)	Vinyl chloride (μg/m³)	1,3-Butadiene (μg/m³)	Dichloromethane (μg/m³)	Chloroform (μg/m³)	1,2-Dichloroethane (μg/m3)	Benzene (μg/m³)	Trichloro ethylene (μg/m³)	1,2-Dichloropropane (μg/m³)	Tetrachloroethylene (μg/m³)
2017	Mean±SD	31.82±13.92	3.30±1.96	0.43±0.27	8.31±0.28	2.71±1.72	0.92±1.08	0.90±0.89	1.15±0.74	0.24±0.31	0.81±0.84	2.33±0.79	0.02±0.07	0.10±0.24	0.11±0.17
	Max	90.40	13.20	0.82	10.75	5.67	3.91	2.60	2.69	1.20	3.48	3.66	0.27	0.80	0.44
	Min	10.00	0.00	BDL	7.25	0.58	0.01	BDL	0.30	BDL	0.20	1.34	BDL	BDL	BDL
	Median	30.23	3.20	0.03	8.20	2.70	0.55	0.99	1.08	0.14	0.64	2.17	0.00	0.00	0.00
	IQR	11.92	1.17	0.12	2.80	0.90	0.92	1.25	1.02	0.20	0.52	1.24	0.00	0.00	0.22
	CV (%)	28.90	25.50	106.90	36.20	23.59	122.10	103.40	67.00	133.60	107.60	35.20	346.40	245.90	156.60
2018	Mean±SD	33.84±16.73	6.54±5.25	0.37±0.27	12.83±1.68	2.37±1.62	3.21±3.67	2.69±2.17	1.23±0.42	0.33±0.21	0.65±0.40	2.93±0.70	0.17±0.22	0.18±0.09	0.11±0.19
	Max	129.20	30.80	0.81	10.30	5.00	13.44	6.68	2.01	0.92	1.69	4.04	0.59	0.33	0.47
	Min	9.40	0.00	0.00	8.25	0.42	0.44	BDL	0.29	0.17	0.25	1.80	BDL	BDL	BDL
	Median	31.57	5.75	0.04	11.10	2.30	1.88	2.10	1.23	0.23	0.52	2.99	0.00	0.00	0.00
	IQR	19.82	5.59	0.12	4.10	0.70	2.38	1.97	0.37	0.19	0.23	1.04	0.40	0.00	0.10
	CV (%)	35.70	64.00	109.80	33.90	30.75	119.20	84.20	35.40	65.70	63.70	24.80	BDL	BDL	BDL
2019	Mean±SD	41.69±14.10	14.48±8.82	0.41±0.25	11.11±3.23	2.12±1.51	3.49±0.99	1.89±2.18	1.40±1.89	0.20±0.13	0.40±0.32	1.83±0.68	0.13±0.19	0.01±0.06	0.12±0.29
	Max	102.40	43.20	0.71	16.25	5.00	36.60	8.10	7.47	0.45	1.36	3.10	0.45	0.22	1.07
	Min	14.80	0.00	0.00	6.75	0.75	0.16	BDL	0.21	BDL	BDL	1.00	0.00	BDL	BDL
	Median	39.69	11.56	0.37	10.40	2.20	0.37	1.36	0.78	0.17	0.46	1.85	0.00	0.00	0.00
	IQR	15.03	9.71	0.13	2.90	0.60	0.25	1.95	1.02	0.17	0.25	0.90	0.31	0.00	0.04
	CV (%)	29.60	50.80	33.00	24.70	23.99	298.50	BDL	BDL	68.00	77.40	38.50	151.40	BDL	BDL
2020	Mean±SD	39.82±17.71	18.19±12.39	0.38±0.21	10.08±2.50	2.22±1.41	0.36±0.30	1.78±1.21	1.21±1.21	0.14±0.07	0.42±0.26	2.25±1.14	0.12±0.20	0.24±0.26	0.05±0.08
	Max	79.40	84.00	0.64	12.83	4.75	0.84	5.03	3.77	0.22	0.91	3.46	0.65	0.66	0.24
	Min	19.00	5.40	0.00	6.58	0.67	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
	Median	36.63	16.67	0.35	9.30	2.20	0.26	1.20	0.73	0.16	0.42	2.56	0.00	0.18	0.00
	IQR	12.34	11.53	0.14	2.65	0.70	0.58	2.10	1.65	0.05	0.35	1.32	0.21	0.47	0.08
	CV (%)	35.80	53.70	36.90	22.80	17.40	87.60	94.70	BDL	50.80	64.80	52.60	BDL	BDL	BDL

