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Spatio-Temporal Assessment of Air Quality and AQI in Former Khanh Hoa Province, Vietnam (2021-2024)

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ABSTRACT

Air pollution has become an increasingly important environmental and public health concern, particularly in rapidly urbanizing coastal provinces. This study aimed to evaluate the spatio-temporal variation characteristics of key air quality parameters (TSP, SO_2, NO_2, and CO) and the Air Quality Index (AQI) in former Khanh Hoa Province during the period 2021-2024. Periodic monitoring data collected from 28 monitoring sites across four functional zones (North, South, West, and Central) were analyzed using descriptive statistics, seasonal comparison, Pearson correlation analysis, AQI calculation, and GIS-based spatial interpolation (IDW). The results showed that SO_2 and CO concentrations significantly decreased by 62% and 22%, respectively ($p<0.05$), while NO_2 remained relatively stable and TSP showed signs of increasing, particularly in 2024. TSP was identified as the dominant pollutant, accounting for more than 95% of AQI deterioration and frequently exceeding the annual average standard in the Central region. Overall air quality was generally classified as "Good" and "Moderate"; however, localized pollution hotspots and short-term unhealthy AQI events were observed, especially during the dry season in urbanized areas with high traffic density and intensive construction activities. Pearson correlation analysis revealed that humidity and wind speed played important roles in pollutant dispersion and washout effects, while noise levels showed significant positive correlations with TSP, NO_2, and CO, indicating the strong influence of transportation-related emissions. These findings suggest that air quality management should prioritize TSP source control, particularly in the Central region, and strengthen seasonal monitoring strategies to support sustainable environmental management in rapidly developing coastal provinces of Vietnam.

HIGHLIGHTS

- GIS-AQI analysis across four zones in Khanh Hoa (2021-2024)
- TSP dominates pollution, contributing more than 95% of AQI deterioration
- SO_2 and CO decreased significantly; NO_2 remained stable
- Hotspots occur in urban areas during the dry season
- Traffic emissions strongly influence TSP, NO_2, and CO levels

1. INTRODUCTION

Air quality is currently one of the most serious environmental and public health challenges on a global scale, causing negative impacts on human health, ecosystems, and sustainable economic development (Li et al., 2014; Rakholia et al., 2023). Urban air pollution is not only occurring in megacities but is also rapidly increasing in medium and small-sized cities due to the development of industrial activities and regional economic growth (Dadhich et al., 2018). According to the World Health Organization (WHO), approximately 99% of the world's population is exposed to air quality levels that exceed recommended limits, causing millions of premature deaths and significant economic losses worldwide (Alsowaidan et al., 2024; Rad et al., 2022; WHO, 2024). However, the severity and spatial distribution of air pollution vary considerably among regions depending on urbanization intensity, industrial activities, and local meteorological conditions. Studies have confirmed a strong link between major air

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pollutants such as total suspended particles (TSP), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) and adverse human health effects. High concentrations of TSP can penetrate the respiratory system, causing respiratory irritation, reduced lung function, chronic bronchitis, asthma aggravation, and increased risks of cardiovascular and pulmonary diseases, particularly among children, the elderly, and sensitive groups (Lang et al., 2025; Makinde et al., 2023). SO_2 exposure is associated with airway inflammation, bronchoconstriction, and worsening of asthma symptoms, while prolonged exposure to NO_2 may damage lung tissue, reduce immune defenses of the respiratory system, and increase the risk of cardiovascular and neurological disorders such as Alzheimer's or Parkinson's disease (Makinde et al., 2023; Rad et al., 2022). Although CO concentrations are often lower than regulatory limits, prolonged exposure can reduce oxygen transport in the blood through hemoglobin binding, leading to headaches, dizziness, cardiovascular stress, and serious health risks under high exposure conditions (Rad et al., 2022; WHO, 2024).

In Vietnam, rapid industrialization and urbanization have led to a serious decline in air quality in major cities like Hanoi and Ho Chi Minh City, frequently exceeding national and international permissible levels (Ho et al., 2025; Nguyen et al., 2022; Rakholia et al., 2023). Not only in major economic centers, but also in key economic regions like Dong Nai and coastal provinces like Bac Lieu, are experiencing pollution pressure from traffic, production, and waste management (Lang et al., 2025; Nguyen et al., 2025). In particular, transportation is identified as the main source of emissions, accounting for over 70-80% of emissions in developing cities, due to the enormous volume of motorcycles and underdeveloped infrastructure (Nguyen et al., 2022; Nguyen et al., 2025).

The former Khanh Hoa Province, with its position as a center for coastal tourism and a strategic economic corridor, is undergoing a strong recovery of socio-economic activities after the Covid-19 pandemic. Extreme temperature changes and extreme weather events in the locality over the past decades have shown clear signs of climate change (Pham et al., 2023), this can further complicate the dispersion and accumulation of air pollutants. Studies in tropical monsoon regions show that air pollutant concentrations vary dramatically seasonally, often peaking during the dry season due to calm atmospheric conditions and temperature inversions (Ho et al., 2025; Nguyen et al., 2025; Xu et al., 2019). Although former Khanh Hoa Province generally maintains relatively good air quality compared to major metropolitan areas in Vietnam, localized pollution hotspots still occur, particularly in densely urbanized and traffic-concentrated areas such as the Central region. Short-term increases in TSP concentrations during the dry season and periods of intensive construction activity may lead to temporary deterioration of AQI (Air Quality Index), especially for sensitive groups. Therefore, understanding the spatial and temporal variability of pollution is more important than evaluating only the overall annual air quality status (Dang and Vu, 2024; Watcharavitoon et al., 2013; Xu et al., 2019). Urban noise has also been shown to have a very strong positive correlation with CO and NO_2 concentrations, which serve as important representative indicators of traffic intensity (Nguyen et al., 2025).

In modern air quality research, the application of Geographic Information Systems (GIS) has become a powerful and flexible tool for spatially estimating and analyzing pollution levels (Dadhich et al., 2018; Nguyen et al., 2025). GIS provides a digital environment that integrates data from various sources, enabling the visualization of pollution trends (Dadhich et al., 2018). Through spatial interpolation techniques such as Inverse Distance Weighting (IDW) or Kriging, GIS allows for the forecasting of particulate and air pollutant concentrations in areas without monitoring stations based on sample data from known locations (Dadhich et al., 2018; Nguyen et al., 2025; Zaib et al., 2022). This GIS-based approach effectively supports the identification of pollution "hotspots" and the assessment of air quality differences between various functional areas such as residential areas, industrial zones, or major transportation routes (Dadhich et al., 2018; Nguyen et al., 2025). The use of high-resolution map layers helps managers accurately identify critical zones that require priority emission control to protect public health (Nguyen et al., 2022; Sharma and Mauzerall, 2022).

Although several studies have assessed climatic characteristics and general environmental conditions in Khanh Hoa province (Nguyen, 2003; Pham et al., 2023), however, comprehensive spatio-temporal assessments of air quality during the post-Covid-19 economic recovery period (2021-2024), particularly those integrating pollutant trends, AQI spatial distribution, and their relationships with

meteorological and noise factors across different functional zones, remain limited. Previous studies have mainly focused on climate patterns or isolated environmental indicators, while updated assessments of key air pollutants and their relationships with meteorological and anthropogenic factors are still lacking (Dang and Vu, 2024; Watcharavitoon et al., 2013; Xu et al., 2019). In particular, no previous study has systematically integrated annual, monthly, and seasonal variations of major pollutants (TSP, SO_2, NO_2, CO), dominant pollutant identification, GIS-based AQI spatial distribution, and correlation analysis between air pollutants, meteorological parameters, and noise levels across different functional zones of the province. This gap limits the understanding of local pollution dynamics and hinders the development of effective and sustainable air quality management policies for this rapidly urbanizing coastal province. Therefore, this study aims to provide the first comprehensive spatio-temporal assessment of air quality in former Khanh Hoa Province during 2021-2024. The main objectives are to: (i) assess the trends of key air quality parameters (TSP, SO_2, NO_2, CO) across annual, monthly, and seasonal cycles; (ii) identify dominant pollutants and analyze AQI evolution across different functional zones using GIS-based interpolation; and (iii) examine the correlations between meteorological factors (temperature, humidity, pressure, wind speed), noise levels, and air quality parameters. The findings are expected to provide a scientific basis for targeted air pollution control strategies and sustainable environmental management at the local level.

