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Machine Learning-Based Assessment of Air Quality and Its Impact on Respiratory Health in Urban Environments

Battula Greeshma[1], Marella Naga Chaitanya Sneha[2], Valini Sunthwal[3], Thota Satya Veera Manikanta[4], Lakshmi Ramani Burra[5], Praveen Tumuluru[6]

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Abstract: Air pollution, primarily driven by emissions of nitrogen dioxide (NO2), ozone (O3), and fine particulate matter (PM2.5), presents a critical environmental concern with significant implications for public health. Air quality in urban areas is critical in public health, particularly respiratory illnesses. This study uses advanced machine learning algorithms to analyze the relationship between air quality parameters and respiratory health outcomes. Specifically, we employ Linear Regression, Random Forest Regression, and Gradient Boosting Regression algorithms to assess and model the impact of air quality on respiratory health in urban settings. Our analysis utilizes a comprehensive dataset collected from various urban areas, encompassing data on air quality factors such as pollutant concentrations, meteorological conditions, and geographical attributes. Concurrently, we compile information on respiratory health indicators, including hospital admissions, prevalence of respiratory diseases, and symptom reports, from healthcare records and surveys.
Linear Regression is employed to establish baseline relationships between individual air quality parameters and respiratory health outcomes, providing insight into the linear associations between pollutants and health. Random Forest Regression then captures non-linearities and interactions within the data, accommodating complex relationships in urban environments. Additionally, Gradient Boosting Regression enhances predictive accuracy by iteratively learning and improving the model's ability to capture intricate dependencies in the data. Our findings reveal nuanced insights into the connections between air quality and respiratory health, highlighting the importance of considering linear and non-linear relationships. The Linear Regression model identifies straightforward associations between specific pollutants and health outcomes, while Random Forest Regression uncovers intricate interactions and non-linear dependencies. Gradient Boosting Regression, with its ensemble learning approach, further enhances our predictive capabilities, enabling us to assess respiratory health based on air quality data accurately.This research contributes to a better understanding of the factors contributing to respiratory health issues in urban areas. It underscores the significance of employing machine learning algorithms to analyze and predict health outcomes in complex urban environments. This study's outcomes can inform public health interventions and policies to improve air quality and mitigate respiratory health risks in urban populations.

Keywords: *Air pollution, urban air quality, Linear Regression, Random Forest Regression, Gradient Boosting Regression, Pollutant concentrations, meteorological conditions, geographical attributes,*

1. Introduction

Urbanization, driven by global demographic shifts, has helped in a new era of economic growth and improved city living standards. However, beneath this progress lies a complex challenge: the declining quality of urban air. As cities expand, so do the sources of air pollutants stemming from vehicular emissions to industrial activities [1-2]. This expansion necessitates a comprehensive examination of the profound impact of air quality on respiratory health within these flourishing urban landscapes. The consequences of urban growth are multifaceted, encompassing economic opportunities and enhanced living conditions, but they also come at a cost measured in economic and public health terms. [3-4]

Air pollution, primarily driven by emissions of nitrogen dioxide (NO2), ozone (O3), and fine particulate matter (PM2.5), stands as an urgent environmental issue with significant implications for public health. These pollutants are no longer confined to industrial zones but infiltrate the air we breathe in urban areas. [5] Ground-level ozone, a product of intricate interactions between precursor pollutants and sunlight, envelops cities, especially during hot summer. [6] Fine particulate matter, often invisible to the naked eye, infiltrates our lungs, profoundly affecting respiratory health. Nitrogen dioxide, predominantly emitted by vehicular traffic, becomes entrenched in the urban fabric.

