ORIGINAL ARTICLE

Environmental challenges and air pollution in Bac Lieu, Vietnam: assessing sources and impacts

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Abstract

Bac Lieu, a region with diverse industries like handicrafts, agriculture, tourism, and a thriving marine economy, faces environmental challenges from climate change, resource exploitation, and rising air pollution due to vehicular, industrial, and agricultural emissions, along with waste management issues. The materials and methods employed in this study encompassed various phases critical for assessing air quality and devising an Air Quality Management Plan (AQMP) for Bac Lieu province. The AQMP framework involved activities such as baseline assessments, emission inventories, air quality monitoring, and modeling using dispersion models like AERMOD. The study proposed the application of the AirQ + model to analyze the correlation between air quality and human health, emphasizing the short-term effects of pollutants on respiratory and cardiovascular diseases, and estimating potential avoidable cases in Bac Lieu province. The emissions inventory in Bac Lieu province categorizes sources into point, mobile, and area. Major CO emissions come from waste burning, cooking, and mixed sources, while traffic significantly impacts CO levels. Residential areas show significant PM10, PM2.5, and NO_2 emissions. Point sources impact nearby areas, notably in districts like Hong Dan and Phuoc Long. Cooking activities lead to high PM10 and CO emissions, especially in Bac Lieu city. Traffic emissions, particularly in urban hubs, significantly contribute to pollution, notably in Bac Lieu City, Vinh Loi, and Hoa Binh districts. Transportation emissions in urban zones contribute significantly to air pollution, while rural areas are influenced by various activities like burning, construction, and cooking, shaping diverse local air quality.

Keywords Air quality management plan · AQMP · Emissions inventory · AERMOD dispersion model · AirQ + model

1 Introduction

Urban air pollution is a pressing global challenge [1, 2] serving as a poignant case study illustrating this pervasive issue. Worsened by industrialization, urbanization, and vehicular emissions, this environmental issue has far-reaching implications for public health and ecological well-being [3–6]. The profound impacts on human health, including respiratory and cardiovascular diseases, underscore the urgency of mitigation efforts. Challenges such as limited information, inadequate understanding of air pollution concerns, institutional constraints, and insufficient coordination among governmental bodies responsible for air quality management persist, hindering effective interventions.

Highlighting the significant public health ramifications of air pollution is imperative, as evidenced by extensive research demonstrating its correlation with respiratory diseases, cardiovascular complications, and premature mortality. Roth [7] offered compelling evidence, estimating millions of premature deaths annually due to air pollution exposure. Moreover, ongoing research continues to elucidate the intricate ways in which pollutants such as particulate matter (PM), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3) detrimentally impact human health, exacerbating conditions like asthma and heightening cardiovascular risks. These findings underscore the urgent need for effective air quality management

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strategies to safeguard public health, as emphasized by reputable institutions like the World Health Organization (WHO) [8].

Bac Lieu, Vietnam, shows economic promise [9] with diverse industries like handicrafts, agriculture, and industry [10]. Its strategic location along National Highway 1A, approximately 110 km from Can Tho City and 280 km north of Ho Chi Minh City, supports for economic growth. In Bac Lieu, vehicular emissions, industrial pollutants, and agriculture elevate airborne contaminants, posing risks on rain-aerosol relationships, greenhouse gas emissions, and biomass burning impacts [11–13], urging research and sustainable policies.

The cultivation and advancement of various industries in Bac Lieu have raised concerns about the quality of air and its potential impacts on both the environment and human health. The need for this research arises from the imperative to understand the current state of air pollution in Bac Lieu, identify the sources contributing to its degradation, and evaluate the associated health risks. By addressing these aspects, this study aims to contribute valuable insights for the development of effective air quality management strategies tailored to the region's specific needs.

In contrast to developed regions like Europe and North America [14], Southeast Asia faces challenges due to rapid urbanization, as seen in recent Chinese studies [15, 16]. Nguyen et al. [17] suggest a "climate benefit" in Continental Southeast Asia, resembling European practices, while Amnuaylojaroen et al. [18] emphasize the role of anthropogenic emissions in increased surface ozone. Lee et al. [19] find that non-fire aerosols significantly impact low visibility days in ASEAN cities.

Previous research provides benchmarks for air quality management, but a critical gap remains in understanding Bac Lieu's unique challenges. This study aims to fill this gap by analyzing air quality parameters and comparing them with international standards and neighboring province.

Utilizing the AirQ+ Model [20–22], renowned for assessing air quality's health impacts, this research quantified health risks in Bac Lieu, aiding in targeted interventions within the Provincial Air Quality Management Plan (AQMP) [23–25].

Action plans for Bac Lieu province are essential to address environmental concerns in alignment with governmental directives and regulations like Decision No. 1973/QD-TTg, Directive No. 03/CT-TTg, Official Dispatch No. 3051/BTNMT-CTMT, and Law on Environmental Protection No. 72/2020/QH14. These guidelines emphasize comprehensive strategies for pollution mitigation and environmental management. Implementing a Provincial AQMP is crucial for effective pollution mitigation and environmental management. The AQMP aligns with national regulations, utilizing advanced technologies to track pollutant levels effectively. This plan assesses pollution sources, sets emission controls, monitors air quality, and protects public health, fostering sustainable environmental conservation in Bac Lieu province.

2 Materials and methods

2.1 Site study: Bac Lieu province

Bac Lieu, strategically positioned along major routes like Quan Lo—Phung Hiep and the Southern bank of Hau River (see Fig. 1), serves as a pivotal hub for socio-economic development and maritime growth. The province experiences a tropical monsoon climate, featuring high temperatures and distinct seasonal changes. The Rainy Season spans from May to November, while the Dry Season occurs from December to April, exhibiting significant variations in temperature, rainfall, and hydrological patterns. Humidity levels in Bac Lieu fluctuate between 76.1 and 85.7% annually, peaking in September and declining in March. The region experiences two prevailing wind directions: the Northeast

Fig. 1 Location of Bac Lieu province (Vietnam). Reprinted from Wikimedia Commons [26] and Department of Construction of Bac Lieu province [27]
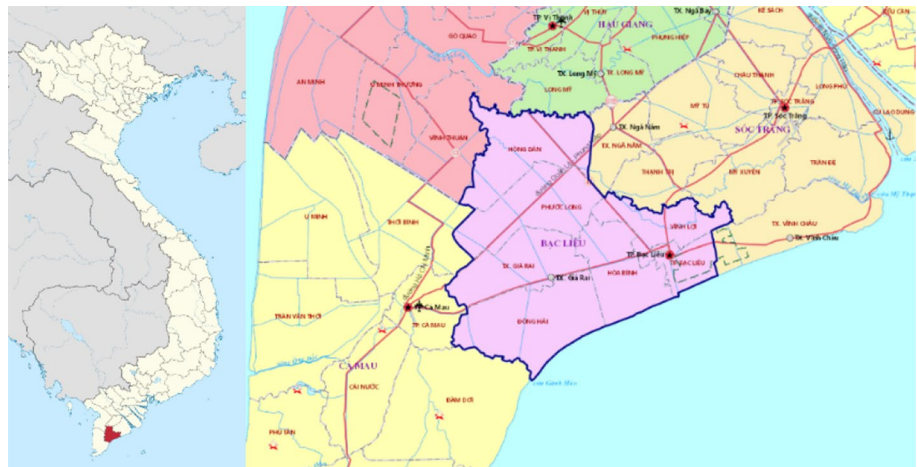
monsoon (during the dry season) and the Southwest monsoon (during the dry season). The Northeast-Southeast wind, dominant from October to April, peaks in February and March, significantly influencing the climate in the Mekong Delta region.