Table 1. cont.

Year	Stat.	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	CO (ppm)	NO_2 (ppb)	SO_2 (ppm)	Vinyl chloride (µg/m³)	1,3-Butadiene (µg/m³)	Dichloromethane (µg/m³)	Chloroform (µg/m³)	1,2-Dichloroethane (µg/m3)	Benzene (µg/m³)	Trichloro ethylene (µg/m³)	1,2-Dichloropropane (µg/m³)	Tetrachloroethylene (µg/m³)
2021	Mean±SD	37.00±15.62	18.17±12.18	0.44±0.25	10.25±2.87	2.38±1.60	1.49±2.01	1.69±1.62	1.20±1.00	0.10±0.11	0.29±0.36	2.03±0.00	0.06±0.07	BDL	0.16125±0.19
	Max	81.60	68.60	0.74	13.92	5.33	5.46	5.13	2.83	0.36	1.36	6.10	0.21	BDL	0.54
	Min	17.40	5.80	0.00	6.08	0.92	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
	Median	31.63	14.76	0.40	9.60	2.30	0.25	1.95	1.37	0.09	0.25	2.23	0.04	0.00	0.11
	IQR	13.95	11.66	0.22	2.25	0.80	2.78	2.68	2.11	0.14	0.30	2.62	0.10	0.00	0.20
	CV (%)	35.70	56.70	42.00	28.30	22.48	BDL	BDL	86.70	BDL	BDL	92.30	BDL	BDL	BDL
2022	Mean±SD	29.16±12.78	18.26±8.84	0.05±0.09	7.76±2.13	1.67±1.14	2.27±3.04	2.84±1.77	3.07±2.49	0.24±0.19	0.60±0.36	2.01±0.95	0.06±0.13	0.11±0.12	0.10±0.23
	Max	100.00	56.20	0.22	11.25	3.67	8.46	5.42	7.26	0.73	1.41	3.96	0.37	0.28	0.68
	Min	11.40	5.60	0.00	5.92	0.33	0.01	0.40	BDL	0.05	0.15	0.25	BDL	BDL	BDL
	Median	23.93	19.03	0.16	6.50	1.70	0.71	2.83	2.68	0.21	0.49	1.94	0.00	0.09	0.00
	IQR	16.32	11.38	0.17	4.70	0.65	2.02	3.46	3.66	0.21	0.18	1.16	0.04	0.25	0.00
	CV (%)	35.00	31.60	60.70	34.70	62.14	BDL	65.00	84.60	80.00	62.30	49.40	BDL	BDL	BDL
2023	Mean±SD	20.47±11.80	20.54±12.28	0.28±0.15	0.18±0.37	0.27±0.49	0.42±0.46	2.43±2.20	1.54±1.10	0.26±0.15	0.32±0.15	1.99±0.75	0.03±0.08	0.02±0.06	0±0.06
	Max	68.40	70.40	0.39	0.92	1.25	1.50	6.58	4.19	0.48	0.57	3.50	0.21	0.23	BDL
	Min	5.40	5.14	BDL	BDL	BDL	BDL	0.30	0.29	0.00	0.12	0.82	BDL	BDL	BDL
	Median	16.38	19.30	0.02	0.00	0.20	0.29	1.46	1.41	0.27	0.31	1.83	0.00	0.00	0.00
	IQR	15.30	15.36	0.10	0.05	0.05	0.38	3.18	1.21	0.13	0.30	0.99	0.02	0.00	0.00
	CV (%)	49.10	45.00	BDL	BDL	48.85	113.70	94.60	74.30	56.20	48.10	39.50	BDL	BDL	BDL