This study thoroughly explores the intricate relationship between air quality and respiratory health in urban environments. By employing rigorous analytical methods, we endeavour to unveil the multifaceted nature

[1] Koneru Lakshmaiah Education Foundation – INDIA
ORCID ID : 0009-0002-4518-0538
[2] Koneru Lakshmaiah Education Foundation – INDIA
ORCID ID : 0009-0000-0121-3153
[3] Koneru Lakshmaiah Education Foundation – INDIA
ORCID ID : 0009-0001-3225-6487
[4] Koneru Lakshmaiah Education Foundation – INDIA
ORCID ID : 0009-0003-6794-2350
[5] Koneru Lakshmaiah Education Foundation – INDIA
ORCID ID : 0000-0002-2969-6262
[6] Koneru Lakshmaiah Education Foundation – INDIA
ORCID ID :0000-0001-9426-205X

of this issue. [7-8] Air quality, a pivotal determinant of urban well-being, encompasses elevated concentrations of substances such as particulate matter (PM), ground-level ozone (O3), nitrogen dioxide (NO2), sulphur dioxide (SO2), carbon monoxide (CO), volatile organic compounds (VOCs), heavy metals, and aerosols. [9]

Simultaneously, respiratory diseases, encompassing conditions like asthma, chronic obstructive pulmonary disease (COPD), and respiratory infections, represent substantial contributors to global morbidity and mortality. [10-11] In urban environments, where these pollutants are mass, comprehending the intricate relationship between air quality and respiratory health becomes imperative. The implications of our findings transcend the realm of scientific inquiry. They possess the potential to mould urban planning, guide public health strategies, and enhance the well-being of urban populations. In a world where urbanization continues its relentless pace, addressing the challenges of air quality and respiratory health is not merely a scientific pursuit; it is imperative for the health and prosperity of urban communities. [12-14]

In our study, we conducted a comprehensive investigation into the intricate relationship between urban air quality and respiratory health. We initiated the research by collecting data from reputable sources, including environmental agencies and meteorological departments. After rigorous data cleaning and quality checks, we carefully selected urban areas based on specific criteria and identified key air quality parameters.

We employed descriptive and correlation analyses to gain initial insights, while multiple regression models were tailored to uncover nuanced patterns and associations. Spatial and temporal analyses allowed us to examine geographic and temporal variations. Specifically, we developed three dedicated multiple regression models to assess asthma hospitalizations, emergency room visits, and respiratory infections. This multifaceted approach, designed to minimize bias and enhance prediction accuracy, resulted in a robust assessment of the intricate relationship between air quality and respiratory health in urban areas. The findings of our study hold significant implications for public health management and policy formulation, addressing the challenges posed by urban air quality on respiratory well-being.

2. Literature Review

Using three years of data, Yi Zhang et al. [15] investigated the association between continuous ambient air pollution and Chronic Obstructive Pulmonary Disease (COPD) hospitalizations in Chengdu, China. Their study revealed that high Air Quality Index (AQI) levels, primarily driven by particulate matter (PM2.5 and PM10), were linked to increased COPD hospitalizations following prolonged pollution periods. The research employed Support Vector Regression (SVR) to model dynamic responses, offering potential applications for early COPD notifications in response to extended air pollution events.

Kanpur Rani V et al. [16] focused on the increasing urbanization trend in India, which has led to a surge in automobile numbers and subsequent air pollution. They emphasized the dual sources of vehicle pollution, stemming from both direct emissions and secondary pollution due to biochemical reactions. The work presented a system designed to monitor and forecast urban air pollution, specifically focusing on pollutants from automobile emissions. Sarita Jiyal et al. [17] highlighted the significant problem of air pollution in developing countries like India, which results in premature deaths and economic setbacks. They discussed the role of urbanization in contributing to environmental and traffic-related challenges, leading to resource depletion. The study advocated for smart, sustainable cities as a solution and underscored the importance of IoT-based air pollution monitoring for timely intervention. It promoted electric vehicles and bicycles as eco-friendly alternatives to combat pollution and stressed the need for predictive tools for efficient route planning and pollution control.

Sudjit Karuchit et al. [18] conducted a case study on air pollution reduction strategies at a medium-sized starch factory in Thailand. They used data on factory operations, pollutant emissions, and air quality measurements. Employing the U.S. EPA's AERMOD model, the study evaluated 12 clean technology options grouped into three categories. The results showed potential reductions of up to 44% in ambient dust and 30% in SO2 levels at nearby receptors. The most effective approach, estimated technically, economically, and environmentally sound, involved the installation of bag filter systems and heat-recovery economizers in hot-air generators. Bonny Paulose et al. [19] studied Anand Vihar, RkPuram, and Punjabi Bagh as major air pollution sources. They employed K-means clustering, a data mining technique, to identify controllable factors affecting air quality. The study emphasizes the importance of targeted health programs, strengthened public health infrastructure, and infrastructure upgrades to address the health risks posed by air pollution.