2. METHODOLOGY

2.1 Research and data collection area

The study area is the mainland region of Khanh Hoa Province (former), a coastal province in South Central Vietnam, notable for its developing tourism, service, and industrial activities (Khanh Hoa PPC, 2023). The topography of Khanh Hoa Province slopes gradually from west to east, with over 67% of its area being hills and mountains, forming an arc that blocks winds from the north to the west, surrounded by narrow coastal plains in the districts of Van Ninh, Ninh Hoa, Dien Khanh, and Cam Ranh (Nguyen et al., 2013). The province's climate is characterized by a typical tropical monsoon climate. It is divided into two seasons, the dry season from January to August, and the rainy season from September to December. The prevailing wind direction during the dry season is southeast, and during the rainy season it is north and northeast (Khanh Hoa PPC, 2023; Nguyen, 2003).

To reflect the diverse characteristics of emission sources and population density, the study area is divided into four main sub-regions based on natural geography, population characteristics, development conditions, and projected development potential according to the Khanh Hoa Province development plan for the period 2021-2030, with a vision to 2050 (Figure 1): The North (NR) comprises Van Ninh District and the Ninh Hoa Town area within the Van Phong Economic Zone, a dynamic economic center developing new, high-level industries, focusing on high-tech industries and high-end integrated tourism; the South (SR) comprises Cam Ranh city and Cam Lam urban area, a logistics and trade center with Cam Ranh International Airport and seaport playing a crucial role in the province's development; the West (WR) comprises Khanh Vinh District, Khanh Son District, and the western area of Ninh Hoa Town, an inland mountainous area with the least developed economy in the province; and the Central (CR) area comprises Nha Trang City and the southern part of Ninh Hoa, Dien Khanh District, serving as the province's administrative, political, tourism, and commercial center (Khanh Hoa PPC, 2023). This zoning allows for a more detailed assessment of air quality variability across space, similar to studies conducted in other coastal cities (Yan et al., 2025; Zhang et al., 2022).

The data used in this study are periodic monitoring data of meteorological parameters and air quality over a four-year period, from 2021 to 2024, and 12 months (12 periods), two seasons of the year (dry season: 8 periods corresponding from January to August; and rainy season: 4 periods corresponding from September to December) at 28 monitoring points, divided into Northern (5 points), Southern (9 points), Western (2 points), and Central (12 points) areas (Figure 1). Meteorological parameters included temperature (°C), humidity (%), pressure (hPa), and wind speed (m/s). Air quality parameters of interest were TSP, SO_2, NO_2, and CO. In addition, noise levels were also collected. All data were provided by the local environmental management agency, ensuring accuracy and representativeness of the current air quality status in Khanh Hoa Province (DONRE Khanh Hoa, 2025).

2.2 Data analysis methods

Descriptive statistical methods (mean, standard deviation, minimum, maximum) were applied to

provide an overview of the characteristics of each air quality and meteorological parameter. Trends in pollutant concentrations over the year, month, and season were analyzed to identify patterns and cycles. Percentage changes between years were calculated to quantify the increase/decrease in pollutant concentrations. The independent sample t-test was applied to evaluate the statistical significance of interannual differences in mean concentrations of air pollutants (TSP, SO_2, NO_2, and CO) during the monitoring period from 2021 to 2024. The primary objective of this analysis was to compare annual variations and determine whether changes between monitoring years were statistically significant, rather than to detect monotonic long-term temporal trends. Given that the dataset was based on periodic monthly monitoring observations over a relatively short period (four years), the t-test was considered appropriate for assessing year-to-year differences and supporting practical interpretation of short-term air quality changes, similar to studies on air quality variability over time (Lu et al., 2023; Pham and Nguyen, 2024). In contrast, methods such as the Mann-Kendall test and Sen's slope estimator are generally more suitable for longer continuous time-series data aimed at robust monotonic trend detection.

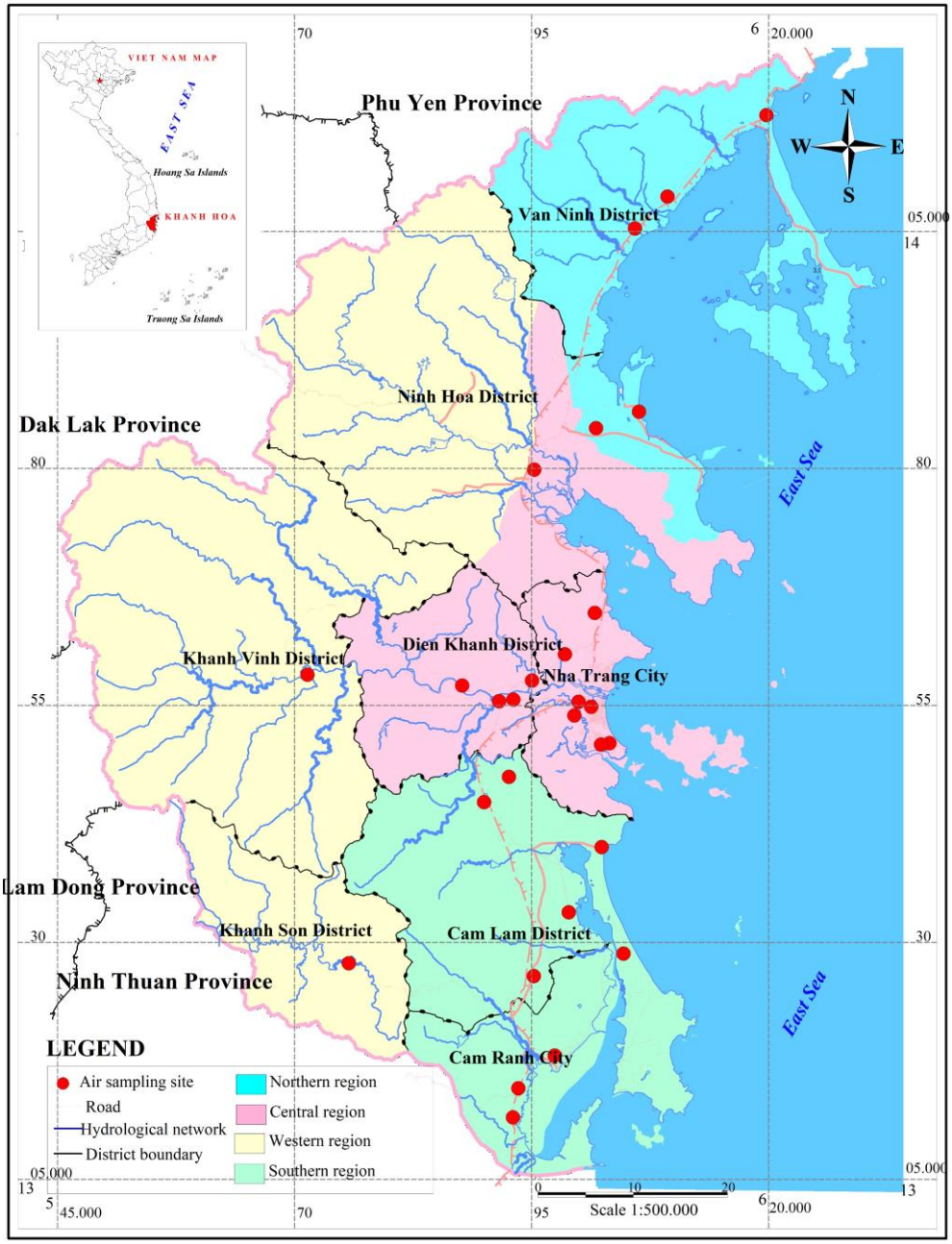

Figure 1. Map of the study area and locations for air quality monitoring sampling