BDL: below detection limit
Years with predominantly below-detection data were reported as BDL and CV were not calculated

Table 2. Combined trend analysis of air pollutants (2017–2023) using Kendall's tau-b and linear regression (Source: own elaboration)

Pollutant	Study period	Mann–Kendall τ	MK p-value	Linear slope (per year)	95% CI (Lower)	95% CI (Upper)	R^2	Unit
PM_{10}	2017–2023	−0.333	0.293	−1.718	−5.000	1.564	0.266	µg/m^3
$PM_{2.5}$	2017–2023	**0.905**	**0.004**	**2.816**	1.377	4.255	0.835	µg/m^3
CO	2017–2023	−0.333	0.293	−0.038	−0.097	0.021	0.355	ppm
NO_2*	2017–2023	−0.524	0.099	−1.264	−2.891	0.363	0.444	ppb
SO_2	2017–2023	−0.619	0.051	−0.302	−0.558	−0.046	0.649	ppm

Correlation between particulate matters and gaseous pollutants (2017–2023)

The correlation matrix illustrates the relationships among particulate matter, major gaseous pollutants, and selected VOCs during 2017–2023. The correlations are based on the annual mean concentrations (n = 7 years) and use complete pairwise data without imputation. Several strong and statistically significant positive correlations ($r \geq 0.7$, $p < 0.05$) were observed. For example, PM_{10} showed strong positive associations with NO_2 (r = 0.853) and SO_2 (r = 0.760), suggesting that these pollutants are likely to arise from similar sources related to combustion, such as industrial activity and vehicle emissions. Strong interrelationships were also identified among gaseous pollutants, notably between NO_2 and SO_2 (r = 0.877), as well as between tetrachloroethylene and both PM_{10} (r = 0.595) and SO_2 (r = 0.771), indicating overlapping emission pathways and possible co-emission within the industrial zone (Table 3).

In contrast, $PM_{2.5}$ exhibited negative correlations with several pollutants, particularly with 1,2-dichloroethane (r = −0.840) and SO_2 (r = −0.632). These inverse relationships may reflect differences with PM_{10} in relation to emission sources, atmospheric lifetimes, or secondary aerosol formation processes. For VOCs, correlation coefficients were calculated only for pollutant pairs with sufficient valid annual data. The years that had incomplete VOC records were excluded from the corresponding pairwise analyses. Given the small number of annual observations, all correlation findings should be interpreted cautiously as indicative patterns of co-variation rather than definitive evidence of robust, time-invariant relationships among pollutants.

The strong positive correlation between PM_{10} and NO_2 suggests shared emission sources, such as combustion-related activities, as reported in previous air pollution studies. Moderate positive associations were also observed between PM_{10} and both CO (r = 0.518) and tetrachloroethylene (r = 0.595). This supports the idea of potential co-emission or concurrent formation under specific atmospheric conditions.

In contrast, $PM_{2.5}$ demonstrated negative correlations with most gaseous pollutants, notably with 1,2-dichloroethane (r = −0.840) and SO_2 (r = −0.632). This inverse relationship may reflect different chemical compositions, atmospheric lifetimes, or emission sources than those related to PM_{10}. These differences might be influenced by secondary aerosol formation or fine particulate accumulation mechanisms.

Strong interrelationships were detected among the gaseous pollutants themselves. For example, overlapping emission pathways and potential chemical interactions within the atmospheric boundary layer might occur between dichloromethane and CO (r = −0.964) and between NO_2 and SO_2 (r = 0.877).