Bac Lieu, a vital hub for socio-economic development in Vietnam, strategically situated along major routes and the Southern bank of the Hau River, plays a crucial role in diverse industries, including handicrafts, agriculture, and aquatic product processing. The region's economic growth raises concerns about air quality and its potential impacts on the environment and public health. This research in Bac Lieu is essential to understanding the current state of air pollution, identifying sources, and evaluating associated health risks. By focusing on this specific region, the study aims to contribute region-specific insights for the development of effective air quality management strategies, aligning with governmental directives and ensuring relevance to broader environmental and health objectives. The implementation of a Provincial AQMP becomes imperative for proactively managing local environmental concerns, minimizing economic losses, and fostering ongoing ecosystem restoration in Bac Lieu province.

2.2 The process of developing an air quality management plan (AQMP)

The development of an AQMP involves a comprehensive approach integrated into an Air Quality Management System (AQMS). This system incorporates various technical and analytical tasks and comprises six key steps: setting goals, conducting a baseline air quality assessment, implementing the AQMS, formulating intervention strategies, executing action plans, and conducting evaluation and follow-up procedures.

Our air quality goal setting for Bac Lieu Province aligns with the National Plan on Air Environmental Quality Management (2023–2025), as specified in Decision No. 1973/QD-TTg dated November 23, 2021, which encompasses various strategic approaches. The Air Quality Goal Setting for Bac Lieu Province entails:

- Identification of Underlying Causes: Pinpoint the specific causes leading to concentration value breaches to facilitate targeted and effective solutions.
- Public Awareness and Monitoring: Implement automated urban air quality monitoring systems and maintain consistent public communication strategies to enhance community awareness.
- Emission Management: Ensure adherence to regulatory compliance by overseeing that 90% of regulated entities transmit monitoring data to the Department of Natural Resources and Environment as per regulatory guidelines.

- Pollution Control: Develop tailored interventions aimed at minimizing emissions from key sectors such as industries, traffic, agriculture, and residential activities to effectively mitigate pollution.
- Transportation Emission Control: Enforce stringent measures on major roads to achieve and maintain compliance with QCVN 05:2023/BTNMT.

The comprehensive framework of air quality management planning encompasses various stages, including baseline assessments, emission inventories, ambient air quality monitoring, identification of measures and control options, implementation strategies, evaluation of changes and impact trends, and subsequent follow-ups. Baseline assessments involve monitoring historical and current pollution data, considering temporal variations. Emission inventories focus on understanding sources, collecting data on production, consumption, and emissions, and modeling for trend estimation. Air quality monitoring establishes networks, ensures compliance, and identifies specific issues. Air quality modeling uses mathematical models like dispersion, impact, economic, and cost/benefit analyses to estimate air quality. It involves developing models, verifying them against data, and applying them to identify sources, establish emission-exposure relationships, and assess control strategies' impact.

2.3 Baseline air quality assessment

Conducting a baseline air quality assessment is critical for comprehending the existing state of air quality in the study area, identifying pollution sources, and establishing a foundation for developing the AQMP. This assessment involves the following key tasks:

2.3.1 Emissions inventory

Emission inventories form the backbone of any AQMP, serving as a comprehensive database outlining the nature and quantity of pollutants released into the atmosphere. Creating an emissions inventory involves categorizing pollution sources into point, mobile, and area sources, estimating emission factors, and calculating the total emissions for each pollutant. The investigation covered 41 entities, categorized into three groups. The first group, point sources, involved 27 subjects, including 2 medical waste incinerators, 2 solid waste landfill sites, 7 healthcare centers, and 16 industrial production facilities. The second group, mobile sources, included 7 entities comprising various transport hubs and ports. The third group, area sources, encompassed 7 locations, consisting of 5 solid waste landfill sites and 2 cooperative rice-growing farms. The survey focused on factors like operational status and environmental impact, presenting a

comprehensive overview of diverse sources contributing to environmental conditions in Bac Lieu Province.

The inventory process addresses diverse sources like open burning, cooking, and agriculture, following the United States Environmental Protection Agency (USEPA) guidelines [28] and reference materials like Document AP-42 [29], EMEP/CORINAIR [30], and emission inventory guidebooks. The emission factor, whether controlled or uncontrolled, determines the emission level based on the formula

$$E = A \times EF \tag{1}$$

Here, 'E' represents the emission rate, 'A' is tied to emission activities and sources, while 'EF' signifies the emission factor. The USEPA Document AP-42 provides these factors for various industries, agriculture [31], fuel emissions [32], and dust emissions.

Assessing emissions from specific sources like open burning and agriculture presents unique challenges due to the variability in combustion conditions, fuel types, and emission factors. Open burning, a common practice for waste disposal and land clearing in Bac Lieu, emits pollutants such as carbon monoxide (CO), particulate matter (PM), and volatile organic compounds (VOCs). However, obtaining precise emission factors for open burning is hindered by factors like the composition of materials burned (e.g., agricultural residues, biomass), combustion temperatures, and atmospheric conditions. Similarly, emissions from agricultural activities, including crop residue burning, vary depending on factors like crop type, field management practices, and weather conditions.

The bottom-up approach constructs a mobile source emission inventory, distinguishing between road motor vehicles (e.g., cars, commercial vehicles) and other mobile vehicles (e.g., boats, trains). The formula

$$E_{ij} = FC_j \times EF_{ij} \tag{2}$$

defines the emission rate of pollutant 'i' in road motor vehicles using fuel type 'j'. The European Environment Agency's documentation [33] and EMEP/CORINAIR [30] offer these emission coefficients. PM2.5 is aggregated from dust emission inventory results for mobile sources due to the negligible impact of coarse dust larger than 2.5 μm. For other mobile vehicles, the emission inventory incorporates water transport, agricultural machinery, and construction vehicles, following Document AP-42 [34, 35].

The emissions inventory uses Eqs. (3) and (4) for estimating emissions. Equation (3), denoted as

$$Em_{i,j} = \sum_j Fc_j \times EF_{i,j}, \tag{3}$$

represents the summation of emissions of pollutant 'i' from all types of road motor vehicles, considering the distinct fuel types and their corresponding emission factors. On the other hand, Eq. (4),

$$Em_{i, j, r} = Nv_j \times Mv_{j, r} \times e_{i,j,r}, \tag{4}$$

calculates the emissions of pollutant 'i' from other mobile vehicles, delineating the number of vehicles Nv_j, their mileage $Mv_{j, r}$, and the emission rate $e_{i,j,r}$ associated with the specific type of vehicle, fuel, and pollutant.

While Eq. (3) provides a simplified estimation, it may be overestimated due to the exclusion of emission reduction technologies. Equation (4), requiring specific data on emissions and vehicle details, enables a more complex estimation. This approach minimizes variables but increases uncertainty due to its dependence on fuel consumption data. For emissions estimation related to traffic, this study utilizes the ABC EIM Excel Workbook, guided by the Global Atmospheric Pollution Forum Air Pollutants Emission Inventory Manual [36] and IPCC Guidelines [37].

In assessing traffic emissions, accounting for variations in vehicle types and fuel quality is crucial for accurately quantifying pollutant emissions. The data provided on vehicle counts categorized by type and fuel offer valuable insights, but accurately estimating emissions requires detailed emission factors specific to different vehicle types and fuels. For example, older vehicles and those with outdated emission control technologies may emit higher levels of pollutants like nitrogen oxides (NOx) and particulate matter. Additionally, variations in fuel quality, such as sulfur content in diesel fuel, can significantly impact emissions of pollutants like sulfur dioxide (SO_2) and PM. Thus, understanding the vehicle fleet composition and fuel characteristics is essential for robust emission inventory development.

Despite these challenges, emission inventories in Bac Lieu province aim to comprehensively capture emissions from various sources, including point sources, mobile sources like road transport, and air sources such as waste burning and domestic cooking. However, uncertainties and limitations associated with data availability, emission factors, and modeling methodologies must be acknowledged. Emission factors were obtained from internationally recognized databases, scientific literature, and local studies, ensuring relevance to Bac Lieu's context. The emissions inventory covered major pollutants, including carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter (PM10 and PM2.5), volatile organic compounds (VOCs), and ammonia (NH_3).