Pearson correlation analysis was used to assess the linear relationship between meteorological parameters (temperature, humidity, pressure, wind speed), noise levels, and concentrations of air pollutants (TSP, SO_2, NO_2, CO), as well as the AQI (Lu et al., 2017; Shrestha and Kazama, 2007). The correlation coefficient (r) and p-value ($p<0.05$; $p<0.01$; $p<0.001$) were used to determine the magnitude and statistical significance of the relationship. Understanding this correlation is crucial for identifying factors influencing air quality and proposing effective control solutions (Tian et al., 2024; Xia et al., 2025). Data processing and charting were done using Rstudio 2023.06.0 Build 421 statistical software and Excel 2016.

The Air Quality Index (AQI) is calculated according to the guidelines of Decision No. 1459/QD-TCMT of the Vietnam General Department of Environment (VEA, 2019), based on parameters such as TSP, SO_2, NO_2, and CO, the AQI is a composite index reflecting the level of air pollution and its impact on human health. It is classified into six levels where, Green (0-50, Good); Yellow (51-100, Moderate); Orange (101-150, Unhealthy for sensitive groups); Red (151-200, Unhealthy); Purple (201-300, Very Unhealthy); and Maroon (301-500, Hazardous). Analyzing the AQI across space and time helps to assess the overall air quality situation and identify areas and times with a high risk of pollution (Ali et al., 2026).

Spatial interpolation for the AQI was performed using the IDW algorithm in ArcGIS 10.8. According to Vorapracha et al. (2015), IDW demonstrates significant advantages over kriging methods in forecasting air pollution trends. In this study, IDW utilized data collected from 28 monitoring points to predict AQI in areas lacking direct data. The IDW interpolated maps were then visualized using a color scale, clearly illustrating the spatial distribution of AQI.

3. RESULTS AND DISCUSSION

3.1 Trends in the concentration of air quality parameters over time and space

3.1.1. Trends in the concentration of air quality parameters over the year

Table 1 shows that the average air pollutants values for SO_2, CO, and NO_2 during the period 2021-2024 were all lower than the limits of QCVN 05:2023/BTNMT: Vietnam National Technical Standard on Air Quality (MONRE, 2023) calculated based on annual and hourly averages. However, although TSP levels reached the hourly average (300 µg/Nm^3), there were signs of exceeding the annual average (100 µg/Nm^3) in 2021, 2022, and 2024. The average noise level still met QCVN 26:2010/BTNMT: National Technical Standard on Noise (MONRE, 2010). During the study period, SO_2 decreased significantly (by 62%), CO decreased by 22%, while TSP increased slightly by 2.83% and NO_2 decreased slightly by 7.10%. The sharp decrease in SO_2 and CO concentrations demonstrates the effectiveness of controlling emissions from industrial zones and improving vehicle engine technology (Dang and Trinh, 2022; Nguyen et al., 2025). However, TSP is trending slightly upward in 2024, reflecting a strong recovery in infrastructure construction and transportation activities after the pandemic (Xu et al., 2019; Zhang et al., 2022).

Simultaneously, meteorological factors also showed notable fluctuations during this period. Average temperature tended to increase slightly by 1.8% ($p<0.05$), while humidity increased by 5.1% ($p<0.05$). Notably, wind speed decreased significantly by -26.0% ($p<0.05$). This decrease in wind speed may reduce the dispersion of pollutants, contributing to the maintenance or increase of local pollutant concentrations, especially dust (Tian et al., 2024). Noise levels also increased slightly by 2.9% ($p<0.05$), indicating a strong correlation between increased economic activity, traffic, and physical environmental noise pollution (Goldberg et al., 2001; Pope III et al., 2002). These changes in meteorological factors need to be carefully considered when assessing air quality trends in Khanh Hoa. The standard deviation of TSP is relatively large compared to the annual average, implying the existence of short-term increases due to events (construction, increased traffic density during the tourist season, unfavorable dispersal conditions, or regional dust sources).

The statistical comparison of annual mean concentrations using the t-test showed that SO_2 and CO significantly decreased during the study period ($p<0.05$), while NO_2 remained relatively stable and TSP showed an increasing tendency in 2024.

3.1.2. Variation in the concentration of air quality parameters between months of the year

Figure 2 illustrates the monthly fluctuations of air quality parameters in four sub-regions within the study area from 2021 to 2024. CO and NO_2 exhibit an inverted "U-shaped" curve pattern, with the peak (high

concentration) in May and June each year, and gradually sloping towards the lowest points in January and December. This fluctuation is consistent across all four sub-regions, suggesting that this trend may be related to overall climatic conditions in the province rather than emission intensity or sub-regional climatic differences. Research by Pham et al. (2023) shows that the monthly temperature variation in Khanh Hoa Province observed from 1981 to 2020 follows a similar trend of an inverted "U-shaped" curve (temperature peaks in June and gradually decreases in both directions). This is in contrast to the U-shaped trend of wind speed observed at the Nha Trang station over the 30 years from 1986 to 2016 (Tu and Tran, 2018): Wind speeds are lowest in June and gradually increase towards January and December. As wind speeds increase, the dilution and dispersion of pollutants occur more quickly, helping to reduce local concentrations (Watcharavitoon et al., 2013). Conversely, low wind speeds result in stagnant atmospheric conditions, leading to pollution to accumulate, especially in urban areas with high traffic density (Dadhich et al., 2018; Watcharavitoon et al., 2013).

Table 1. Descriptive statistics (mean±standard deviation) of periodic observation data on meteorological parameters, noise levels, and air quality in Khanh Hoa Province (former) from 2021 to 2024

Parameters	Year				Change level [(a)]	QCVN 05:2023 (1h avg/annual avg)
	2021	2022	2023	2024		
Temp. (°C)	30.2±3.1	29.9±2.6	30.9±2.6	30.8±2.4	1.8%*	-
Humidity (%)	66.4±11.0	72.9±8.9	72.6±8.4	69.8±6.1	5.1%*	-
Pressure (hPa)	1,006.6±8.2	1007.5±7.7	1,007.9±8.2	1,007.8±9.1	0.12%	-
Wind speed (m/s)	1.1±0.93	1±0.68	0.83±0.54	0.81±0.58	-26.0%*	-
Noise level (dBA)	61.6±5.7	60.3±7.2	62.9±6.5	63.4±5.21	2.9%*	70 / - [(b)]
TSP (µg/Nm^3)	110.6±130.1	105.6±124.1	92.1±130.6	113.8±153.0	2.8%	300 / 100
SO_2 (µg/Nm^3)	18.8±2.1	18.5±2	16.1±5.4	7.1±2.4	-62.4%*	350 / 50
NO_2 (µg/Nm^3)	10.2±5.8	8.62±3.3	9.2±2.6	9.4±5.6	-7.1%	200 / 40
CO (µg/Nm^3)	2,704±1,222	2,069±724	1,714±321	2,092±350	-22.7%*	30,000 / -

Note: [(a)] Change level %: Indicates the relative rate of change between 2021 and 2024; *: The change between the two years tested was statistically significant ($p<0.05$). [(b)] QCVN 26:2010/BTNMT: National technical standard on noise (in normal areas, from 6-21 hours). QCVN 05:2023 is an abbreviation of QCVN 05:2023/BTNMT: Vietnam National technical standard on air quality.