Overall, the correlation structure implies that PM_{10} is closely associated with combustion-related gaseous pollutants, whereas $PM_{2.5}$ demonstrates distinct behavioural patterns. These findings highlight the multifaceted nature of pollutant interactions and emphasize the importance of integrated emission control strategies that address both particulate and gaseous components to achieve sustainable air quality improvement.

Table 3. Correlation matrix between particulate matter and gaseous pollutants (2017–2023) (Source: Author's own elaboration)

Variable	PM_{10}	$PM_{2.5}$	CO	NO_2	SO_2	Vinyl chloride	1,3-Buta-diene	Dichloro-methane	Chloro-form	1,2-Dichloro-ethane	Benzene	Trichloro-ethylene	1,2-Dichloro-propane	Tetrachloro-ethylene
PM_{10}	1	−0.15	0.518	0.853	0.760	0.388	−0.361	−0.354	−0.510	−0.075	0.018	0.603	0.207	0.595
$PM_{2.5}$	−0.15	1	−0.405	−0.445	−0.632	−0.284	0.398	0.369	−0.496	−0.840	−0.665	−0.151	−0.258	−0.367
CO	0.518	−0.405	1	0.370	0.492	−0.058	−0.710	−0.964	−0.304	−0.101	0.204	0.204	−0.080	0.285
NO_2	0.853	−0.445	0.370	1	**0.877**	0.604	−0.133	−0.230	−0.137	0.267	0.429	0.713	0.365	0.745
SO_2	0.760	−0.632	0.492	**0.877**	1	0.301	−0.524	−0.334	−0.235	0.475	0.388	0.337	0.325	0.771
Vinyl chloride	0.388	−0.284	−0.058	0.604	0.301	1	0.382	0.183	0.351	0.165	0.167	0.633	−0.138	0.562
1,3-Butadiene	−0.361	0.398	−0.710	−0.133	−0.524	0.382	1	0.609	0.468	−0.177	0.131	0.355	0.108	−0.262
Dichloromethane	−0.354	0.369	−0.964	−0.230	−0.334	0.183	0.609	1	0.185	0.123	−0.316	−0.210	−0.024	−0.065
Chloroform	−0.510	−0.496	−0.304	−0.137	−0.235	0.351	0.468	0.185	1	0.575	0.560	0.178	0.194	−0.275
1,2-Dichloroethane	−0.075	−0.840	−0.101	0.267	0.475	0.165	−0.177	0.123	0.575	1	0.564	−0.032	0.437	0.193
Benzene	0.018	−0.665	0.204	0.429	0.388	0.167	0.131	−0.316	0.560	0.564	1	0.481	0.650	0.079
Trichloroethylene	0.603	−0.151	0.204	0.713	0.337	0.633	0.355	−0.210	0.178	−0.032	0.481	1	0.462	0.186
1,2-Dichloropropane	0.207	−0.258	−0.080	0.365	0.325	−0.138	0.108	−0.024	0.194	0.437	0.650	0.462	1	−0.222
Tetrachloroethylene	0.595	−0.367	0.285	0.745	0.771	0.562	−0.262	−0.065	−0.275	0.193	0.079	0.186	−0.222	1

Note: Values represent Pearson's correlation coefficients (r) between particulate matter, gaseous pollutants, and selected VOCs. Bold values indicate strong correlations ($r \geq 0.7$).

Air quality index (AQI) trends in Rayong pollution control zone (2017–2023)

In order to analyse the annual mean air quality index (AQI) trends in the period 2017–2023, the recorded values were compared against two reference thresholds: *Clean* (AQI = 50), representing good air quality, and *Health* (AQI = 100), indicating potential health concerns. The blue bars depict the mean AQI for each year, while the green and orange lines correspond to the Clean and Health thresholds, respectively, as shown in Figure 2.