2.3.2 Ambient air quality monitoring

In assessing the air quality of Bac Lieu province comprehensively, this study analyzed data collected from

ambient air monitoring sessions spanning 2014–2021. Utilizing information from local air quality monitoring programs, the study focused on 11 ambient air locations and five emission sites of production facilities in Bac Lieu province. Figure 2 illustrates the diverse sampling locations, covering areas influenced by traffic, industry, craft villages, and daily activities.

The data, sourced from the Department of Natural Resources and Environment (DONRE), covered key pollutants such as CO, SO_2, NO_2, PM10, PM2.5, VOCs, and NH_3. Monitoring stations were strategically chosen based on factors like population density, traffic flow, industrial activities, and wind directions. The collected data validated the emissions inventory, identified pollution hotspots, and analyzed spatial and temporal variations in air quality. Meteorological parameters were also recorded for a comprehensive understanding of pollutant dispersion patterns. In 2023, two monitoring phases, covering 63 points, were conducted to assess current conditions and anticipate changes in air quality, focusing on parameters like SO_2, CO, NO_2, TSP, PM10, PM2.5, and Pb.

2.4 Air quality modeling

The AERMOD application portrays alterations in air quality through mapped pollutant concentrations across Bac Lieu province. Validated for accuracy by comparing model results with actual monitoring data, adjustments are made based on observed and modeled data discrepancies. Detailed procedures for using AERMOD are outlined in Fig. 3, followed by a comparison against National Technical Regulation on Air Quality thresholds.
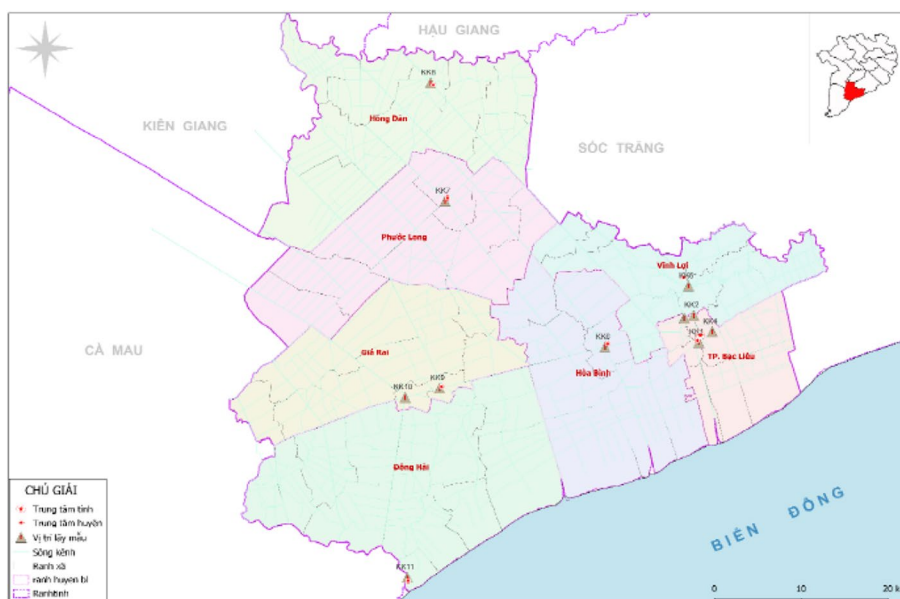
2.5 Assessing air quality and health impact with the AirQ + model in Bac Lieu Province

This study proposes the utilization of the AirQ + model to understand the correlation between air quality and human health. Complying with World Health Organization (WHO) guidelines [38], the investigation utilizes air environment monitoring data, hospital patient surveys, and household questionnaires in Bac Lieu province. Data for assessing air pollution's health impact in Bac Lieu province was collected via hospital statistics and local health facilities, analyzing admissions and mortality rates. Air pollution-health correlations were studied, using air quality data and the AirQ + model to evaluate health effects. Population demographics and health records from provincial authorities informed the analysis. Concurrently, structured household questionnaires gathered residents' perceptions of air quality and health status.

Information encompassing air quality monitoring, patient survey data related to respiratory and cardiovascular diseases, population statistics, and environmental assessments was gathered from 2017 to 2021. The study aims to reveal the short-term effects of PM10 and NO_2 parameters on respiratory and cardiovascular diseases, estimating potentially avoidable cases under Scenario 1 (based on WHO Air Quality Guidelines) and Scenario 2 (based on QCVN 05:2023/BTNMT standards).
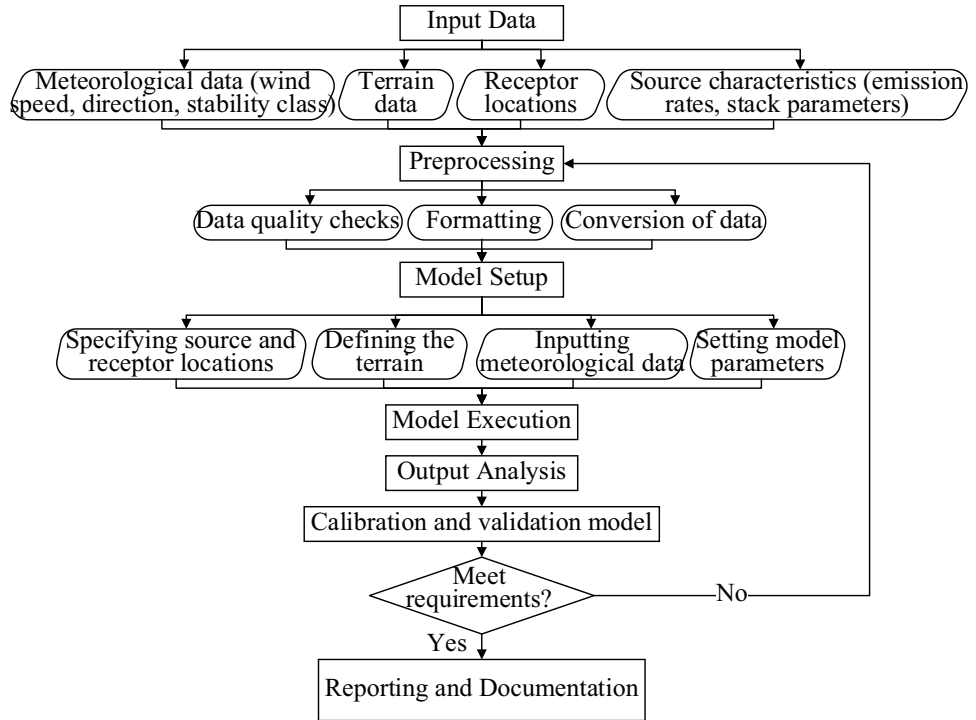
The differences between two scenarios in terms of disease incidence patterns have significant implications for public health management. In Scenario 1, where WHO guidelines are applied, notably higher levels of PM10 and NO_2 are associated with increased respiratory and cardiovascular disease cases compared to Scenario 2. This indicates that