Regarding SO_2 concentrations, significant changes were observed between the dry season (January-August) and the rainy season (September-December) in all four sub-regions. During the dry season, the average SO_2 concentration ranged from 15.65 to 16.49 µg/Nm^3, which was statistically significantly higher than during the rainy season (values ranging from 12.92 to 13.38 µg/Nm^3). The four rainy months in Khanh Hoa account for 75-80% of the province's total annual rainfall (Nguyen, 2003). Rain helps dissolve and remove dust particles as well as water-soluble air pollutants in water such as SO_2 (Nghiem et al., 2021), therefore, this process reduces the concentration of these pollutants compared to the dry season .

The monthly fluctuations of TSP concentration (Figure 2(d)) during the study period show a "U" shaped curve with the highest peak values in January (124.5 µg/Nm^3) at the beginning of the year and October (129.8 µg/Nm^3) near the end of the year. Interestingly, the lowest TSP values (the two troughs of the U) occurred in February (88.3 µg/Nm^3) and September (72.5 µg/Nm^3) - the months adjacent to the two peaks. This variation may be the result of a complex interaction between meteorological factors: rainfall, wind patterns, temperature, humidity, and continuous dust emissions from socio-economic activities. Increased rainfall during the rainy season likely helps remove suspended particles from the atmosphere, resulting in lower TSP concentrations. Higher humidity and frequent rainfall may also contribute to this decrease. However, this interpretation is based on monthly monitoring data and general seasonal trends, since detailed rainfall data such as intensity and duration were not available. Therefore, the effect of individual rainfall events on TSP concentrations could not be quantitatively evaluated. Although rain helps clean the air, high humidity after rain can cause small dust particles to clump together, forming larger particles that are more difficult to disperse in low wind conditions (Ali et al., 2026). October had the lowest average wind speed at the monitoring points in this

study, at 0.72 m/s, further reinforcing the above conclusion. In January, the low temperature (27.7°C - the lowest in 12 months) may contribute to temperature inversion conditions, creating a barrier that prevented pollutants from dispersing upwards, leading to a surge in concentration (Ho et al., 2025; Xu et al., 2019), at the same time, low wind speeds this month (reaching 0.87 m/s - the second lowest in the 12 months) can stagnant atmospheric conditions, causing pollution to accumulate, especially in urban areas with high traffic density (Dadhich et al., 2018; Watcharavitoon et al., 2013). To gain a more accurate picture, more continuous and detailed data are needed regarding rainfall intensity, duration, and other meteorological factors, as well as the activity of emission sources in the area.

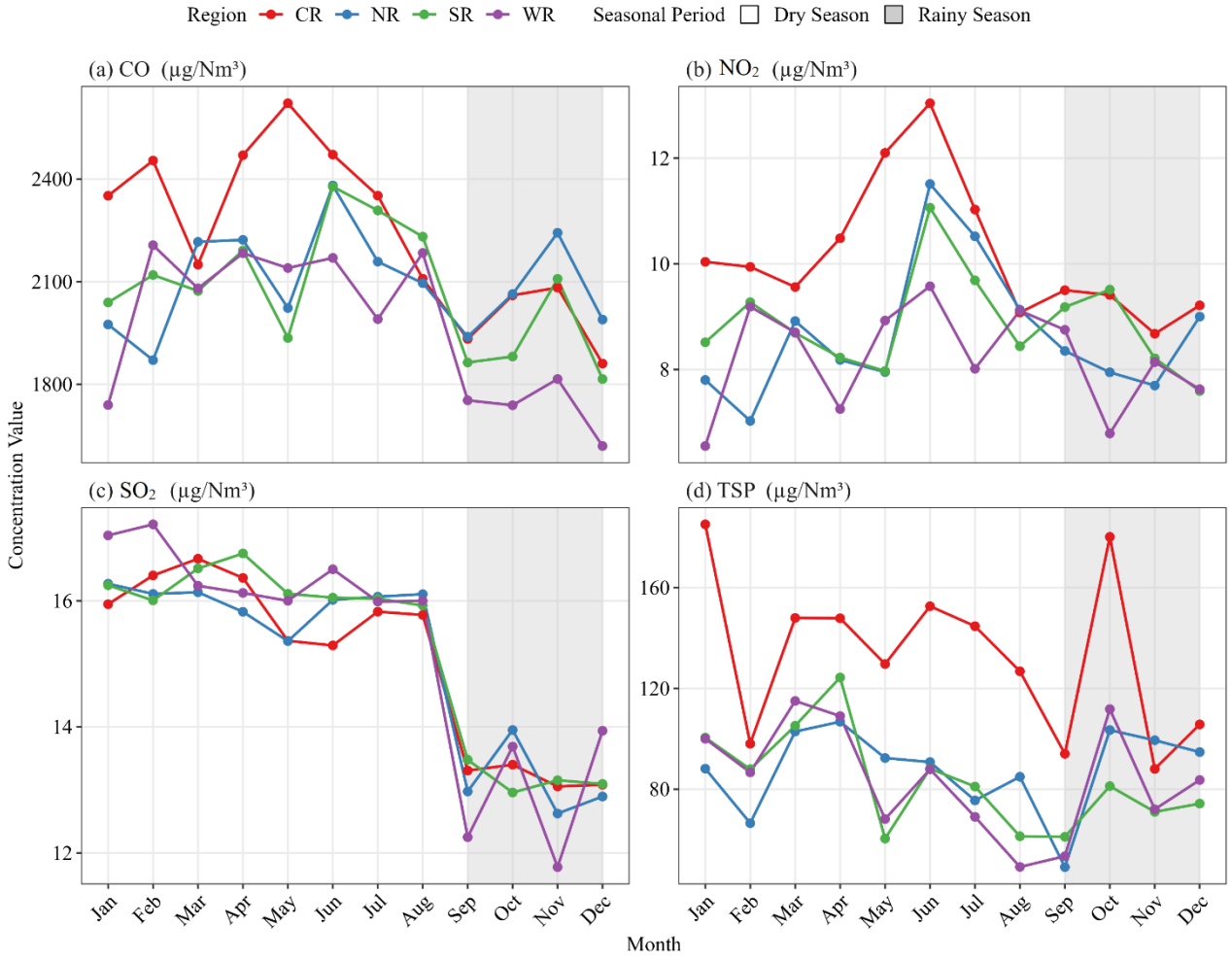

Figure 2. Monthly variations of the four key air quality parameters (TSP, SO_2, NO_2, CO) in the four sub-regions (NR, SR, WR, CR) of Khanh Hoa Province (former) from 2021-2024.

In terms of monthly spatial distribution, the Central (CR) zone generally had higher concentrations of TSP, CO, and NO_2 than the other areas at many times, especially for TSP: The Central zone consistently recorded the highest TSP concentrations, with an average TSP value of 129 µg/Nm^3 (exceeding the average annual TSP limit of 100 µg/Nm^3 according to the Vietnamese National Standard), while all three other sub-regions had values below 100 µg/Nm^3 (ranging from 83-88 µg/Nm^3) (Figure 2). This can be explained by the significantly higher population density and traffic volume in the central urban area compared to the surrounding areas (Lu et al., 2017; Lu et al., 2023). Conversely, the Northern (NR), Southern (SR), and Western (WR) regions have more stable air quality due to lower building density and larger open spaces. For SO_2, concentrations across these areas are relatively uniform and significantly lower than the standard, suggesting that SO_2 emissions may not be heavily related to urban emission sources.

