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CLIMATE-RESPONSIVE ENVIRONMENTAL MONITORING IN SUSTAINABLE MANAGEMENT OF AIR QUALITY AND POLLUTION

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Background. Air pollution is a significant threat to human health and the global environment. In the context of climate change, air pollution is becoming increasingly severe and challenging to control. In regions with harsh climates, such as Nghe An Province (Vietnam), controlling air pollution becomes even more difficult. Climate change has accelerated the formation of ozone (O_3), prolonged the retention time of pollutants in the air, and increased the risk of forest fires, leading to the dispersion of particulate matter and other impacts. Appropriate air quality management measures are necessary to ensure that the air environment of Nghe An Province meets national standards.

Purpose. This study aims to examine the current level of air pollution in Nghe An Province by analysing monitoring data and air quality management policies. The air quality monitoring data will be compared with Vietnam's National Technical Regulation on Air Quality (QCVN 05:2023/BTNMT) to assess the pollution status. The study also proposes sustainable air quality management solutions tailored to climate change in Nghe An Province, addressing both the short-term and long-term implications.

Findings. The study used data from 119 air quality monitoring points across Nghe An Province, with areas including rural, urban, industrial, construction, mining, landfill, traffic, and tourist areas. An analysis of the concentrations of pollutants such as SO_2, CO, NO_2, and Total Suspended Particulates (TSP) showed that Nghe An's air quality was good, with most indicators remaining within the safe limits prescribed by QCVN 05:2023/BTNMT. However, some monitoring points recorded values that exceeded the permissible threshold. Of the 119 monitoring points, seven exceeded the limit for TSP (accounting for 5.9%). The TSP concentration fluctuated from 111 $\mu g/Nm^3$ to 432 $\mu g/Nm^3$ during the study period. Although the province has directed efforts toward air quality management, several bottlenecks remain, including the limited application of modern technology and the inadequate management of agricultural waste burning. To ensure sustainable development under climate change, several air quality management measures have been proposed for Nghe An Province to improve air quality.

Implications. The air environment faces challenges as climate change significantly impacts environmental pollution. An analysis of air quality monitoring data from 119 stations across Nghe An Province indicated that the air quality was generally good, with only 5.9% of the stations reporting TSP concentrations that exceeded national standards. Although the current air quality in Nghe An Province is within safe limits, appropriate management solutions are necessary to ensure the health and safety of the local population and to guarantee sustainable development.

Keywords: Air Pollution, Air Quality, Environmental Management, Climate Change, Sustainable Development.

1. Introduction.

Air pollution and climate change are two of the significant environmental challenges, which are closely linked and mutually impactful. Air pollution has emerged as one of the most pressing global environmental issues, with profound and far-reaching effects on human health, ecosystems, and climate. The World Health Organization (WHO) consistently emphasises air pollution as the single most significant environmental health risk, causing 8.1 million deaths annually, primarily from cardiovascular and respiratory diseases (World Health Organization, 2021). Notably, over 90% of pollution-related deaths occur in low- and middle-income countries (Fuller et al., 2022).

Numerous studies have shown that long-term exposure to air pollution causes inflammation in human cells, predisposing individuals to conditions such as reduced lung function, asthma, cardiovascular issues, and, more dangerously, cancer (Dominici et al., 2022; Jenwitheesuk et al., 2020; Peng et al., 2025; Wu et al., 2025). In 2013, the International Agency for Research on Cancer (IARC), a part of the WHO, classified outdoor air pollution as a leading cause of lung cancer (Loomis et al., 2014). The primary air pollutants include particulate matter (PM), carbon monoxide (CO), ground-level ozone (O_3), nitrogen oxides (NOx), sulfur oxides (SOx), and volatile organic compounds (VOCs) (Manahan, 2017). Among these, particulate matter $PM_{2.5}$ (with a diameter smaller than 2.5 micrometres) is considered one of the most hazardous pollutants due to its ability to penetrate deep into the respiratory system and enter the bloodstream, leading to severe cardiovascular and respiratory illnesses (World Health Organization, 2021). Carbon monoxide, a product of incomplete combustion, can bind to haemoglobin in the blood, reducing the capacity for oxygen transport to tissues and organs (Jacob & Winner, 2009). Ground-level O_3, formed from the photochemical reaction of NOx and VOCs in sunlight, is a powerful oxidant that damages lung tissue and impairs respiratory function (Bai et al., 2022). Furthermore, NOx and SOx are precursors to acid rain, which harms natural ecosystems and damages man-made structures (Seinfeld & Pandis, 2016).

The mitigation of air pollution is becoming increasingly challenging owing to the complex and two-way relationship between air quality and climate change. Climate change phenomena, such as more frequent and intense heatwaves, prolonged droughts, and altered precipitation patterns, can exacerbate air pollution levels. For instance, rising temperatures can accelerate the formation of ground-level ozone (O_3), a key component of smog. Simultaneously, dry conditions can increase the suspension of delicate particulate matter ($PM_{2.5}$ and PM_{10}) from dust and agricultural waste burning (IPCC, 2021). These interconnected crises require an integrated and holistic approach to management and policy that extends beyond traditional approaches.

In Vietnam, rapid urbanisation, industrialisation, and socioeconomic development have led to a significant decline in air quality in major urban centres and developing provinces (Anh The Hoang et al., 2024; Dominutti et al., 2024; Ho et al., 2023; Nhung et al., 2022). According to the World Air Quality Report 2019 (IQAir, 2019), Vietnam's average $PM_{2.5}$ concentration in 2019 was 34.1 $\mu g/Nm^3$, ranking 21st among 106 surveyed countries (Vuong et al., 2024). While the majority of studies focus on large metropolitan areas such as Hanoi and Ho Chi Minh City (Le Tran et al., 2025; Nguyen et al., 2020; Tan Hoi, 2020; Vuong et al., 2024), provinces with rapidly growing industrial zones and large-scale agricultural activities are also facing equally, if not more, serious challenges (Huy & Kim Oanh, 2017; Ngo et al., 2023; Nguyen et al., 2024).