Fig. 2 Sampling Locations in Bac Lieu Province: 11 Sites Affected by Traffic, Industry, Craft Villages, and Population Daily Activities
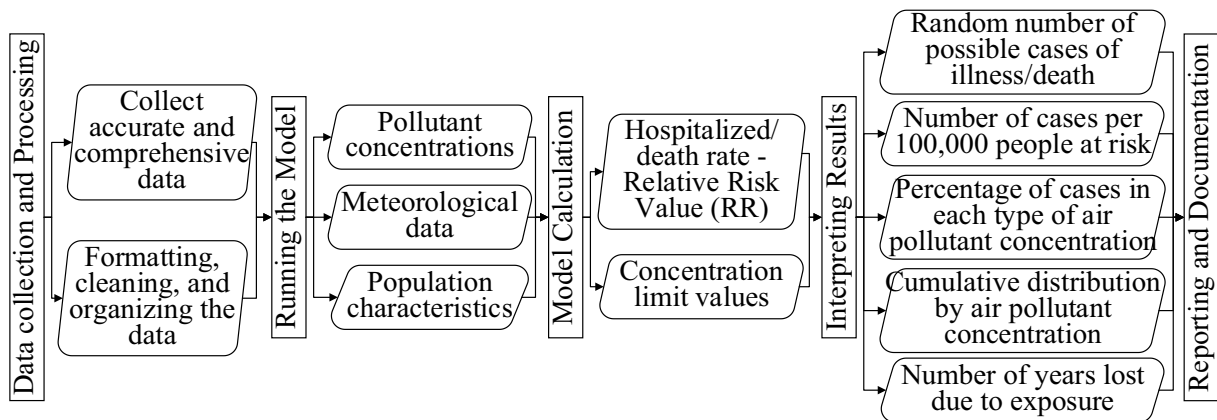
Fig. 3 Flowchart of AERMOD dispersion model

Input Data

Meteorological data (wind speed, direction, stability class) — Terrain data — Receptor locations — Source characteristics (emission rates, stack parameters)

Preprocessing

Data quality checks — Formatting — Conversion of data

Model Setup

Specifying source and receptor locations — Defining the terrain — Inputting meteorological data — Setting model parameters

Model Execution

Output Analysis

Calibration and validation model

Meet requirements? — No

Yes

Reporting and Documentation

adherence to stricter international standards may lead to more conservative estimates of disease incidence, potentially underestimating health risks. Conversely, Scenario 2, based on national standards, suggests lower disease incidence rates, which might give a false sense of security regarding public health impacts. These disparities underscore the importance of harmonizing standards and adopting more stringent regulations to better protect public health from the adverse effects of air pollution.

The comprehensive procedure is detailed in Fig. 4, illustrating the step-by-step process used in the analysis linking PM10 and NO_2 with health outcomes.

This study emphasizes the correlation between air pollution and public health, utilizing the AirQ + model to assess respiratory and cardiovascular diseases. However, the paper lacks specific details on data collection methodologies and validation processes for health data from the Department of Health and statistical yearbooks. To ensure the reliability and representativeness of health data, transparent reporting practices and cross-validation with independent sources are essential, warranting further attention in future research and policy interventions.

Data collection and Processing

Collect accurate and comprehensive data

Formatting, cleaning, and organizing the data

Running the Model

Pollutant concentrations

Meteorological data

Population characteristics

Model Calculation

Hospitalized/ death rate - Relative Risk Value (RR)

Concentration limit values

Interpreting Results

Random number of possible cases of illness/death

Number of cases per 100,000 people at risk

Percentage of cases in each type of air pollutant concentration

Cumulative distribution by air pollutant concentration

Number of years lost due to exposure

Reporting and Documentation

Fig. 4 Mapping the AirQ + model process

3 Results and discussion

3.1 Current status of air quality in Bac Lieu province

3.1.1 Results of air emission inventory

Figure 5 presents the average concentrations of various air quality parameters, including TSP, PM10, NO_2, and SO_2, across the years 2017 to 2021. In 2017, TSP levels were relatively high at 143.55 μg/m³, while PM10, NO_2, and SO_2 concentrations were moderate. Over the years, there were fluctuations in the values, with a significant decrease in TSP in 2018. However, 2021 saw a notable increase in TSP, PM10, and NO_2. The average population across these years ranged from 894.3 to 918.51 thousand people, showing a stable demographic context.

Based on investigative, survey, and collected data, the task of calculating emissions for cooking and living activities with low, medium, and high emission options is undertaken using the ABC EIM Excel Workbook [36]. Figure 6 presents the results of calculating emissions loads for administrative units, with population data sourced from the 2022 statistical yearbook.

Figure 7 covers both on-road and off-road transport, including light vehicles, heavy vehicles, and motorcycles, alongside non-road transport like civil aviation and marine transport. Road vehicles, including cars, commercial vehicles, buses, and motorcycles, significantly contribute to air pollution by emitting PM, ozone precursors (CO, NOx, NMVOC), greenhouse gases (CO_2, CH_4, N_2O), and acidifiers (NH_3, SO_2).

In Fig. 7c, f, Motorbikes exhibit high pollutant levels, particularly CO and PM10. Cars generally show lower emissions, but still contribute, while buses and heavy trucks demonstrate lower emissions but significant NOx contributions
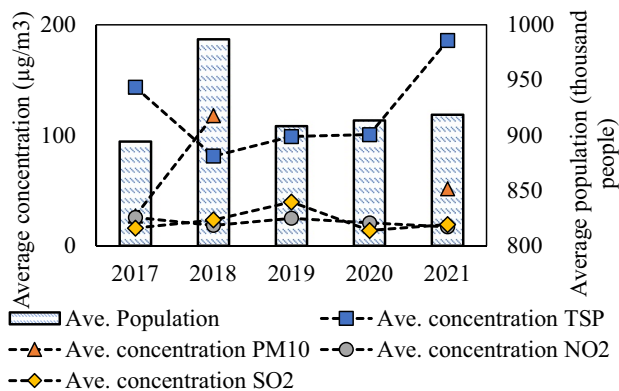
(see Fig. 7b). The data underscores the need for cleaner transportation options, emission control technologies, and stricter regulations to mitigate air pollution. Addressing vehicle-specific impacts is crucial for improving urban air quality and reducing associated health risks. Furthermore, including off-road transport modes highlights the necessity for holistic strategies to tackle air pollution across all sectors.

3.1.2 Comprehensive analysis of air quality in Bac Lieu province: monitoring data and trends (2014–2023)
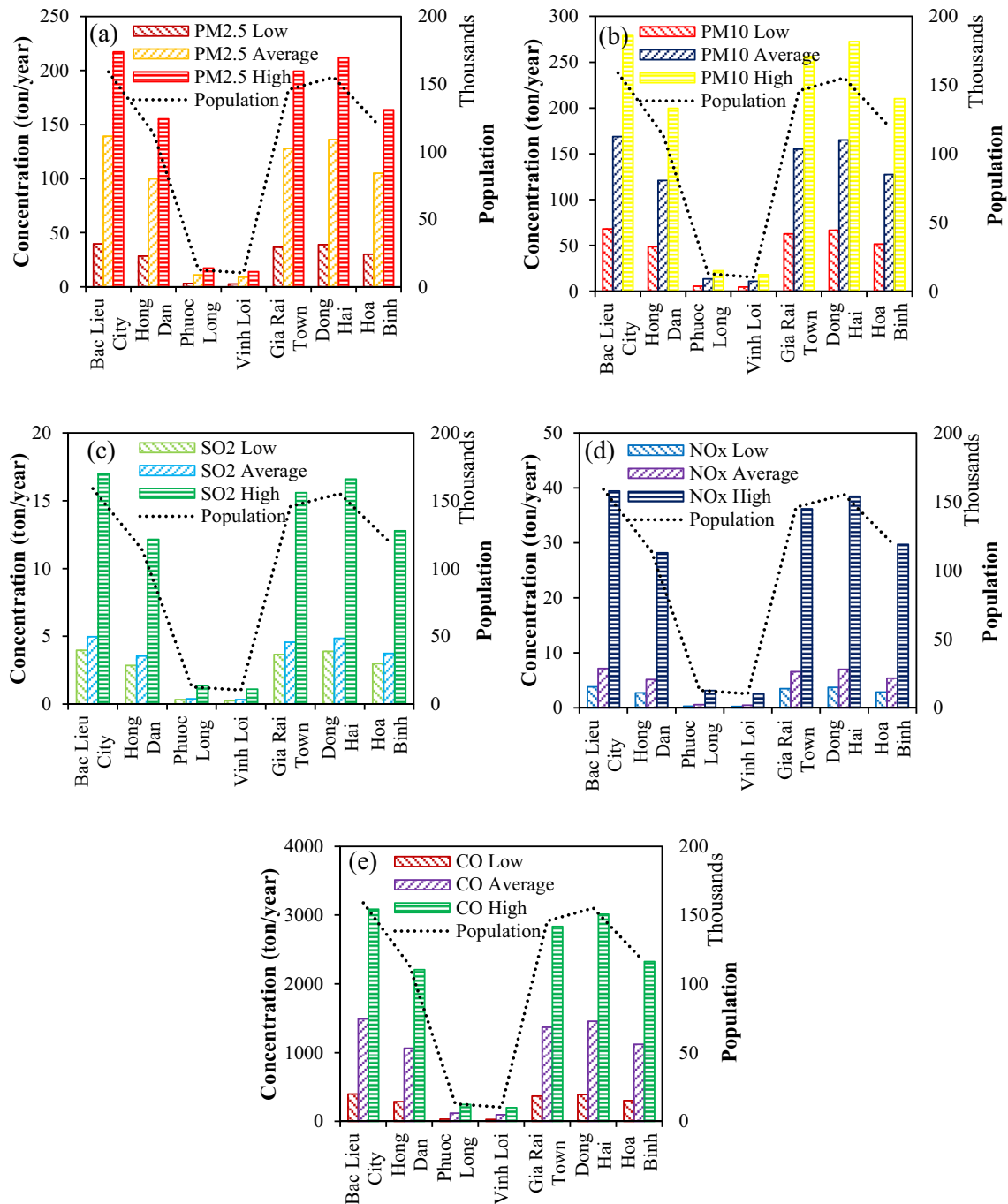
To comprehensively assess the current state and trends in air quality within Bac Lieu province, an analysis was conducted involving data compilation from air environment monitoring sessions spanning from 2014 to 2021. Simultaneously, it aimed to assess the contemporaneous state of the air environment on an annual basis. Additionally, for an improved assessment of the current condition and future changes in air quality, two monitoring phases were conducted in 2023 across 63 monitoring points. The focus was on parameters such as SO_2, CO, NO_2, Total Suspended Particles (TSP), PM10, PM2.5, and lead (Pb). The air environment monitoring activities occurred biannually, conducting observations twice per year (Phase 1 and Phase 2).