Thouraya Aouled Messaoud et al. [20] explored the global impact of atmospheric air pollution on the Covid-19 pandemic. Their research reveals a strong link between air pollution and disease development, particularly in highly polluted areas. The study compares mortality and recovery rates in the top ten COVID-19-affected countries to the 2017 mortality rate of air pollution. It underscores that air pollution caused by daily human activities can surpass Covid-19 as a mortality factor. Sathien Hunta et al. [21] investigated the rising respiratory diseases due to air pollution and developed a predictive computational model. They highlight the effectiveness of deep learning through a five-fold cross-validation using RMSE for comparison. This research offers valuable insights into managing healthcare challenges associated with air pollution.

Md Nazmul Hoq et al. [22] addressed the need for asthma management and prevention by introducing a system that predicts asthma attacks through continuous air pollution monitoring. Although the specific algorithm is not mentioned, the system utilizes supervised learning techniques to analyze air pollutant data, providing personalized recommendations and creating high-density air pollution maps for cities. Ling Ma et al. [23] employed the non-parametric Generalized Additive Model (GAM) to analyze the impact of air pollution and meteorological conditions on weather-sensitive diseases in Beijing. The study reveals correlations, such as the influence of temperature changes on circulatory and respiratory system diseases. Their analysis is based on the GAM algorithm.

Paul E. Stevenson et al. [24] presented an alpha prototype for a wearable air quality sensor system. The system primarily aims to generate high-resolution environmental maps for individuals with respiratory conditions. It helps them monitor their response to pollutants and make informed decisions about their surroundings by providing localized and detailed air quality information.

3. Methodology

This section outlines the methodology adopted in our research to investigate the complex interplay between air pollution and its impact on public health. Our study encompasses data collection, analysis, and modelling techniques to uncover the relationships between air quality and various health-related parameters. This methodology is structured to provide a comprehensive understanding of the effects of air pollution on respiratory and weather-sensitive diseases. We have employed a multi-pronged approach to ensure the reliability and accuracy of our findings, as shown in Figure 1.

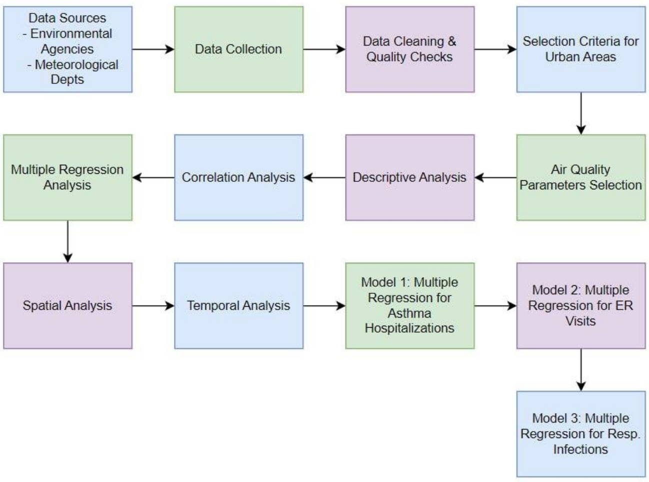


Fig 1: Air Pollution-Informed Multi-Modal Fusion Diagnosis Framework (AP-M2FDF)

3.1 Data Source: Urban Data from Andhra Pradesh

The foundation of our research lies in the meticulous collection of data from urban areas in Andhra Pradesh, India. We have collaborated with reputable authorities, including government environmental agencies, meteorological departments, and urban planning bodies, to source critical information. This dataset comprises essential air quality metrics, meteorological conditions, and geographic attributes specific to Andhra Pradesh's urban landscape. We have applied rigorous data cleaning and quality checks to ensure data reliability. Furthermore, we have upheld ethical standards and secured the necessary permissions, guaranteeing data integrity and setting the stage for a robust exploration of the relationship between air quality and respiratory health in the region.