Nghe An Province, located in the North-Central Coast region of Vietnam, is a prime example. As the largest province in Vietnam by area, Nghe An has a diverse economy encompassing agriculture, forestry, mining, and a rapidly growing manufacturing sector. While this rapid economic growth is crucial for poverty reduction and social development, it is a primary cause of air pollution. The unique combination of industrial emissions, vehicular exhaust, agricultural activities (the burning of agricultural waste), and the province's meteorological conditions has created a complex air pollution landscape that demands the attention of the regulatory bodies.

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Additionally, Nghe An's distinctive climate, particularly the hot, dry, and strong foehn wind (locally called "Lao wind" in Central Vietnam) during the summer months, further complicates air quality. These weather patterns, which are becoming increasingly extreme and unpredictable owing to climate change, can significantly affect the transport, dispersion, and concentration of air pollutants. For example, dry winds can lift dust and pollutants from the ground, whereas a lack of rain during drought periods prevents the natural cleansing process of the atmosphere (Jacob & Winner, 2009).

However, these critical issues have not yet been explicitly addressed in Nghe An Province, a region where the air environment is significantly impacted by climate change. Therefore, a comprehensive understanding and effective management of air quality in Nghe An is not only a local requirement but is also crucial for the national strategy on sustainable development and climate change adaptation.

2. Theoretical Framework.

2.1. Theoretical Framework for Sustainable Air Quality Management.

The theoretical foundation of this study is an integrated sustainable development framework incorporating three pillars: environmental protection, economic viability, and social equity. The interrelations between these sustainability factors are illustrated in Figure 1 (World Commission on Environment and Development, 1987).

Traditionally, air quality management has been viewed primarily through an environmental lens, focusing on end-of-pipe solutions to mitigate air pollution. However, a sustainable approach recognises that effective air quality policies must support economic growth and ensure social well-being (Cohen et al., 2021). This includes promoting green technologies, enhancing public health, and ensuring that the burden of pollution and mitigation costs is equitably distributed throughout society.

An important concept within this framework is the co-benefits. This refers to the synergistic gains that arise from policies aimed at addressing multiple issues simultaneously. For example, reducing emissions from fossil fuels not only improves local air quality by reducing particulate matter and nitrogen oxides (NOx) but also mitigates climate change by lowering carbon dioxide (CO_2) emissions. A study by Xie et al. (2018) demonstrated that reducing CO_2 emissions can simultaneously decrease NOx emissions by at least 15%.

This co-benefit approach has been highlighted as a powerful tool for policy integration and has been adopted by international organisations such as the United Nations Environment Programme (UNEP) (Shindell et al., 2012). Previous research indicates a link between air quality and climate change. According to the IPCC (2021), reports have shown that fossil fuel combustion is the primary source of both air pollutants and greenhouse gases.

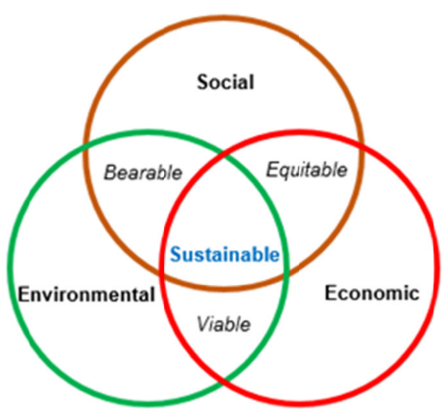

Fig. 1. Social, Environmental, and Economic Factors Interrelation.
Source: based on World Commission on Environment and Development (1987).

Jacob and Winner (2009) highlighted that climate change can alter atmospheric circulation patterns, boundary layer heights, and precipitation, all of which affect the transport, dispersion, and removal of air pollutants. For countries with tropical climates, such as Vietnam, studies have shown that high temperatures and intense solar radiation can accelerate photochemical reactions that form secondary pollutants, including ozone (O_3) (Bai et al., 2022).

Furthermore, a study by Zhang et al. (2022) on transboundary haze in Southeast Asia emphasised that forest and agricultural fires can contribute to regional air pollution, which is a concern for Nghe An, given its vast agricultural land. Studies on the current status, causes, and solutions for air pollution management in large Vietnamese cities, such as Hanoi (Vanderbloemen et al., 2025) and Ho Chi Minh City (Vu et al., 2020), provide a solid foundation for studies in Nghe An Province.

2.2. Legal and Policy Framework for Air Quality Management in Vietnam.

Vietnam has made significant progress in establishing a comprehensive legal framework for environmental protection, particularly in air quality management. The cornerstone of this framework is Environmental Protection Law No. 72/2020/QH14 (National Assembly of Vietnam, 2020), which took effect on January 1, 2022. This Law represents a crucial update that introduces new regulations on environmental quality standards, emission control, and legal liabilities. It explicitly mandates that organisations and individuals engaged in production, business, and service activities must comply with national technical standards for environmental quality.

Although significant investments have been made in air quality protection, the nationwide coverage rate of air quality monitoring technology remains limited and uneven. The current network of automatic air quality monitoring stations (103 operational stations nationwide) is primarily concentrated in large cities, such as Hanoi and Ho Chi Minh City.

Meanwhile, rural provinces with many new industrial zones, such as Nghe An, have not yet received adequate investment in air quality monitoring. The key National Technical Regulations (QCVN) establishes specific permissible limits for air pollutants in Vietnam.

- QCVN 05:2023/BTNMT is the National technical regulation on air quality, which sets permissible limits for common pollutants such as $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2, and O_3.
- QCVN 19:2024/BTNMT is the National technical regulation for industrial emissions.
- QCVN 30:2025/BNNMT is the National technical regulation for waste incinerators.

These regulations provide the legal and technical basis for provincial authorities, primarily the Nghe An Provincial Department of Natural Resources and Environment (now the Nghe An Provincial Department of Agriculture and Environment), to monitor and enforce compliance.

However, the effective implementation of these regulations in a large and geographically diverse province, such as Nghe An, poses a significant challenge. At the same time, the legal framework outlines the "what" and "how" of management, effective enforcement requires robust and modern monitoring systems, advanced technological solutions, close inter-agency coordination, and community engagement. All these issues are addressed in this study.