Table 1 provides a summary of air quality monitoring data in Bac Lieu province, covering various pollutants and monitoring periods. It outlines concentrations, compliance with standards, and notable observations for each pollutant. Further details and analysis are elaborated upon in the subsequent content.

(a) TSP

TSP assessment in Bac Lieu province's air quality (2014–2021) revealed variable concentrations from 2 to 550 μg/m³, with some sites exceeding QCVN 05:2023/BTNMT limits. Notably, Ganh Hao and Gia Rai surpassed limits in 2014, especially during dry periods; Vinh Loi exceeded standards in 2016–2017. Most areas stayed below 160 μg/m³ in 2018–2019. Bac Lieu City peaked in 2020, and 2021 exhibited notable spikes, particularly during dry seasons.

The spikes in TSP concentrations, particularly in Bac Lieu City during 2021, may stem from rapid urban development, intensified vehicular activity, and dry meteorological conditions. Construction-related dust, increased traffic emissions, and wind patterns exacerbate particulate matter dispersion. These factors, combined with industrial and agricultural activities, contribute to elevated TSP levels. These findings highlight the necessity for ongoing monitoring and regulatory measures to address air pollution in urban areas like Bac Lieu City.

Fig. 5 Annual average concentrations of air quality parameters and population in Bac Lieu Province (2017–2021). Source: [39, 40]

Fig. 6 Emissions load of **a** PM2.5, **b** PM10, **c** SO$_2$, **d** Nox, and **e** CO by different locations in Bac Lieu Province

Monitoring data for 2023 displayed TSP concentrations within allowable limits. Both phases recorded values ranging from 120 to 284 μg/m^3 and 120–260 μg/m^3, respectively. Bac Lieu City and Gia Rai town reported higher TSP concentrations (250–280 μg/m^3) due to intense vehicular activity and rapid urban development, including construction-related dust generation.

(b) SO$_2$

The SO$_2$ assessment in Bac Lieu province from 2014 to 2021 consistently met QCVN 05:2023/BTNMT limits. Concentration fluctuations were observed initially, peaking in 2014 and 2015 in Hoa Binh town and Bac Lieu city, respectively. By 2016, levels in both areas were similar. From 2017 to 2021, concentrations remained below 100 μg/m^3, indicating reduced emissions and a positive downward trend.
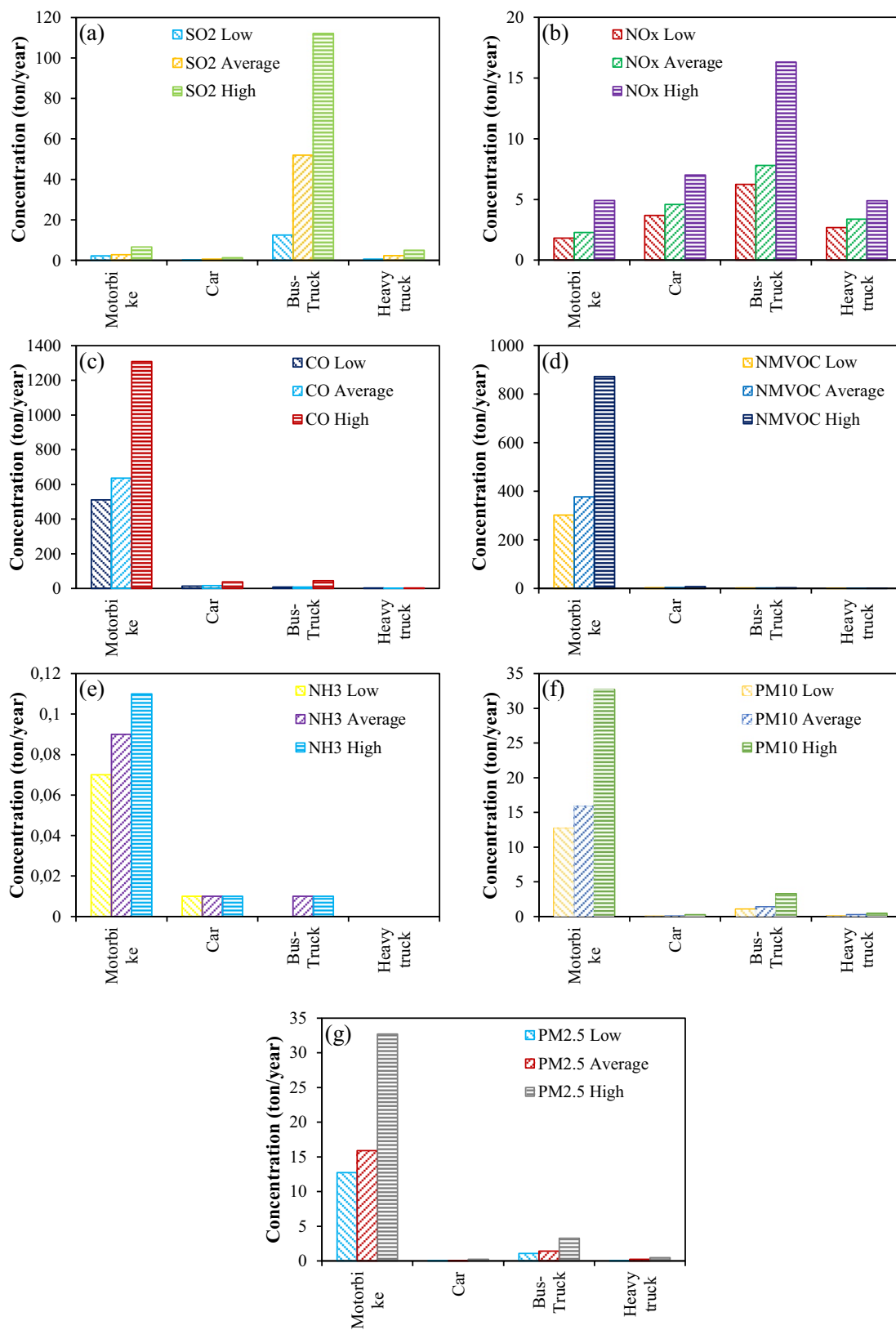
Fig. 7 Comparison of pollutant emissions from different vehicle types