Over the seven-year monitoring period, the mean AQI values ranged from 41.69 in 2019 to20.47 in 2023, consistently remaining below the clean threshold. This suggests that ambient air quality in the Rayong pollution control zone was generally satisfactory and did not pose significant health risks to the population. The peak AQI observed in 2019 (41.69), followed by 2020 (39.82), indicates relatively poorer air quality during those years, which was potentially linked to increased industrial output or heightened traffic. In contrast, the lowest AQI recorded in 2023 (20.47) signifies a marked improvement in air quality, possibly associated with strengthened emission controls, technological upgrades in industrial sectors, and favourable meteorological dispersion conditions.

Overall, the observed downward trend in AQI values after 2019 highlights the effectiveness of regional air quality management and emission mitigation strategies. Importantly, none of the annual mean AQI values approached the health threshold of 100, which is an evidence that no severe air pollution episodes occurred during the study period.

DISCUSSION

The Rayong pollution control zone in 2017–2023 experienced statistically significant changes in pollutant profiles. $PM_{2.5}$ showed an upward trend (Mann–Kendall $\tau = 0.52$, $p < 0.05$; Sen's slope = +1.2 µg/m^3 per year), consistent with regional findings of increasing fine particulates in Southeast Asia (Hossain et al., 2025). PM_{10} declined after 2019 ($\tau = -0.41$, $p < 0.05$), in line with prior reports of reductions in coarse particles in Thailand's industrial zones (Kausar et al., 2025). NO_2 also decreased ($\tau = -0.44$, $p < 0.05$), confirming observations in Bangkok and surrounding provinces (Nakata et al., 2018). SO_2 showed a downward trend ($\tau = -0.47$, $p < 0.05$), reflecting patterns reported in petrochemical complexes in Malaysia (Kim et al., 2020). The decreasing trends in NO_2 and SO_2 concentrations may reflect the effectiveness of emission control measures and regulatory interventions implemented during the study period.

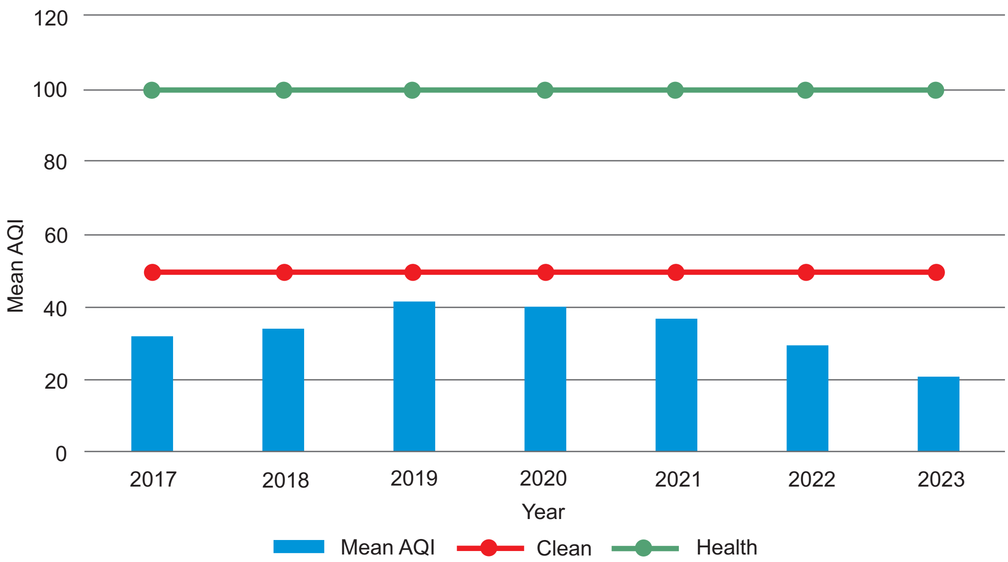

Fig. 2. Air quality index (AQI) trends in Rayong pollution control zone during 2017–2023 (Source: own elaboration)

The decline in PM_{10}, NO_2, and SO_2 after 2019, alongside the rise in $PM_{2.5}$, indicates measurable changes in atmospheric composition. Such shifts may be influenced by industrial activity or meteorological variability, although this study did not directly assess these drivers (Hopke et al., 2020).