This study evaluated the current state of air pollution and air quality management in Nghe An Province, Vietnam. Based on an analysis of the strengths and weaknesses of the current management efforts, solutions are proposed to ensure air quality in the context of climate change. The research questions (RQ) are as follows:

RQ1. The current status of air quality in Nghe An Province was analysed.

RQ2. The air quality management situation in Nghe An Province was analysed, and the advantages and difficulties in management were identified.

RQ3. Propose groups of solutions for managing air quality to ensure sustainable development in the context of climate change in Nghe An Province.

3. Literature Review.

Numerous studies on air quality management have been conducted to ensure sustainable development and identify effective solutions for maintaining a safe and healthy air environment that supports human well-being. Many countries and regions have achieved significant success in air quality management by adopting multifaceted strategies to reduce air pollution. These models typically combine three main groups of solutions: economic, technological, and planning approaches.

Economic tools, such as carbon taxes, Emission Trading Systems (ETS), and emission fees, have been used effectively to incentivise businesses and individuals to reduce pollution (European Environment Agency, 2019). Economic tools in environmental protection management are a policy approach built upon market economic principles that impact the costs and benefits of an organisation's operations to encourage producer behaviour that is environmentally beneficial. Li et al. (2021) studied the impact of environmental tax (ET) on over 30 fuel-powered power plants in China and showed that the use of ET had a positive effect on reducing pollution emissions compared to the previous pollution fee policy.

The study demonstrated that ET yielded encouraging results: sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter from fossil fuel power plants were significantly reduced by 2,186 tons (7.7%), 1,550 tons (6.84%), and 1,064 tons (16.1%), respectively, after the policy implementation. Xue et al. (2024) studied the effect of the Environmental Protection Tax (EPT) on the efficiency of urban O_3 pollution reduction in China.

Using data from 21 cities between 2015 and 2020, the results showed that the EPT reform policy could effectively curb near-surface urban O_3 pollution by approximately 2.1%. A study in Thailand found that the implementation of Environmental Protection Plans (EPPs) in quarry operations resulted in a high Social Return on Investment (SROI) of 59.55:1 (Ngwu et al., 2025).

The adoption of advanced technologies has become a core solution for air quality management.

These technologies include implementing cleaner production processes, installing advanced air filtration systems, transitioning to renewable energy, developing electric vehicles, and utilising modern environmental monitoring technologies. The IEA (2021) highlights the importance of investing in green technologies to achieve environmental goals. Recent studies provide further evidence of the effectiveness of these technological approaches. Li et al. (2025) applied a machine learning model combined with low-cost sensors to monitor and forecast $PM_{2.5}$ pollution in Hongshan District, Wuhan, Hubei, China. The model achieved high-resolution predictions with a spatial resolution of 100 m × 100 m and an hourly temporal resolution, demonstrating good predictive capability with an overall R^2 of 0.93 and a Root Mean Square Error (RMSE) of 3.09 μg/Nm^3. In a separate study, Kozłowski et al. (2024) utilised a mobile automatic Airpointer station to measure pollutant concentrations and found that these concentrations were highly dependent on meteorological conditions. Their results showed that air quality was significantly affected by the lime and cement industries operating in the study area. The study also concluded that short-term automatic air pollution measurements are indispensable for air quality protection action plans aimed at achieving Sustainable Development Goals (SDG).

Regarding electric vehicle policies, Skrúcaný et al. (2019) analysed 420 electric vehicles in 2016 across seven European countries (Austria, the Czech Republic, Germany, Hungary, Poland, Slovakia, and Slovenia) and found positive environmental effects from their increased use. Devihosur et al. (2024), who studied in Singapore, showed that with 100% vehicle electrification and the integration of low-carbon technologies into the power system, the potential for emission reduction reaches 89.30 ± 2.64%. This suggests that the widespread deployment of electric vehicles will result in the expected sustainability of transportation. However, the study cautioned that for EVs to have a genuinely positive environmental impact, countries must focus on developing environmentally friendly forms of electricity generation and increasing electricity transmission efficiency.

Integrating air quality management into land-use planning has become a prominent trend in urban planning. The creation of extensive green spaces and green corridors, along with the promotion of smart urban planning, can help mitigate pollution and enhance community health. Nieuwenhuijsen (2016) revealed significant differences in environmental exposure to factors such as air pollution, noise, temperature, and green spaces within cities. These differences are determined by urban development and traffic planning indicators, such as road networks, proximity to major highways, traffic density, population density, industrial activity, and the presence of natural and green spaces.

Based on urban land use data and the Air Quality Index (AQI) from a network of 340 monitoring stations, Yan et al. (2021) analysed the correlation between land use patterns and air quality in Lanzhou, China. Their findings showed a strong correlation between urban land use and air quality, with seasonal changes in the relationship. The main factors contributing to urban air quality degradation were identified, including industrial production, transportation activities, and infrastructure construction, and it was confirmed that green spaces can aid in reducing urban pollution levels.

Liu and Wan (2025) utilised data from 280 Chinese cities over a five-year period (2007–2012) and a multi-period Difference-in-Differences (DID) model to investigate the impact of smart city pilot policies on urban pollution emissions. The results demonstrate that smart city development effectively reduces urban pollution levels. The study concluded that upgrading industrial structures, enhancing green innovation capacity, and improving energy efficiency are crucial for smart cities to mitigate pollution.

Using data from 443 monitoring stations in South Korea, Gunwon et al. (2025) established a computational model to analyse the correlation between the air quality index (CO, NO_2, SO_2, O_3, PM_{10}, and $PM_{2.5}$) and natural characteristics such as land cover, topography, and vegetation index. Their results showed that an extensive urban environment can have a significant impact on air quality.

This highlights that future changes in land use or land-use planning should consider specific air quality parameters that can be effectively analysed to assess environmental impacts. While previous studies have demonstrated the effectiveness of various air quality management methods, research tailored to regions with distinctive climatic conditions, such as Nghe An Province, Vietnam, remains limited. To date, this issue has not been fully addressed in the existing literature.