Table 1 Bac Lieu province air quality monitoring data

Pollutant	Monitoring period	Concentrations ($\mu g/m^3$)	Compliance with standards	Observations
TSP	2014–2021	2–550	Not always	Higher during dry seasons, decreasing trend overall
SO_2	2014–2021	Below 100	Yes	Reduced emissions trend
CO	2014–2021	2000–15,000	Yes	Surged during dry seasons, declined post-2021 interventions
NO_2	2014–2021	Below 100	Yes	Fluctuations within limits, possible decline post-2018
Lead	2014–2021	<0.0002	Yes	Detected only in 2016–2017, negligible levels
PM2.5	2021	Below 40	Yes	Seasonal fluctuations, generally compliant
PM10	2017, 2021	Below 100	Yes	Decreasing trend, occasional exceedances in 2017

In 2023, monitoring revealed SO_2 concentrations within 55–152 $\mu g/m^3$ (Phase 1) and 51–153 $\mu g/m^3$ (Phase 2), below the QCVN 05:2023/BTNMT threshold (350 $\mu g/m^3$). Across the province, concentrations ranged from 50 to 150 $\mu g/m^3$, complying with standards, except in Bac Lieu city and Phuoc Long district, surpassing 100 $\mu g/m^3$. Elevated SO_2 levels in Bac Lieu City and Phuoc Long district in 2023 may stem from traffic emissions, industrial activities, domestic practices, and inadequate waste management. Bac Lieu City's dense urban setting likely intensifies vehicle exhaust emissions, while industrial and household activities contribute to SO_2 release. Phuoc Long's lacking waste management measures could result in open burning of sulfur-containing waste. Additionally, local geographical factors may exacerbate SO_2 dispersion. Additionally, 2023 monitoring data remain below set limits, with specific areas showing elevated SO_2 levels due to distinct local influences.

(c) CO

From 2014 to 2018, CO levels in Bac Lieu province stayed notably below QCVN 05:2023/BTNMT. Concentrations fluctuated annually, peaking at various locations such as 9000 $\mu g/m^3$ in Gia Rai town (dry season, 2014) and 8000 $\mu g/m^3$ in Bac Lieu City (rainy season, 2014). Subsequent years showed varied levels like 6000–7000 $\mu g/m^3$ (dry season, 2015) and 5000–6000 $\mu g/m^3$ (rainy season, 2015) in Bac Lieu City. However, during the 2019–2020 dry seasons, CO surged province-wide to 5000–15,000 $\mu g/m^3$, particularly peaking above 10,000 $\mu g/m^3$ in the Ganh Hao area. This rise might relate to shrimp farming and increased transport. Following 2021's environmental interventions, CO levels declined to 2000–5000 $\mu g/m^3$, well below regulations. In 2023, monitoring data indicated CO concentrations between 4890 and 6670 $\mu g/m^3$ (Phase 1) and 4910–6580 $\mu g/m^3$ (Phase 2), below the 30,000 $\mu g/m^3$ limit, ensuring compliance. These interventions could include regulatory measures aimed at reducing emissions from sources such as transportation and agriculture. Additionally, public awareness campaigns promoting cleaner practices may have played a role. In summary, CO levels in Bac Lieu province stayed within acceptable limits (5000–6500 $\mu g/m^3$) across monitoring periods, complying with QCVN 05:2023/BTNMT.

(d) NO_2

The NO_2 concentration evaluation in Bac Lieu province from 2014 to 2021 showcased compliance with QCVN 05:2023/BTNMT. Initially, in 2014, concentration levels were mostly below standard, except along National Highway 1A in Hoa Binh town during the dry season. Subsequent years showed fluctuations within limits, and from 2018 to 2021, NO_2 levels consistently remained below 80 $\mu g/m^3$. NO_2 concentrations in Bac Lieu province decreased from 2014 to 2021, possibly due to improved energy management, waste treatment, and regulatory measures. Advancements in technology, public awareness efforts, urban planning strategies, and natural factors like climate variations likely contributed. Elevated NO_2 levels in 2023 were seen in traffic-heavy zones and industrial parks but remained within permissible limits. Bac Lieu province predominantly recorded NO_2 concentrations below 100 $\mu g/m^3$, except in specific areas in Bac Lieu City and Phuoc Long town.

(e) Lead

Lead, a highly toxic element commonly found in diesel fuels, poses severe health risks upon exposure, primarily damaging the nervous system. From 2014 to 2021, lead was detectable only during two monitoring periods, registering levels below 0.0002 $\mu g/m^3$ in 2016 and 2017. No further monitoring or analysis occurred during these years, while the remaining periods showed either undetectable amounts or insignificant levels of lead (<0.1 $\mu g/m^3$). One possibility for the lack of lead presence is the combustion of leaded gasoline, which was once commonly used in vehicles before being phased out due to its harmful effects on health and the environment. Industrial activities such as metal processing or waste incineration may have also

released lead into the air during these years. Additionally, natural sources like volcanic eruptions or soil erosion can contribute to atmospheric lead levels. In 2023, no significant lead detection was observed during two monitoring periods, indicating levels below 0.1 μg/m^3 or registering as undetectable.

(f) PM2.5

PM2.5 indicates fine dust, tiny particles under 2.5 micrometers, poses health risks by affecting the lungs. Monitoring occurred exclusively in 2021. During the 2021 dry season, Bac Lieu City and Hoa Binh district showed heightened PM2.5 concentrations (40–48 μg/m^3) pose increased health risks, particularly affecting the lungs. Despite being under QCVN 05:2023/BTNMT limits, other areas remained below 40 μg/m^3. In the rainy season, concentrations decreased, mainly in Bac Lieu City (30–60 μg/m^3), suggest improved air quality and reduced health risks. In 2023, PM2.5 levels were consistently below 10 μg/m^3 across all areas, well under the 50 μg/m^3 standard threshold. Fluctuations were minimal, ranging from 0 to 7 μg/m^3 for both monitoring periods.

(g) PM10

PM10, fine dust particles ≤ 10 micrometers, significantly contribute to air pollution and health risks. Monitoring occurred only in 2017 and 2021. In 2017, Hoa Binh and Vinh Loi districts exceeded QCVN 05:2023/BTNMT with levels of 150–170 μg/m^3. By 2021, PM10 levels decreased in which Bac Lieu City and Hoa Binh district were 70–100 μg/m^3 (below standards), others below 70 μg/m^3. Rainy seasons saw lower levels, except in a few Bac Lieu City. In 2023, PM10 concentrations remained below 100 μg/m^3. Phase 1 and 2 monitoring revealed concentrations of 0–12 μg/m^3 and 0–11 μg/m^3, respectively.

The detailed assessment of Bac Lieu province's air quality from 2014 to 2023, with concentration trends and compliance status, will be provided in Table S1 in the supplementary materials.