3.1.3. Characteristics of seasonal variations in the concentration of air quality parameters throughout the year

The differences between the dry and rainy seasons (Figure 3) play a key role in understanding the local pollution dispersion mechanisms. The results show that the concentrations of most air pollutants are significantly higher in the dry season than in the rainy season ($p<0.05$). For example, in the CR, the TSP concentration in the dry season was 141.6 µg/Nm^3 compared to 116.9 µg/Nm^3 in the rainy season. Studies in Vietnam and the tropical regions also note that TSP concentrations are generally higher in the dry season and lower in the rainy season (Hien et al., 2002; Nguyen et al., 2024).

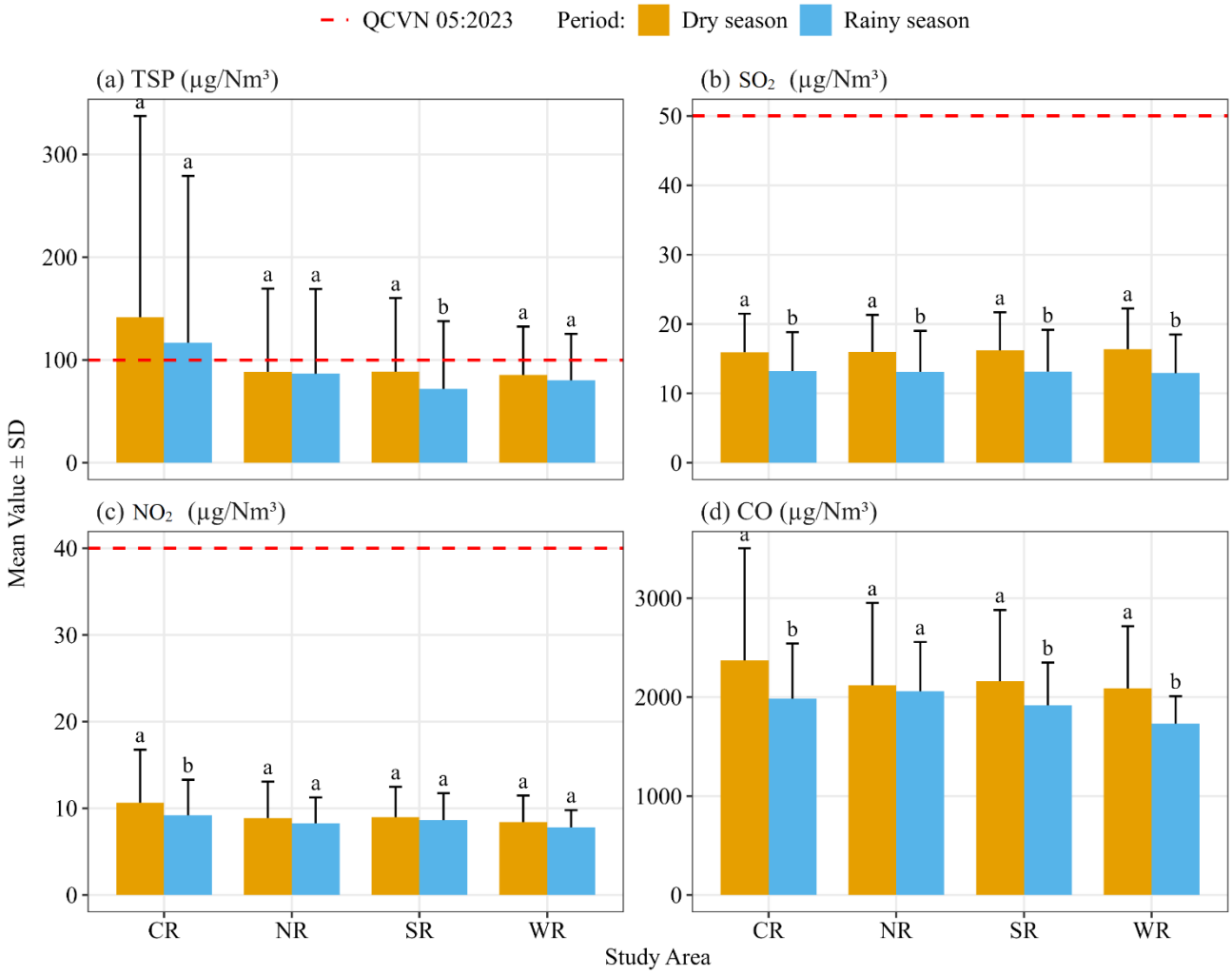

Figure 3. Seasonal changes of the four key air quality parameters (TSP, SO_2, NO_2, CO) in the four areas (NR, SR, WR, CR) of Khanh Hoa Province (former) from 2021-2024. (Note: error bars represent the standard deviation of the mean. Statistically significant differences ($p<0.05$) are indicated by the letters a, b)

This is consistent with the climate characteristics of Khanh Hoa, where the rainy season is concentrated in the last months of the year (usually from September to December) and the dry season is longer, with an average annual rainfall of about 2,000 mm in the North and gradually decreasing towards the South (Nguyen, 2003; Tu and Tran, 2018). Rainwater runoff is a crucial natural mechanism for cleaning the atmosphere, removing dust particles and dissolving air pollutants (Ali et al., 2026; Tian et al., 2024). Conversely, during the dry season, high temperatures, low humidity, and reduced wind speed create favorable conditions for the accumulation of suspended particulate matter and for chemical reactions leading to secondary pollutant formation. Heavy and very heavy rainfall, often concentrated in October and November, plays a crucial role in cleaning the air, significantly improving air quality during these periods (Nguyen et al., 2013). It is noteworthy that TSP is a pollutant with concentrations

exceeding the average annual standard in both the rainy and dry seasons. However, this excess is only observed in the central area**,** due to high traffic and construction density combined with rapid urbanization. Although the dry season values are higher than the rainy season, there is no statistically significant difference ($p>0.05$), indicating that the mechanism of pollutant accumulation from TSP emission sources is quite high in the Central area, leading to a relatively weak influence of meteorological factors on concentration reduction. Therefore, pollution control solutions at the source for TSP are needed in the central urban areas of the study region.

3.2 Major air pollutants

Analysis of the dominant pollutant (Figure 4) shows that TSP is the primary pollutant in most cases. Across the province, TSP accounted for 96% of samples throughout the year; seasonally, TSP remained dominant (93% in the rainy season and 97% in the dry season), reaching as high as 98% in the central area during the dry season. CO was the second most dominant pollutant, but with a small percentage (4.2% of the province), while SO_2 and NO_2 were almost non-dominant, with values of 0.15% and 0.00% respectively. The monthly distribution of pollutant variations (Figure 5) also shows this, with TSP being the dominant pollutant in all months from 2021-2024, except for September 2021, when CO was the dominant pollutant. Among particulate pollutants, TSP was the only parameter consistently monitored across all monitoring sites during the study period, allowing for a spatially and temporally comparable analysis. However, $PM_{2.5}$ and PM_{10} were not included due to data limitations, although these finer particles are more closely associated with adverse health effects, far surpassing gaseous pollutants such as SO_2 or NO_2 (Xu et al., 2019; Zhang et al., 2022). This result implies that dust control measures (traffic, construction, secondary dust-emitting activities) play a crucial role in improving AQI.