4. Methodology.

4.1. Data.

Nghe An Province, located in Vietnam's North Central Coast region, has diverse topography, including mountains, a coastal plain, and a long coastline. The province's strategic location on the North-South and East-West transportation routes facilitates international trade in the region. Its tropical monsoon climate is characterised by hot, dry foehn winds and cold northeast monsoons, which can occasionally lead to extreme weather events. The climate is divided into two distinct seasons: a hot, humid, and rainy summer (from May to October) and a cold, less rainy winter (from November to April). Nghe An is experiencing strong economic growth, driven by agriculture, industry (including construction materials and processing), and tourism. Although the province's infrastructure is undergoing significant investment, this rapid economic development poses environmental challenges that require sustainable management.

Monitoring data from the Nghe An Provincial Environmental Monitoring Program (2021–2023) were used to assess air pollution levels in the study area. The program, conducted by the Center for Natural Resources and Environmental Monitoring (under the Nghe An Provincial Department of Agriculture and Environment), was carried out across the entire province at 119 locations, with a monitoring frequency of six times per year in January, March, May, July, September, and November. The monitoring results are documented in the Report on the Task of Developing a Plan to Manage Air Quality in Nghe An Province for the Period 2022–2025, with a Vision to 2030.

For monitoring sites at traffic intersections, background locations, concentrated residential areas, tourist areas, and the perimeters of factories and industrial parks, six parameters were measured: Total Suspended Particulates (TSP), SO_2, NO_2, CO, noise, and wind direction. For locations at the perimeters of landfills and solid waste treatment plants, eight parameters were measured: TSP, SO_2, NO_2, CO, NH_3, H_2S, noise, and wind direction. In this study, the mean of the observed results was employed to analyse and evaluate pollution levels within the study area. Data processing was performed using Excel software. The distribution of the monitoring sites is presented in Table 1.

Table 1. Distribution of Air Quality Monitoring Sample Areas.

No.	Sampling Area	Number of Samples
1	Rural area	19
2	Urban area	31
3	Industrial area	16
4	Mining area	11
5	Construction area	21
6	Landfill area	14
7	Other areas (traffic, tourist, etc.)	7
	Total	**119**

Source: Nghe An Provincial Department of Natural Resources and Environment (2024).

4.2. Research Methodology.

This study used several research methods to achieve its objectives.

- Data collection methods used for all air quality monitoring data for the research area were collected from the Nghe An Province Environmental Monitoring Program (2021-2023), conducted by the Center for Natural Resources and Environmental Monitoring. In this program, samples were collected manually and subsequently analysed in a laboratory. Key socio-economic data were gathered from Nghe An's economic development reports and statistical yearbooks for 2020–2024. These quantitative and qualitative data were crucial for analysing the factors influencing air pollution in the study area.
- Methods of statistical and document analysis were employed to describe, summarise, and analyse quantitative data systematically. Specifically, descriptive statistics were used to clarify the status of air pollution and its relationship with the influencing factors. Document analysis, a qualitative research technique, was used to analyse reports, policy documents, and legal regulations. This method helped identify key themes, patterns, and regulations related to environmental management, allowing for the evaluation of their effectiveness and limitations.
- The comparative method is a vital analytical technique in scientific research that highlights the differences and similarities between objects, phenomena, or data. Its primary purpose is to draw insightful and objective conclusions to clarify research problems. Air quality monitoring results were compared with current national technical standards to determine the level of pollution and assess the evolution of air quality over time.

5. Results.

5.1. Current Status of Air Quality in Nghe An Province.

5.1.1. Air Quality in Rural Areas.

A total of 19 air quality monitoring points were used across coastal, mountainous, and midland rural areas. The air quality in these regions is safe, with SO_2, CO, and NO_2 levels within safe limits according to QCVN 05:2023/BTNMT. However, two monitoring points showed total suspended particulate (TSP) levels exceeding the permissible threshold (accounting for 10.5%): point K12 (329 µg/Nm^3) in a rural plain area and K93 (340 µg/Nm^3) in a rural mountainous area. The TSP concentration fluctuated from 146 µg/Nm^3 to 340 µg/Nm^3, with a mean of 237.89 µg/Nm^3, a variance of 2861.43 µg/Nm^{3,} and a standard deviation (SD) of 53.49 µg/Nm^3 (Figure 2).

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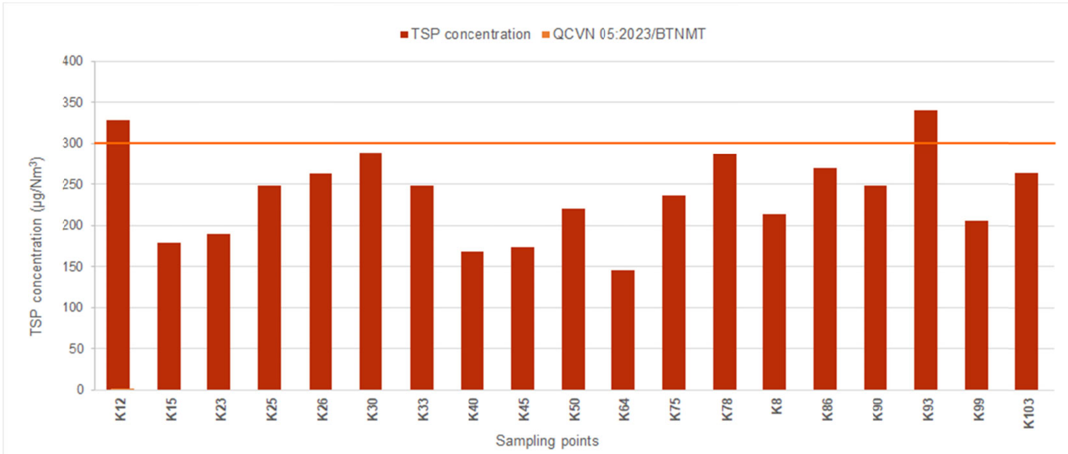

Fig. 2. TSP Concentration Dynamics in Rural Monitoring Locations (1-hour average).
Source: Nghe An Provincial Department of Natural Resources and Environment (2024).