3.1.3 Air quality assessment using AERMOD model in Bac Lieu province

Following data collection, the AERMET tool is utilized to process surface and vertical structure meteorological data, which is crucial for the model's computations. The model operates under flat terrain conditions due to the province's even landscape, employing the VN-2000 coordinate system aligned with Bac Lieu's meridian axis. Once the input data is established, the AERMOD model calculates the concentration distribution of exhaust gases—TSP or PM10, NO$_2$, CO, and SO$_2$—over 365 days, outputting hourly average concentration results. The emission concentration distribution is visualized in Fig. 8.
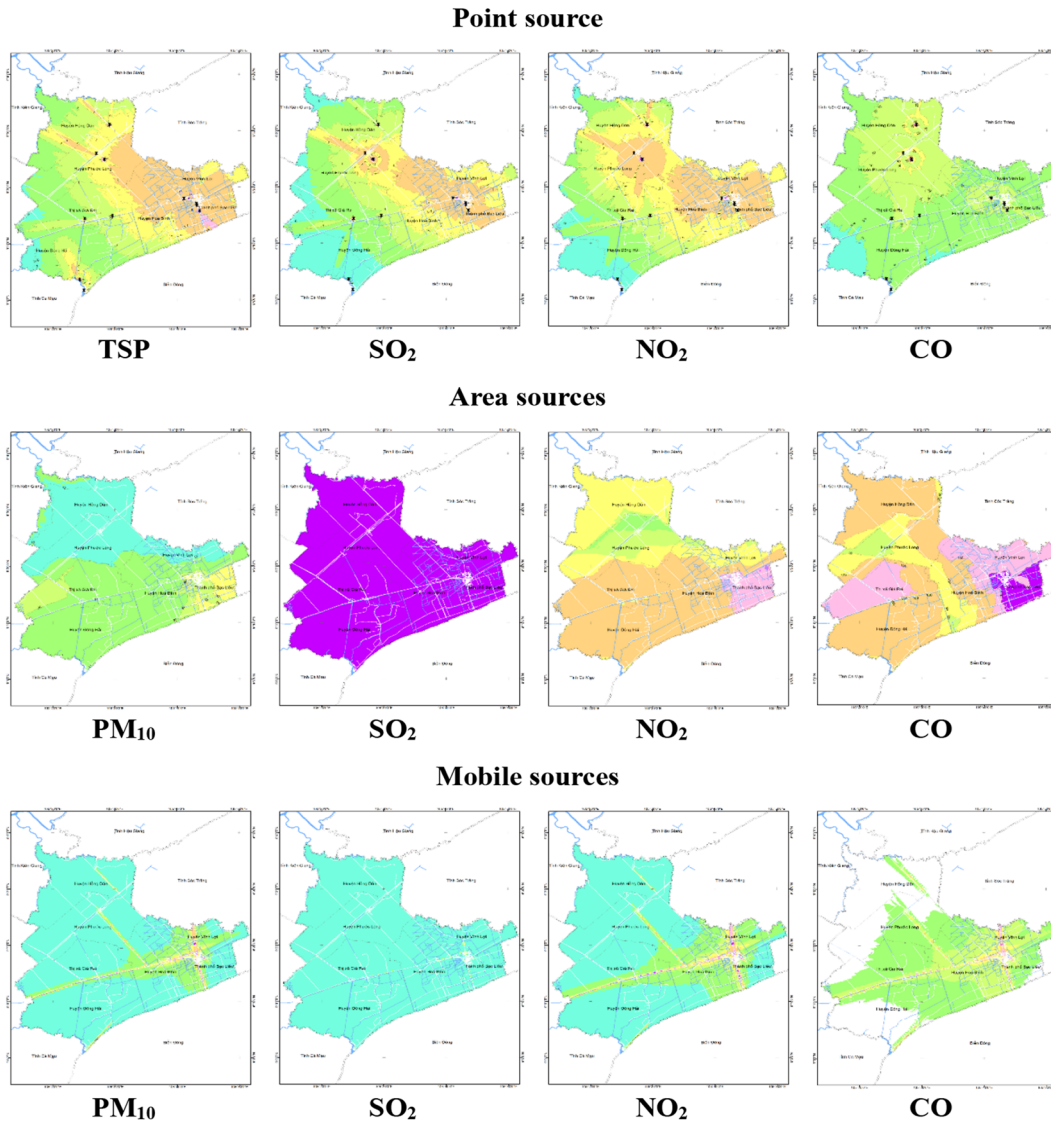
Utilizing the AERMOD model, the study examined emission concentration distributions of TSP, NO$_2$, CO, and SO$_2$. Point sources insignificantly impacted broad provincial areas, with higher CO concentrations in specific districts. Household activities contributed to CO and PM10, with notable concentrations in Bac Lieu city. Vehicles primarily influenced CO, NO$_2$, and PM10 emissions, with concentrations near roads approaching limits. The model highlighted regional variations in gas and dust concentrations, notably in Bac Lieu City and Vinh Loi district.

The emission sources primarily affect their immediate vicinity due to their limited discharge flow. For instance, point emission sources release pollutants like TSP, NO$_2$, CO, and SO$_2$ insignificantly below 6 μg/m^3 within Bac Lieu Province, having a minimal impact on a broader provincial scale. Notably, areas like Hong Dan and Phuoc Long districts show higher CO gas concentrations (10–30 μg/m^3), possibly due to increased vehicle density and the expansion of agricultural areas.

Assessing Bac Lieu Province's air quality associated with household activities using the AERMOD model revealed hourly exhaust pollutant concentrations, spatially represented in Fig. 4 as area sources. PM10 from household activities ranged from 10 to 30 μg/m^3 province-wide, peaking in Bac Lieu city. NO$_2$ emissions were notably low, below 2 μg/m^3 province-wide. CO emissions varied from 80 to 350 μg/m^3, peaking in Bac Lieu city (200–350 μg/m^3), Gia Rai town, and Vinh Loi district. SO$_2$ emissions were negligibly low, below 2 μg/m^3 across the province. Household activities are notable sources of CO emissions, followed by PM10, whereas NO$_2$ and SO$_2$ exhibit minimal dispersion.

The model also calculated exhaust pollutant concentrations in mobile sources, offering hourly averages and emissions representation in Fig. 8. PM10 from vehicles measured 10–30 μg/m^3 province-wide. Areas near roads hit 50–100 μg/m^3, nearing QCVN 05:2023/BTNMT limits. NO$_2$ from vehicles stayed under 10 μg/m^3, but near roads, it ranged 30–100 μg/m^3, within QCVN 05:2023/BTNMT limits. CO emissions varied 100–1000 μg/m^3 province-wide. Near roads, they reached 1000–10,000 μg/m^3 but stayed below limits. SO$_2$ from vehicles spanned 10–30 μg/m^3 province-wide, with road-adjacent areas at 50–100 μg/m^3, below limits. In summary, vehicles mainly impact CO emissions near major routes. Regions like Bac Lieu City and Vinh Loi district show higher concentrations of gases and dust compared to other areas.

Phan et al. [41] reported significant variations in PM concentrations among different sampling sites within HCMC. PM10 and PM2.5 concentrations were observed to be higher on roads and at roadsides, correlating strongly with vehicular

Point source

TSP **SO₂** **NO₂** **CO**

Area sources

PM₁₀ **SO₂** **NO₂** **CO**

Mobile sources

PM₁₀ **SO₂** **NO₂** **CO**

Fig. 8 Emission concentration distributions from point, area, and mobile sources in Bac Lieu Province by AERMOD dispersion model

activity. Overall, PM concentrations varied among the sampling sites in the order of city zoo < rural area < residential area < roadside < city road. The average PM10 concentrations during the 2014 rainy season and 2015 dry season were 131.77 ± 42.13 μg m^{-3} and 233.13 ± 79.88 μg m^{-3}, respectively.