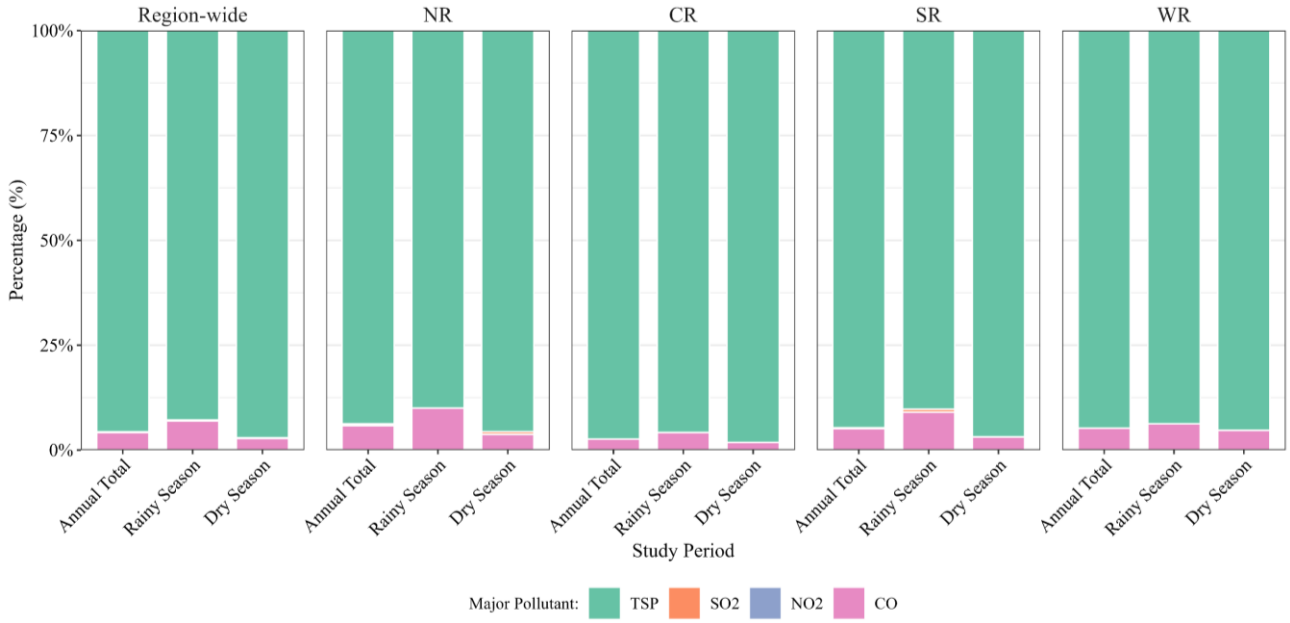

Figure 4. Percentage of major pollutants by season and year in different zones and across the entire Khanh Hoa Province (Note: The percentage of dominant pollutants was determined based on the AQI value of the representative pollutant for each observation. Specifically, for each sample, the AQI was defined by the highest sub-index among the four pollutants (TSP, SO_2, NO_2, and CO), and the pollutant with the highest AQI was considered the dominant pollutant. A total of 1,344 observations were analyzed (28 monitoring sites × 12 months × 4 years). The percentage of each pollutant was calculated as the frequency at which it was identified as the dominant pollutant divided by the total number of observations.)

3.3 The spatial and temporal variations of the AQI

The AQI provides an overview of air safety levels for public health (Figure 6, Figure 7). Analysis of the IDW interpolation map of AQI values (Figure 6) shows a clear spatial and temporal variation in air quality in Khanh Hoa. Overall, most of Khanh Hoa Province maintained “Good” air quality (Green, AQI 0-50) throughout the 2021-2024 study period, particularly in the NR, SR, and part of the WR areas. This reflects the relatively clean natural environment and low density of polluting activities in these regions.



Figure 5. Monthly fluctuations of major pollutants across sub-regions from 2021-2024

However, the Central (C) and parts of the Western areas (the central part of the Western area may be affected by high concentrations of pollutants, especially total particulate matter in the Central area, which can be dispersed by the Southeast monsoon in summer) frequently show areas with "Moderate" (AQI: 51-100) and sometimes "Unhealthy for Sensitive Groups" (AQI: 101-150) air quality. This is particularly evident in the annual maps (Figure 6(a-d)) and the dry season maps (Figure 6(e-h)). The Central area, with its high population density and traffic and construction activity, is a hotspot for air pollution. The appearance of yellow/orange spots here indicates that the concentrations of pollutants, especially TSP, frequently exceed safe levels for sensitive groups (Lu et al., 2017; Lu et al., 2023).

The differences between the dry and rainy seasons are also clearly shown in Figure 6. During the dry season (Figure 6(e-h)), the area of yellow and orange zones tends to expand, especially in the central area and some points in the west. This is consistent with the previous analysis of dry season meteorological conditions (weak winds, little rain) creating conditions for pollutant accumulation. Conversely, during the rainy season (Figure 6(i-l)), the maps are mostly green, indicating that the washout effect of rain has significantly improved air quality throughout the province. Nevertheless, there are still localized areas and times (such as the central region) that appear yellow even during the rainy season, indicating that emission sources remain active and need to be controlled. Particularly during the 2024 rainy season, the percentage of "Moderate" AQI increased to 40% and "Good" decreased to 57%, suggesting that the AQI was more adversely affected during this period compared to previous years, possibly related to the economic recovery process after the Covid-19 pandemic.

Overall, although air quality was mostly "Good" (57%-85% according to Figure 7), the occurrence of "Unhealthy", "Very Unhealthy", and even "Hazardous" samples (especially during the dry seasons of 2022, 2023, and 2024) is a warning sign. These extreme AQI values were mainly due to local spikes in TSP concentrations. This indicates that although the province's baseline air quality is quite good, short-term pollution events still occur and may pose health risks to sensitive groups (Goldberg et al., 2001; WHO, 2018). AQI maps provide a visual overview of areas requiring priority monitoring and air

quality management. Additionally, for a more accurate picture, it's necessary to analyze topographic and meteorological factors in air pollution dispersion models to more accurately assess the spread of pollutants between areas.