5.1.2. Air Quality in Urban Areas.

To monitor urban air quality, results from 31 sampling points were used, including 10 points in markets, 13 at traffic intersections, and the rest in residential areas. The monitoring results indicate that the air quality in Nghe An's urban areas is good, with SO_2, CO, and NO_2 levels all within safe limits according to the QCVN 05:2023/BTNMT. As for Total Suspended Particulates (TSP), 4 out of the 31 stations (12.9%) exceeded the safe 1-hour average limit of 300 µg/Nm^3 set by QCVN 05:2023/BTNMT.

The TSP concentration fluctuated from 111 µg/Nm^3 to 396 µg/Nm^3, with a mean of 210.30 µg/Nm^3, a variance of 3758.28 µg/Nm^3, and a standard deviation (SD) of 61.30 µg/Nm^3 (Figure 3). Among these, station K85 recorded the highest pollution level at 396 µg/Nm^3, which is 1.32 times the allowable limit. Station K85 is located near a transport station in an area characterised by heavy traffic. This high traffic volume could generate substantial dust, potentially contributing to an increase in the TSP concentration at the monitoring station.

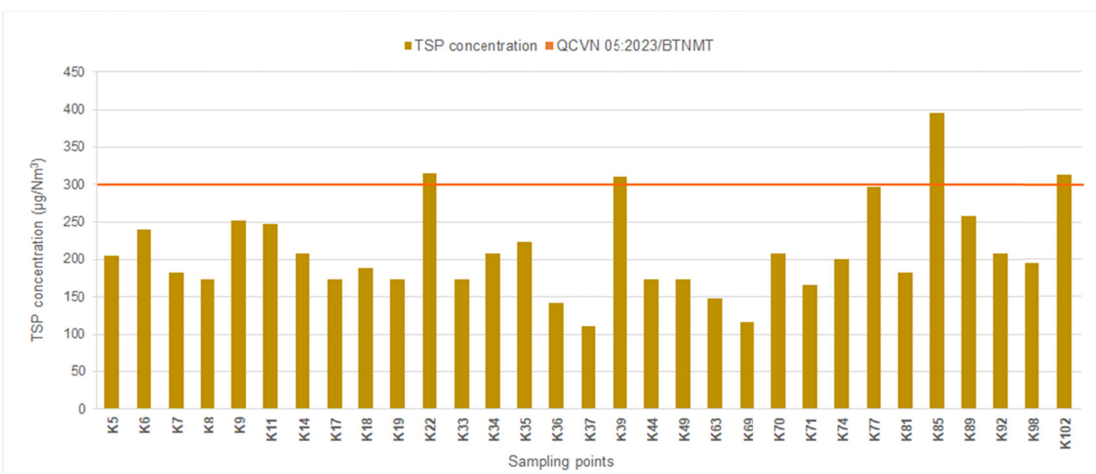

Fig. 3. TSP Concentration Dynamics in Urban Monitoring Locations (1-hour average).
Source: Nghe An Provincial Department of Natural Resources and Environment (2024).

5.1.3. Air Quality in Industrial Zones.

Nghe An is promoting industrial development, attracting numerous companies and raising concerns about air quality due to the high number of manufacturing plants operating in the province. Monitoring data were collected from all industrial zones in Nghe An Province, with a total of 16 monitoring points.

The results indicate that the air quality in these industrial zones is safe, with levels of SO_2, CO, NO_2, and Total Suspended Particulates (TSP) all within safe limits according to QCVN 05:2023/BTNMT.

The TSP concentration fluctuated from 174 µg/Nm^3 to 284 µg/Nm^3, with a mean of 210.62 µg/Nm^3, a variance of 1079.05 µg/Nm^{3,} and standard deviation (SD) of 32.85 µg/Nm^3. The highest TSP index was recorded at point K67 (284 µg/Nm^3) in the Nghia My Industrial Zone (Figure 4).

This finding is consistent with the results from the automatic monitoring stations installed at factories within these industrial zones, which continuously transmit data to the Nghe An Provincial Department of Agriculture and Environment.

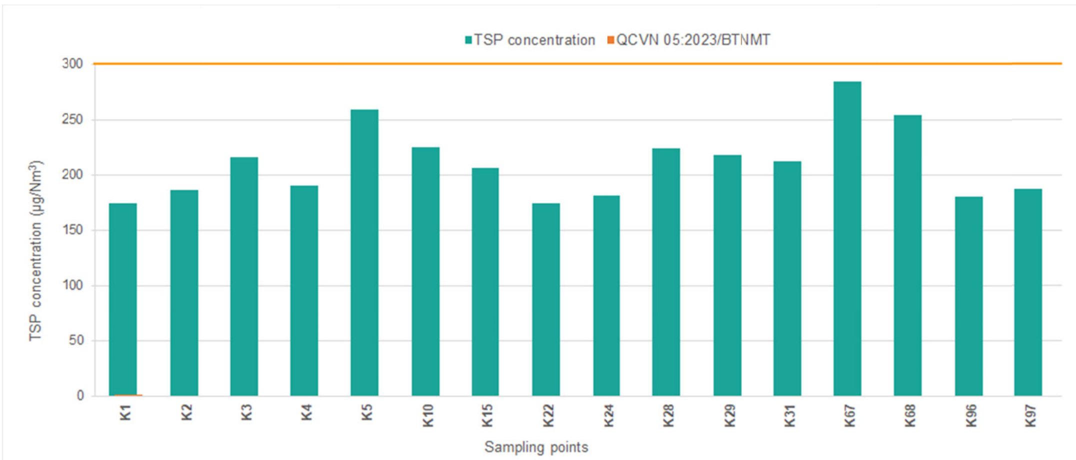

Fig. 4. TSP Concentration Dynamics in Industrial Monitoring Locations (1-hour average).
Source: Nghe An Provincial Department of Natural Resources and Environment (2024).