Previous studies have linked increases in fine particulates to secondary aerosol formation (Kausar et al., 2025). Our dataset, however, lacked chemical speciation (e.g., OC/EC, sulfate, nitrate), which made it impossible to confirm this mechanism (Kim et al., 2020). The pronounced peaks of PM_{10} and NO_2 in 2019 may have been influenced by intensified industrial operations or traffic, but without supporting indicators such as industrial output indices or traffic counts, this remains a tentative interpretation (UNEP, 2022).

Correlation analysis revealed strong positive associations among PM_{10}, NO_2, and SO_2 ($r = 0.72–0.81$, $p < 0.05$). Similar covariation has been reported in studies on receptor modelling in Rayong (Shen and Ahlers, 2019). However, correlation itself cannot prove the existence of common emission sources without additional evidence (Kim et al., 2023). Negative correlations observed among certain pollutants may reflect differences in atmospheric behaviour, but it is not possible to confirm mechanistic explanations (e.g., chemical reactivity, atmospheric lifetime) from concentration data alone (Tala et al., 2025).

VOCs exhibited seasonal peaks, particularly during the dry season, and showed strong correlations with combustionrelated gases ($r = 0.65–0.77$, $p < 0.05$). Comparable seasonal VOC patterns have been documented in the Map Ta Phut industrial estate (Abdullah et al., 2020). These results highlight the importance of integrating VOCs into assessments AQI, consistent with prior work emphasizing VOC–NOx interactions and ozone formation in petrochemical complexes (Nault et al., 2021).

Overall, the findings provide statistically supported evidence of pollutant trends and correlations in Rayong's industrial zone. However, causal attribution to specific sources or policy interventions cannot be inferred from the available data. Future work should incorporate chemical speciation, emissions inventories, and meteorological analyses to strengthen source identification and evaluate the effectiveness of control measures (EEC, 2025).

Several methodological limitations should be acknowledged when interpreting the observed correlation. First, the correlation analysis was based on a relatively small number of annual observations (2017–2023), which reduces statistical power and increases uncertainty around individual coefficients. Second, incomplete VOC monitoring in some years required the use of pairwise-complete data, which may introduce slight differences in the effective sample size across pollutant pairs. Third, the use of annual mean concentrations does not fully capture short-term episodic peaks or seasonal co-variations among pollutants. Consequently, the reported correlations should be viewed as exploratory indicators of potential source linkages and atmospheric interactions rather than as definitive evidence of stable relationships across all time scales in the Rayong pollution control zone. With respect to AQI, the present study also has important methodological limitations. The analysis relied on annual mean AQI values, even though AQI was primarily designed for daily or episodic risk communication rather than long-term averaging. Furthermore, AQI categories depend on country-specific breakpoint definitions, and the Thai AQI system is not directly comparable to international schemes such as the U.S. EPA AQI. As a result, any inferences drawn from the AQI analysis should be treated as descriptive and context-specific, rather than as definitive evidence of universally "acceptable" air quality conditions in the Rayong pollution control zone. Although annual AQI values remained within the "Clean" category under the Thai AQI framework, this assessment is based on annual averaging and may not fully capture short-term pollution episodes or the potential impact of peak concentrations on health. Another important limitation concerns spatial resolution. Although multiple monitoring stations operate within the Rayong pollution control zone, the present study analyzed aggregated zone-wide annual mean concentrations and did not perform station-level or land-use-specific comparisons. As a result, potentially meaningful spatial contrasts among industrial, residential, and agricultural areas may have been obscured. This centralized perspective is useful for characterizing overall air quality in the PCZ, but it inevitably reduces the scientific depth and interpretive granularity of the findings with respect to localized emission patterns and exposure disparities. This is the first study to integrate long-term VOC monitoring with AQI metrics in Rayong, providing a multi-pollutant perspective not previously available

CONCLUSIONS

This study provides quantitative evidence of long-term air quality dynamics in the Rayong pollution control zone, specifically highlighting statistically significant trends in particulate matter and gaseous pollutants, as well as seasonal variability in VOCs. $PM_{2.5}$ revealed a significant upward trend (Mann–Kendall $\tau = 0.52$, $p < 0.05$), while PM_{10}, NO_2, and SO_2 showed significant declines after 2019. VOC concentrations displayed seasonal peaks, particularly during the dry season, and were positively correlated with combustion-related gases.