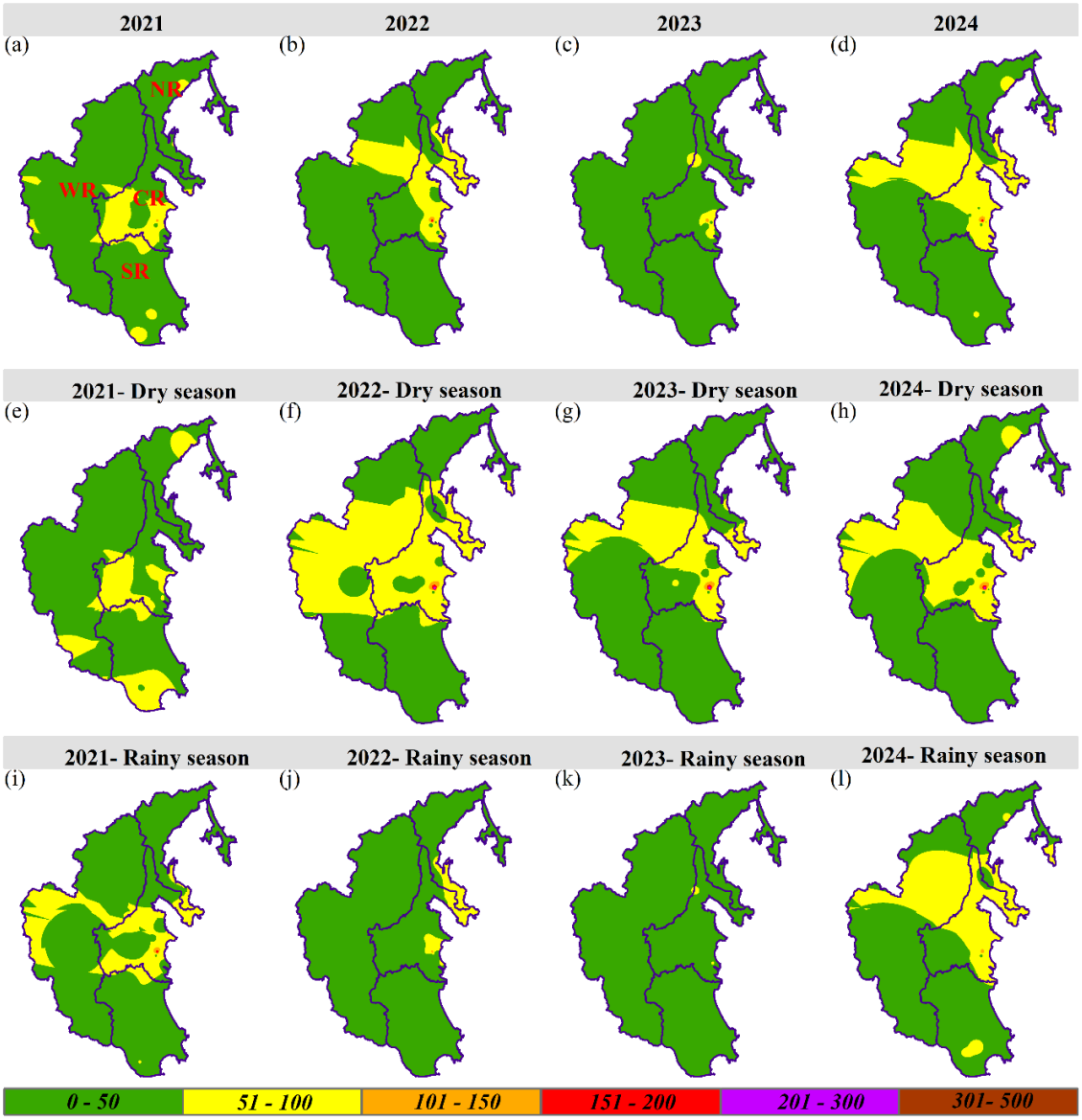

Figure 6. Spatial distribution by year and season of the AQI for the period 2021-2024 in 4 sub-regions of Khanh Hoa Province (former)

3.4. The correlation between meteorological factors, noise levels, air pollutants and AQI

Pearson correlation analysis (Table 2) was performed to quantify the linear relationship between meteorological factors, noise levels, and air quality parameters, and to provide a complex and multi-dimensional picture of air pollution dynamics in Khanh Hoa.

One of the key findings is the clear role of humidity in improving air quality. In most sub-regions, particularly in the SR during the dry season, humidity showed a statistically significant inverse correlation with TSP ($r=-0.202$; $p<0.001$), NO_2 ($r=-0.230$; $p<0.001$), and especially with CO (moderately inverse correlation, $r=-0.311$; $p<0.001$). This confirms the "washout" and wet deposition mechanism, where airborne water vapor particles help remove particulate matter and dissolve air pollutants, a mechanism widely documented in air pollution studies (Ali et al., 2026; Tian et al., 2024). The inverse correlation between wind speed and AQI in the NR ($r=-0.164$; $p<0.05$) during the dry season also indicates the positive role of wind in dispersing and diluting pollutants, improving overall air quality.

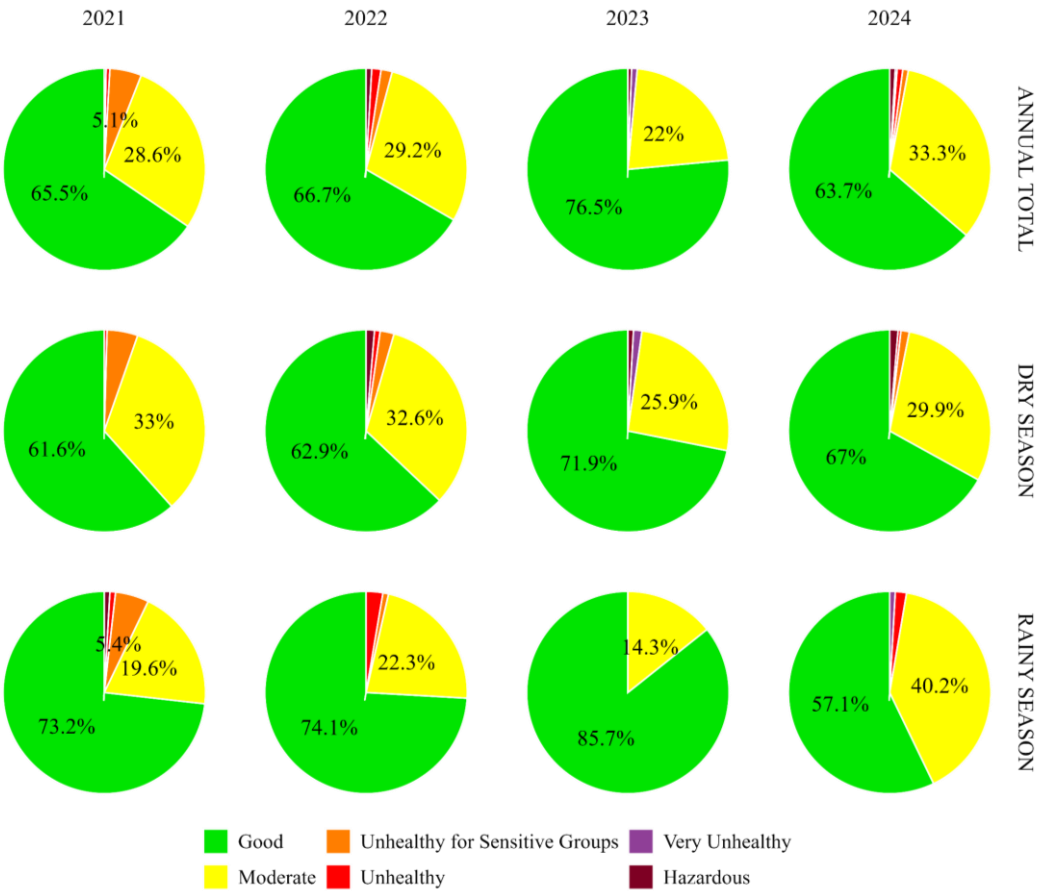

Figure 7. Percentage rates by year and season for AQI classifications in Khanh Hoa Province (former) during the period 2021-2024

In the Central area, where urban activities are concentrated, a positive correlation with high statistical significance was found between noise levels and traffic-specific pollutants such as TSP ($r=0.193$; $p<0.001$), NO_2 ($r=0.276$; $p<0.001$), and CO ($r=0.111$; $p<0.05$) during the dry season. The higher TSP concentrations and noise levels observed in the Central region are likely associated with intensive traffic activities, urban construction, and high population density. This interpretation is supported by the strong positive correlations among noise, TSP, NO_2, and CO, as well as the region's urban characteristics. However, no quantitative emission inventory (e.g., vehicle counts, traffic flow, or construction activity data) was available. Therefore, source attribution was based on spatial patterns and correlation analysis, and the relative contributions of emission sources could not be precisely determined (Goldberg et al., 2001; Pope III et al., 2002). This finding underscores that solutions aimed at reducing traffic congestion not only improve air quality but also positively affect the urban acoustic environment.

The study found several "unusual" correlations that can be explained by scientific mechanisms. Most notably, there was a weak positive correlation between wind speed and AQI in the southern region during the dry season ($r=0.129$; $p<0.05$). This contrasts with the weak negative correlation between wind speed and AQI in the northern region ($r=-0.164$; $p<0.05$), as mentioned above. This may be related to the specific wind patterns of the two study areas: In the northern part of the province during the dry season, there is a distinctive topographic wind pattern called the Tu Bong wind, which blows strongly and continuously from the west towards the Van Phong Bay Area (Nguyen, 2003). This wind pattern may enhance the dispersion and dilution of pollutants, especially the concentration of TSP (an indicator characterizing the AQI value in the study area). Meanwhile, the southern region is strongly influenced by the southeast monsoon during the dry season (Nguyen, 2003). Instead of dispersing, strong winds in dry conditions can increase pollution. This is explained by the phenomenon of "dust entrainment", where wind carries dust particles from dry land surfaces, roads, and construction sites into the air-a mechanism that has been observed in studies in other arid regions (Zhang et al., 2022).