5.1.4. Air Quality in Mining Areas.

The western part of Nghe An Province contains numerous stone quarries with large reserves that supply both domestic and international markets. This mining activity poses a potential risk to the air quality of the surrounding environment. This study collected monitoring data from 11 points at various mineral quarries within the research area.

The air quality in these mining areas is generally safe, with levels of SO_2, CO, NO_2, and Total Suspended Particulates (TSP) all within safe limits according to QCVN 05:2023/BTNMT. Specifically, the TSP concentration fluctuated from 174 µg/Nm^3 to 250 µg/Nm^3, with a mean of 209.55 µg/Nm^3, a variance of 718.27 µg/Nm^{3,} and standard deviation (SD) of 26.80 µg/Nm^3 (Figure 5).

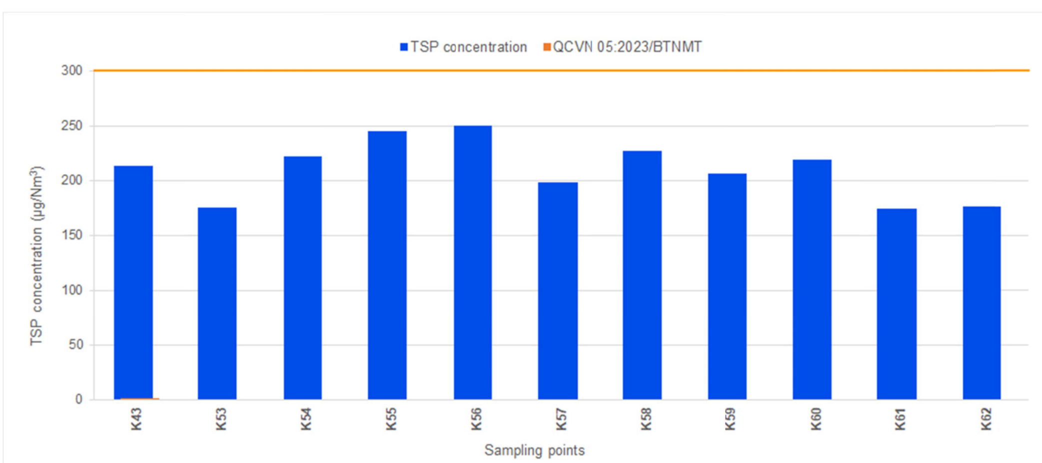

Fig. 5. TSP Concentration Dynamics in Mining Monitoring Locations (1-hour average).
Source: Nghe An Provincial Department of Natural Resources and Environment (2024).

5.1.5. Air Quality at Construction Sites.

As a large province in Vietnam's North Central Coast region, Nghe An is making new strides in economic development, which involves the construction of high-rise buildings, transport infrastructure, and urban areas. Construction activities can significantly impact environmental quality, particularly through the emission of fine dust, such as PM_{10} and $PM_{2.5}$.

This study collected monitoring data from 21 monitoring points at various construction sites across the province.

The samples included 14 civil construction projects, 3 urban area development projects, and 4 transport infrastructure projects. The monitoring results indicate that the air quality in these areas is generally safe. The levels of SO_2, CO, NO_2, and Total Suspended Particulates (TSP) were all within safe limits according to QCVN 05:2023/BTNMT. The TSP concentration fluctuated from 174 µg/Nm^3 to 276 µg/Nm^3, with a mean of 215.48 µg/Nm^3, a variance of 1249.56 µg/Nm^{3,} and standard deviation (SD) of 35.35 µg/Nm^3 (Figure 6).

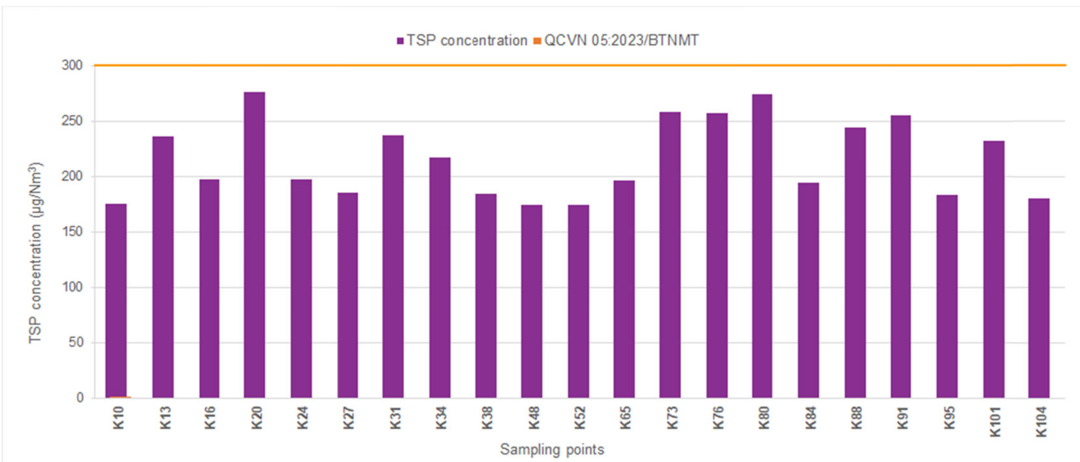

Fig. 6. TSP Concentration Dynamics in Construction Monitoring Locations (1-hour average).
Source: Nghe An Provincial Department of Natural Resources and Environment (2024).

5.1.6. Air Quality at Landfill Area.

To assess the air quality at landfill sites, this study collected data from 14 monitoring points across Nghe An Province. These are large-scale facilities that serve multiple communes. The monitoring results indicate that the air quality at these landfill sites is currently safe, with SO_2, CO, and NO_2 levels within safe limits according to the QCVN 05:2023/BTNMT (Figure 7).