3.2 Air quality and public health

3.2.1 Public health impact assessment using the AirQ+ model

The prevalence of respiratory and cardiovascular diseases in Bac Lieu province during the period from 2017 to 2021, as reported by the ICD 10 statistics obtained from the Department of Health [42], is shown in Fig. 9. Population data for
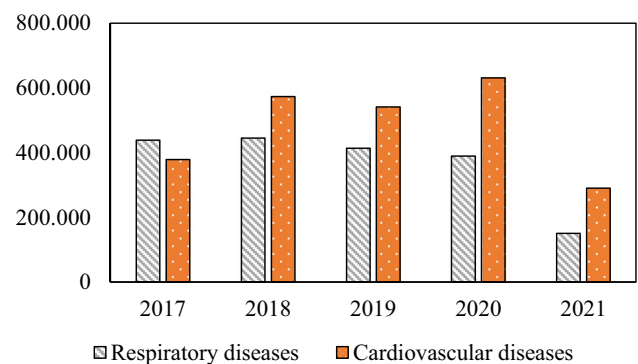
Fig. 9 Number of cases of respiratory and cardiovascular diseases in Bac Lieu province. *Source*: DOH [42]

Bac Lieu province during the same timeframe were derived from the provincial statistical yearbooks [43].

In Fig. 9, there is a significant decline in cases from 2020 to 2021 for both types of diseases. This sharp decrease could be attributed to various factors, including improved healthcare infrastructure, public health interventions such as vaccination campaigns, changes in lifestyle factors, or even the impact of external factors like air pollution or infectious diseases.

The decline in respiratory disease cases could be related to improved air quality, increased awareness about respiratory health, or better management of respiratory conditions. Similarly, the decrease in cardiovascular disease cases could be due to better control of risk factors such as hypertension, diabetes, and obesity, as well as advancements in medical treatments and interventions.

Additionally, the Bac Lieu province's Department of Health records for 2022 and the initial half of 2023 illustrate the link between air quality and public health, with 372,598 respiratory and 300,827 cardiovascular disease cases, resulting in 50 and 69 deaths, respectively. The initial analysis indicates that is not statistically linear correlation (Sig. > 0.05) between air pollutants and these diseases, implying a lack of substantial impact on hospitalization rates (see Table 2).

The statistical analysis presented in Table 2 reveals some correlations that, while not statistically significant (Sig. > 0.05), still provide valuable insights into the complex relationship between air pollutants and health outcomes. The significant correlations were observed between TSP and various pollutants, including strong negative correlations with Respiratory Diseases (ResDis) (-0.805, $p = 0.100$) and PM10 (-0.778, $p = 0.432$). ResDis exhibited notable negative correlations with TSP (-0.805, $p = 0.100$) and positive correlations with CO (0.594, $p = 0.291$). CO showed a positive correlation with SO_2 (0.594, $p = 0.291$) and a negative correlation with PM10 (-0.451, $p = 0.702$). Cardiovascular Diseases (CarDis) had a significant positive correlation with CO (0.754, $p = 0.457$) and a negative correlation with NO_2 (-0.533, $p = 0.356$). These findings contribute to a comprehensive understanding of air quality dynamics in the

Table 2 Correlation analysis table of air pollution concentration and number of hospitalized patients in the period 2017–2022

	TSP	ResDis	CO	CarDis	NO$_2$	SO$_2$	PM10
TSP							
Pearson correlation	1	−0.805	0.344	−0.348	−0.250	−0.345	−0.778
Sig. (2-tailed)		0.100	0.571	0.566	0.685	0.570	0.432
N	5	5	5	5	5	5	3
ResDis							
Pearson correlation	−0.805	1	−0.537	−0.256	0.567	0.182	0.275
Sig. (2-tailed)	0.100		0.351	0.678	0.319	0.769	0.823
N	5	5	5	5	5	5	3
CO							
Pearson correlation	0.344	−0.537	1	0.181	0.259	0.594	−0.451
Sig. (2-tailed)	0.571	0.351		0.770	0.674	0.291	0.702
N	5	5	5	5	5	5	3
CarDis							
Pearson correlation	−0.348	−0.256	0.181	1	−0.533	0.062	0.754
Sig. (2-tailed)	0.566	0.678	0.770		0.356	0.921	0.457
N	5	5	5	5	5	5	3
NO$_2$							
Pearson correlation	−0.250	0.567	0.259	−0.533	1	0.511	−0.595
Sig. (2-tailed)	0.685	0.319	0.674	0.356		0.379	0.594
N	5	5	5	5	5	5	3
SO$_2$							
Pearson correlation	−0.345	0.182	0.594	0.062	0.511	1	0.985
Sig. (2-tailed)	0.570	0.769	0.291	0.921	0.379		0.111
N	5	5	5	5	5	5	3
PM10							
Pearson correlation	−0.778	0.275	−0.451	0.754	−0.595	0.985	1
Sig. (2-tailed)	0.432	0.823	0.702	0.457	0.594	0.111	
N	3	3	3	3	3	3	3

region, acknowledging that disease trends are influenced by multifaceted factors beyond pollution levels alone.

3.2.2 Scenarios analysis

In Scenario 1, PM10 exposure in 2018 correlates with peaks in respiratory (982,629 cases) and cardiovascular diseases (1,266,085 cases), constituting 24.7% of respiratory cases and highest for cardiovascular diseases in 2019 (133,567 cases, 2.61%). NO$_2$ concentration in 2017 relates to 107,645 respiratory cases (2.74%) and the highest cardiovascular cases in 2019. Scenario 2 highlights PM10 exposure in 2018, causing 678,639 respiratory cases (17.06%) and 874,404 cardiovascular cases. TSP exposure in 2017 corresponds to 444,696 respiratory cases (11.33%), and the highest cardiovascular cases in 2021 (547,620 cases, 21.09%) based on QCVN 05:2023/BTNMT. These findings from the AirQ + model delineate the discernible impact of air quality on public health in Bac Lieu province from 2017 to 2021 in terms of frequency and magnitude of influence (see Fig. 10).

4 Conclusions

In summary, Bac Lieu province generally maintains a stable air environment quality, exhibiting low pollution parameters by QCVN 05:2023/BTNMT standards. However, the province's air pollution levels are subject to variation due to multiple factors, including seasonal changes, weather patterns, and human activities such as traffic, industry, and agriculture. Notably, the dry season witnesses elevated pollution levels attributed to agricultural dust and smoke, while the rainy season mitigates pollution due to rain's purifying effect. The primary sources of air pollution primarily stem from surface activities like domestic cooking and open burning, contributing relatively higher CO emissions but generally conforming to QCVN 05:2023/BTNMT. Bac Lieu City

Fig. 10 Disease incidence patterns in Bac Lieu Province (2017–2021) under air quality scenarios

displays the highest pollution concentration, with transportation activities, especially motorbikes, significantly contributing to emissions.

Climatic conditions directly impact air quality, with temperature, humidity, wind speed, and precipitation influencing pollutant dispersion. Seasonal variability in pollution levels, affected by agricultural and industrial activities, underscores the need for targeted management strategies. The The utilization of the AirQ + model underscores the tangible influence of air quality on public health in Bac Lieu province from 2017 to 2021, revealing distinct correlations between pollutant concentrations and the prevalence of respiratory and cardiovascular diseases. These findings elucidate the intricate relationship between air pollution levels and the frequency and severity of respiratory and cardiovascular health issues within the province, emphasizing the critical role of air quality management in safeguarding public health. Management agencies focus on implementing measures to mitigate pollution effectively, including refining regulations, promoting technological advancements, and advocating for eco-friendly practices.

Future strategies aim to enhance air quality management through regulatory refinement, technological advancements, and educational initiatives. The multifaceted approach aims to raise awareness and proficiency in air quality management, contributing to sustained improvements in Bac Lieu province's air quality from 2023 to 2025. The AirQ + model used for air quality assessment in Bac Lieu has limitations, relying on accurate data and assuming linear pollutant-health relationships. It overlooks non-linearities and socioeconomic factors, impacting result accuracy. Despite limitations in the AirQ + model and uncertainties in data and methodologies, the proposed strategies align with key findings and aim to address identified pollution sources, emphasizing public health and environmental sustainability.

Availability of data and materials Data available within the article or its supplementary materials. Other data available on request due to privacy/ethical restrictions.

Declarations

Conflict of interest All authors declare that they have no conflict of interest.

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