Table 2. Correlation analysis between meteorological factors, noise levels, and air quality parameters in different zones within Khanh Hoa Province (former)

Parameters	Dry season					Rainy season				
	TSP	SO_2	NO_2	CO	AQI	TSP	SO_2	NO_2	CO	AQI
Northern										
Temp.	-0.068	-0.046	0.290***	0.224**	-0.078	-0.038	0.054	-0.044	-0.023	-0.074
Humidity	0.034	-0.196*	-0.137	-0.251**	0.038	0.143	0.021	0.189	0.019	0.161
Pressure	0.059	-0.142	-0.136	-0.124	0.079	-0.089	-0.077	0.008	-0.088	-0.088
Wind speed	-0.134	0.114	0.023	0.093	-0.164*	-0.072	0.313**	0.081	0.208	-0.054
Noise level	0.093	-0.204**	0.144	-0.007	0.122	0.084	-0.086	0.063	-0.063	0.093
Southern										
Temp.	-0.089	-0.100	0.185**	0.065	-0.09	0.104	-0.124	0.184*	-0.163	0.142
Humidity	-0.202***	-0.049	-0.230***	-0.311***	-0.189**	-0.131	0.204*	-0.150	0.072	-0.189*
Pressure	0.025	-0.21***	-0.153**	-0.153**	0.015	-0.034	-0.061	0.011	0.004	-0.02
Wind speed	0.112	0.112	0.027	-0.022	0.129*	-0.007	0.310***	-0.178*	0.004	0.009
Noise level	0.098	-0.148*	0.103	-0.013	0.112	-0.083	-0.169*	0.047	-0.178*	-0.019
Western										
Temp.	-0.155	-0.058	0.198	0.173	-0.171	-0.084	-0.159	0.100	0.087	-0.051
Humidity	-0.198	0.011	0.063	-0.185	-0.2	-0.193	-0.001	-0.081	-0.254	-0.188
Pressure	0.026	0.044	0.085	0.224	0.108	0.069	-0.024	0.024	-0.127	0.071
Wind speed	0.076	0.13	0.157	0.164	0.069	0.193	0.148	-0.269	0.210	0.234
Noise level	0.083	0.073	0.064	0.103	0.113	-0.042	-0.073	-0.046	-0.063	0.026
Central										
Temp.	-0.008	-0.030	-0.011	-0.106*	-0.004	0.133	-0.206**	0.032	0.011	0.135
Humidity	0.041	-0.180***	0.027	-0.104*	0.043	-0.069	0.295***	-0.028	0.049	-0.080
Pressure	-0.003	-0.109*	-0.047	-0.003	-0.003	-0.109	0.051	-0.024	-0.034	-0.110
Wind speed	0.059	0.001	-0.081	-0.034	0.056	-0.062	0.105	-0.042	0.069	-0.065
Noise level	0.193***	-0.155**	0.276***	0.111*	0.199***	0.145*	0.010	0.275***	0.151*	0.156*

Note: *, **, *** indicate statistically significant correlations at the 0.05, 0.01, and 0.001 levels (two-tailed test), respectively. Pearson correlation analysis was conducted using monthly monitoring observations. For each monitoring site, dry season data included 32 observations (8 months × 4 years), while rainy season data included 16 observations (4 months × 4 years). The total sample size (n) varied by sub-region according to the number of monitoring points.

Another noteworthy phenomenon is the average positive correlation between wind speed and SO_2 in the Northern ($r=0.313$; $p<0.01$) and Southern ($r=0.310$; $p<0.001$) regions during the rainy season. This contradicts the usual dispersing role of wind. Elevated SO_2 concentrations observed in coastal areas near Van Phong Bay and Cam Ranh Bay may be associated with maritime transportation activities and port operations, as well as the potential transport of ship-related emissions under the influence of the Northeast monsoon during the rainy season. This interpretation is supported by the proximity of monitoring sites to major port areas and the prevailing seasonal wind direction, which may facilitate the transport of coastal air masses toward inland areas. However, the present study did not include atmospheric dispersion modeling, ship emission inventories, or source apportionment techniques to directly verify transport pathways or quantify the contribution of maritime emissions (Jang et al., 2017).

A notable finding is the absence of statistically significant correlations in the Western (WR) area in both seasons. This is not a data defect but rather a significant finding: it suggests that this area has clean, stable air quality and is less affected by major emission sources and meteorological fluctuations. This can be considered an important "background area" for comparing and evaluating pollution levels in other areas of Khanh Hoa Province (Lu et al., 2017). This interpretation is consistent with the actual conditions in the Western area, which is the most mountainous and underdeveloped area of the province (Khanh Hoa PPC, 2023).

4. CONCLUSION

In-depth research on the spatiotemporal characteristics of air quality in Khanh Hoa Province during the period 2021-2024 has yielded important conclusions. Although the concentrations of air pollutants such as SO_2, NO_2, and CO showed significant improvement, reflecting the effectiveness of emission control measures, TSP pollution remains a considerable challenge, especially with the increase in concentrations observed in 2024 after the Covid-19 pandemic. The dominance of TSP in the study area indicates not only an environmental concern but also a significant public health risk, particularly for urban residents frequently exposed to traffic emissions and construction dust. The spatial and temporal differentiation of pollution is evident, with the central area (Nha Trang and surrounding areas) emerging as a TSP hotspot. Seasonal analysis also indicates that the dry season is more sensitive to pollution due to stagnant atmospheric conditions and dust entrainment, while the rainy season plays a crucial role in improving air quality through wet deposition mechanisms. Meteorological factors such as humidity and wind speed were identified as key elements in the dilution and removal of pollutants. In particular, the strong correlation between noise pollution and dust/emission concentrations in urban areas confirms the dominant role of traffic and construction activities as major emission sources. From a policy perspective, air quality management in former Khanh Hoa Province should prioritize TSP control, especially in the Central region. Key actions include dust suppression, stricter emission control, and cleaner transport. Enhanced monitoring in the dry season and GIS-based AQI mapping can support targeted interventions, while the Western region can serve as a background reference area. These findings support sustainable air quality management in rapidly urbanizing coastal areas. The study has several limitations. It only analyzed four pollutants (TSP, SO_2, NO_2, and CO), excluding finer particles like $PM_{2.5}$ and PM_{10}. The use of monthly data limits the ability to capture short-term pollution events. The IDW method for AQI mapping does not fully reflect complex dispersion processes. Additionally, key factors such as traffic intensity, emission inventories, and detailed rainfall data were not included. A limitation of the present trend analysis is that the study focused on interannual mean comparison using the t-test rather than formal monotonic trend detection methods such as the Mann-Kendall test and Sen's slope estimator. Due to the relatively short monitoring period (2021-2024) and periodic monthly observations, the current approach was considered suitable for evaluating short-term annual differences. Future studies with longer continuous datasets should apply more robust non-parametric trend analysis methods to strengthen long-term air quality assessment. Based on these findings, the study recommends prioritizing dust control solutions at the source in construction and traffic activities in the Central region. Furthermore, subsequent research should focus on analyzing fine particulate matter ($PM_{2.5,}$ PM_{10}) together with health risk assessment and applying advanced dispersion models to predict air quality trends more accurately in the context of climate change. Future studies should also apply back-trajectory models such as HYSPLIT, together with ship emission inventories and source apportionment approaches, to better quantify the contribution of maritime emissions to coastal air quality. In addition, incorporating emission inventories and source apportionment techniques would improve the accuracy of pollution source identification and support more targeted air quality management.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF CONFLICT OF INTEREST

The authors declare that this article is the author's own research work, has not been published anywhere else, is not copied from previous research, and is not subject to any conflict of interest.

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