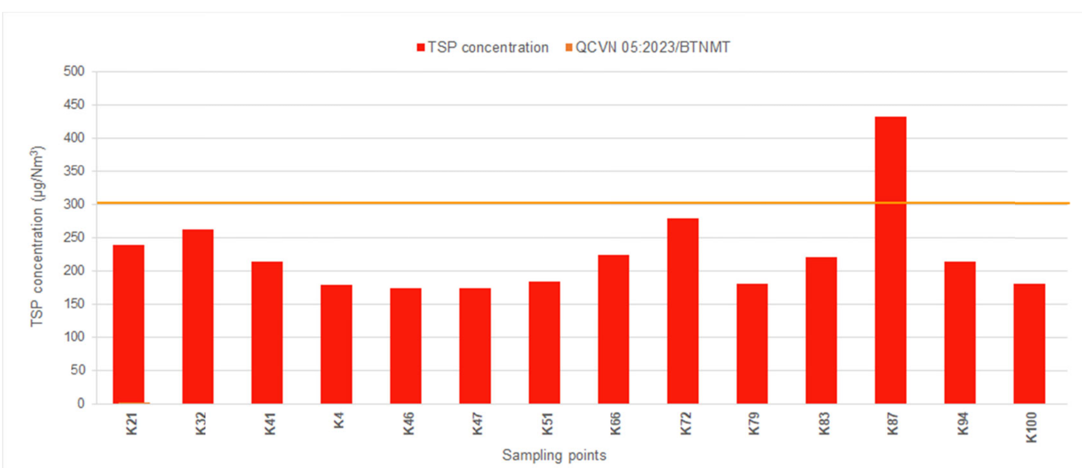

Fig. 7. TSP Concentration Dynamics in Landfill Monitoring Locations (1-hour average).
Source: Nghe An Provincial Department of Natural Resources and Environment (2024).

The TSP concentration fluctuated from 174 μg/Nm^3 to 432 μg/Nm^3, with a mean of 225.21 μg/Nm^3, a variance of 4650.80 μg/Nm^{3,} and standard deviation (SD) of 68.20 μg/Nm^3. At point K87, the total suspended particulate (TSP) value was 432 μg/Nm^3, which is 1.44 times the permissible limit. Station K87 was installed at the Bong Khe landfill in the Nghe An Province. The landfill has a small area, receives a large amount of waste daily, and uses incineration to process waste. These operational characteristics may account for the high TSP concentration at this station.

5.2. Air Quality Management Policies in Nghe An Province.

Nghe An Province has assigned the Department of Natural Resources and Environment (now the Department of Agriculture and Environment) the direct responsibility of managing the province's air quality. In addition to strictly adhering to national air quality standards, the province has issued various Resolutions, Plans, and Official Letters to establish a solid legal framework for air quality management.

The Nghe An Department of Agriculture and Environment regularly conducts periodic and surprise inspections and monitoring in high-risk industrial zones and production facilities. This ensures that businesses operate their emission treatment systems effectively and efficiently. Businesses within the study area are required to install modern emission treatment systems such as electrostatic precipitators (ESP), scrubbers, or selective catalytic reduction (SCR) systems. They are also mandated to have continuous automated monitoring systems that transmit real-time air quality data to the Department's control centre. Any readings that exceeded the permissible limits were addressed promptly.

Regarding urban planning, Nghe An Province is implementing urban development that adheres to national standards and regulations, with a strong emphasis on planning green spaces and water features. The province is promoting urban planning projects that incorporate more trees and parks into the urban environment. This not only enhances the urban landscape but also helps improve air quality.

6. Discussion.

Based on the air quality monitoring results from 2021 to 2023, Nghe An Province's air quality remained at a reasonable level, with no signs of significant pollution. The concentrations of pollutants such as SO_2, CO, and NO_2 showed no significant variation across different monitoring sites and were well below the permissible limits set by QCVN 05:2023/BTNMT. Total suspended particulate (TSP) concentrations were higher in the perimeters of industrial zones and factories than in tourist areas, urban centres, and the perimeters of waste treatment plants.

Comparing the results across different monitoring periods and years for each location revealed that the TSP content was highest during the fourth monitoring period (May and July), which is considered the hottest time of the year. At most monitoring points, TSP concentrations remained within safe limits, as per QCVN 05:2023/BTNMT (1-hour average). Nevertheless, there were still seven stations (accounting for 5.9%) with TSP concentrations exceeding the safety standards. This is noteworthy because the health and economic impacts of air pollution are severe.

In its management and supervision efforts, Nghe An Province has implemented specific management solutions that have yielded positive results in controlling and protecting the air environment. These include enhanced traffic management to reduce vehicular emissions, stepwise control and remediation of pollution from craft villages and industrial production, and maintenance and expansion of the automatic emission monitoring system.

However, air quality management in the study area faces several limitations. Primarily, the provincial government has not adequately invested in modern and advanced technology for air quality monitoring and inspection. Currently, only factories in industrial zones are mandated to have continuous and automated monitoring systems. For other locations, such as residential areas, traffic intersections, and rural zones, monitoring is predominantly conducted through manual sampling. This lack of continuous, automatic data collection prevents the timely detection of pollution issues.

This can delay the implementation of prompt remedial actions and has led to citizen complaints regarding polluted air.

Nghe An Province has over 1.4 million hectares of agricultural land, accounting for 90.1% of its area, and nearly 70% of the population is engaged in agriculture. Consequently, agricultural activities release a significant amount of pollutants, such as NH_3, CH_4, and NOx, especially fine particulate matter ($PM_{2.5}$) from the burning of agricultural waste. It is estimated that burning crop residues in an integrated farming system on 1 hectare of land will emit 6.4 tons of CO_2; 163.5 kg of CO; 26.1 kg of PM_{10}, 25.3 kg of $PM_{2.5}$ and more than 40 kg of other toxic organic substances (Arunrat et al., 2018). With an area of 1.4 million hectares of agricultural land, it is evident that the amount of emissions affecting the environment from burning agricultural waste in Nghe An is significant. However, Nghe An Province currently lacks specific policies to control agricultural pollution and protect air quality. This has led to the release of millions of tons of fine dust into the environment from the burning of agricultural waste in the fields after each harvest, causing severe pollution (Figure 8).

Fig. 8. Farmers Burning Agricultural Waste in the Field.