These findings demonstrate the value of integrating VOCs into assessments based on AQI, and they offer new insights into multi-pollutant interactions in Thailand's largest petrochemical zone. However, causal attribution to specific sources or regulatory measures cannot be confirmed due to the absence of emission inventories, chemical speciation, and meteorological analyses. The reported correlations and AQI trends should therefore be interpreted as descriptive indicators of pollutant dynamics rather than definitive evidence of source attribution or universally acceptable air quality conditions.

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ANALIZA CZASOWO-PRZESTRZENNA WSKAŹNIKÓW JAKOŚCI POWIETRZA W STREFIE KONTROLI ZANIECZYSZCZEŃ PRZEMYSŁOWYCH W RAYONG W TAJLANDII (2017–2023)

STRESZCZENIE

Cel badania

Zanieczyszczenie powietrza stanowi nadal poważny problem środowiskowy w uprzemysłowionych regionach Tajlandii, zwłaszcza w strefie kontroli zanieczyszczeń przemysłowych Rayong – centrum przemysłu petrochemicznego i ciężkiego w ramach Wschodniego Korytarza Gospodarczego (EEC). W niniejszym badaniu przeanalizowano trendy czasowe i wzajemne powiązania głównych czynników zanieczyszczających powietrze, w tym PM_{10}, $PM_{2,5}$, CO, NO_2, SO_2 oraz wybranych lotnych związków organicznych (LZO), w latach 2017–2023, wykorzystując do oceny i analizy korelacji wskaźnik jakości powietrza (AQI).

Materiały i metody

Dane z będących w ciągłym użyciu stacji monitorowania powietrza, obsługiwanych przez Departament Kontroli Zanieczyszczeń (PCD), zostały poddane analizie statystycznej przy użyciu programu SPSS w celu zidentyfikowania wahań rocznych i sezonowych.

Rezultaty i wnioski

Rezultaty wskazują na stały spadek stężenia PM_{10} po 2019 roku, podczas gdy stężenie $PM_{2,5}$ wykazuje tendencję wzrostową, co sugeruje zmianę w kierunku zanieczyszczenia drobnymi cząstkami stałymi. Poziomy NO_2 i SO_2 również znacznie spadły w tym samym okresie, co świadczy o skuteczności polityki kontroli emisji i usprawnień technologicznych. Analizy korelacji wykazały silne dodatnie powiązania między PM_{10} a gazami związanymi ze spalaniem, takimi jak NO_2 (r = 0,853) i SO_2 (r = 0,760), podczas gdy $PM_{2,5}$ wykazało ujemne zależności z kilkoma gazowymi zanieczyszczeniami, co odzwierciedla różnice w źródłach pochodzenia i zachowaniu w atmosferze. Wartości AQI wahały się od 20,47 do 41,69 w całym okresie badania, utrzymując się konsekwentnie poniżej progu „czystego” (AQI = 50) i wskazując na ogólnie akceptowalną jakość powietrza. Wyższe poziomy AQI w latach 2019–2020 były jednak związane ze wzrostem emisji przemysłowych i samochodowych. Ostatecznie wyniki badania wskazują na pozytywną tendencję w zakresie poprawy jakości powietrza w Rayong, szczególnie po 2019 roku, co można przypisać zaostrzonym środkom kontroli zanieczyszczeń i lepszemu zarządzaniu środowiskiem.

Słowa kluczowe: zanieczyszczenie powietrza, wskaźnik jakości powietrza, trendy czasowe, strefa przemysłowa Rayong