In particular, the hot, dry climate caused by the Lao wind is one of the factors that increase the amount of dust in the air. A study by Lou et al. (2017) on the correlation between PM2.5 concentration and air humidity revealed a negative correlation, with the highest levels occurring at relative humidity levels of 45–70%. This is the humidity level commonly found during the Lao wind in Nghe An Province.

Public awareness of environmental protection remains low. Residents have not yet fully grasped the importance of protecting air quality, viewing it as solely the responsibility of the government or businesses. A sense of complacency and a lack of recognition of the negative impacts of air pollution on health and daily life also contribute to inconsistent and unsustainable behaviours among the public.

Failure to address these deficiencies will lead to hazardous air quality in some areas of the province in the near future, particularly in the context of ongoing rapid and intensive economic, industrial, and urban development. Based on these limitations in Nghe An's air quality management efforts, this study proposes several solutions for sustainable air quality management in the province.

Establishing a robust legal framework is fundamental to effective management. Specifically, the Nghe An Provincial government needs to issue more stringent local technical standards tailored to each industrial sector. Additionally, regulations regarding vehicular emissions, particularly for ageing motorcycles and older cars, must be strengthened.

For TSP concentration, the target is that 100% of TSP values at monitoring stations meet QCVN 05:2023/BTNMT standards by 2030. Furthermore, enhancing management capacity requires specialised training for environmental management staff, providing them with modern management tools, and establishing an effective inter-agency coordination system among departments such as the Department of Agriculture and Environment, Environmental Police, and the Department of Construction.

Following institutional changes, the application of science and technology is pivotal in addressing pollution at its source. To minimise pollution at its source, the application of clean technology is a top priority. Incentives should be provided to encourage businesses to invest in low-emission production technologies and to transition to renewable energy sources, such as solar and wind power. Simultaneously, modernising the monitoring system is crucial for obtaining accurate and timely data. More automatic monitoring stations should be installed in sensitive areas such as schools, hospitals, and residential zones.

Additionally, remote sensing technologies, such as those using satellites and drones, should be implemented to monitor pollution over wide areas and detect illegal emission sources. However, a barrier to this method is the high investment cost. An automatic multi-parameter air environment monitoring station currently costs USD 20,000 to USD 30,000, making it challenging to deploy widely within the budget of Nghe An Province.

One indispensable solution in air quality management is the application of economic tools. The Nghe An Provincial government should research and apply economic instruments, such as environmental taxes on highly polluting industries and carbon emission fees. Additionally, financial support packages and tax incentives should be offered to businesses that adopt green technology or undertake environmental protection initiatives. Furthermore, mobilising resources from the private sector through Public-Private Partnerships (PPPs) and seeking international cooperation in technology and finance are crucial to securing the necessary resources for costly solutions.

Community participation is a decisive factor in the success of environmental policies. Regular and diverse public awareness programs should be implemented through various media channels, social media, and educational activities in schools. A green lifestyle should be encouraged by facilitating the use of public transportation and building dedicated lanes for bicycles and pedestrians. Waste reduction and energy conservation programs for households should also be promoted.

Finally, to achieve a comprehensive strategy, air quality management must be integrated with climate change response solutions. Urban and industrial planning needs to be conducted scientifically, with the development of ecological urban areas that feature smart transportation and energy systems. Polluting production facilities should be relocated away from residential and environmentally sensitive areas. Furthermore, developing green spaces is a natural and effective solution. Increasing the number of trees in urban areas, parks, and industrial zones not only helps absorb emissions but also creates ecological buffer zones. Finally, sustainable management of water and land resources will help limit dust pollution from bare ground, especially during dry seasons.

7. Conclusions.

Based on the analysis of air quality monitoring data from 119 locations in Nghe An Province, the overall air quality was good. However, localised pollution is a notable concern. High concentrations of Total Suspended Particulates (TSP) were found in some urban areas due to heavy traffic. The primary sources of TSP are mineral quarries and landfills, where dust is emitted at low altitudes, resulting in concentrated and localised pollution.

Traffic is another source of localised pollution, with SO_2 and NO_2 concentrations in dense urban areas such as Vinh City potentially exceeding standards by 2-3 times during peak hours. While industrial smokestacks also emit pollutants, their impact is less clear due to high-altitude dispersion, which reduces pollution concentration at the source and spreads it over a wider area.

Therefore, the most significant air pollution issues currently facing Nghe An are TSP, SO_2, and NO_2, especially TSP, with 5.9% of stations exceeding safety standards. Although the average concentrations of most pollutants do not exceed permissible standards, for extreme weather events resulting from climate change could negatively impact public health. To enhance air quality management and ensure sustainable development in the context of climate change, close inter-agency coordination is crucial.

Nghe An Province requires the implementation of a comprehensive solutions to ensure positive effects. These include institutional and policy solutions to improve the legal framework and management capacity, science and technology solutions to apply clean technologies and modernise monitoring systems, economic solutions to mobilise resources and apply market-based tools, education and community solutions to raise awareness and promote a green lifestyle, and finally, solutions integrated with climate change response to ensure a holistic strategy.

Therefore, the province's strategic implementation of short-term solutions (1–2 years) should focus on refining the legal framework to establish a robust legal basis for environmental protection, modernising the monitoring system to collect baseline data, encouraging private investment, and launching community communication campaigns to foster social consensus.

Long-term solutions (3–5 years or more) should aim for sustainable transformation. This requires the large-scale application of clean production technology, building centralised waste treatment infrastructure, researching market-based instruments (e.g., discharge taxes), and integrating climate resilience into all provincial development plans. Together, these measures form a comprehensive strategy for environmental improvement.

By 2030, the goal is that 100% of monitoring stations will have TSP concentration values that meet the safety standards prescribed in QCVN 05:2023/BTNMT. The implementation of these solutions is entirely consistent with Vietnam's National Environmental Protection Strategy to 2030, with a vision to 2050, aiming to improve Nghe An's air quality to meet QCVN 05:2023/BTNMT, ensure the safety of people's health, and reduce the socio-economic burden.

Conflict of Interest Statement.

The authors declare that there is no conflict of interest.

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