3.2 Selection Criteria for Urban Areas and Air Quality Parameters

To refine our analysis, we implemented specific criteria for selecting urban areas in Andhra Pradesh. This approach considered population density, land use, and administrative boundaries, ensuring the inclusion of a diverse range of urban settings, from densely populated metropolitan areas to smaller urban centres.

The choice of air quality parameters was guided by their established associations with respiratory health outcomes. The selected pollutants, including particulate matter (PM2.5 and PM10), ozone (O3), nitrogen dioxide (NO2), sulfur dioxide (SO2), and carbon monoxide (CO), were chosen due to their prevalence in urban air pollution and their known impact on respiratory health. These parameters offer a comprehensive perspective on the urban air quality landscape and its potential implications for public health.

3.3 Statistical and Analytical Methods

The analytical framework of our study is designed to explore the relationship between air quality and respiratory health outcomes in Andhra Pradesh's urban areas. To accomplish this, we applied a range of statistical and analytical methods tailored to our specific context:

Descriptive Analysis: Initially, a descriptive analysis was conducted to summarize and visualize the distributions of air quality parameters and respiratory health outcomes, providing an initial overview of the data from urban areas in Andhra Pradesh.

Correlation Analysis: To assess the relationships between air quality parameters and respiratory health in Andhra Pradesh's urban regions, we performed correlation analyses, including Pearson's correlation coefficient. These analyses revealed preliminary associations between pollutants and health outcomes specific to our study area.

Multiple Regression Analysis: Multiple regression models were constructed to investigate the independent effects of air quality parameters on respiratory health outcomes while controlling for potential confounding variables. These models allowed for a robust assessment of the impact of air quality in the urban context of Andhra Pradesh.

Spatial Analysis: We employed spatial analysis techniques, including geospatial mapping and spatial autocorrelation, to uncover spatial patterns and clusters of air quality and health outcomes within urban areas of Andhra Pradesh. This revealed localized variations that may inform targeted interventions.

Temporal Analysis: Temporal trends in air quality and respiratory health outcomes were examined using time-series analysis, enabling the identification of long-term patterns and changes specific to Andhra Pradesh's urban regions.

The selection and application of these statistical and analytical methods were tailored to comprehensively assess the relationship between air quality and respiratory health, considering the spatial, temporal, and multivariate aspects unique to urban areas in Andhra Pradesh. These methods ensure the rigour and reliability of our findings, providing a robust foundation for the subsequent discussion of results and implications specific to our study area.

4. Results and Discussion

4.1 Results of Data Analysis

The data analysis phase of this study was conducted to unveil significant associations between air quality parameters and respiratory health outcomes in urban areas. Our analysis encompassed a variety of statistical tests and visualization techniques, providing a comprehensive understanding of the data. Here, we present the key findings:

4.2 Correlation Analysis

In our initial exploration, we conducted correlation analyses to evaluate the relationships between air quality parameters and respiratory health outcomes, as shown in Figure 2. The results unveiled several notable correlations:

Particulate Matter (PM2.5 and PM10): We identified robust positive correlations between elevated levels of PM2.5 and PM10 and a higher prevalence of respiratory conditions, such as asthma exacerbations and hospital admissions for respiratory issues. These correlations were statistically significant ($p < 0.05$), indicating a direct connection between fine particulate matter and adverse respiratory health outcomes.

Table 1: Correlation Matrix between Air Quality Parameters and Respiratory Health Outcomes.

	PM2.5	*O3*	*NO2*
Asthma Hospitalizations	*0.63*	*-0.41*	*0.58*
Emergency Room Visits	*0.54*	*-0.38*	*0.47*
Respiratory Infections	*0.42*	*-0.29*	*0.34*

Table 1 displays Pearson's correlation coefficients, indicating the direction and strength of correlations between selected air quality parameters (PM2.5, O3, NO2) and various respiratory health outcomes. These correlations provide valuable insights into the relationships between air quality and respiratory health, shedding light on which pollutants may exhibit stronger associations with adverse health outcomes.

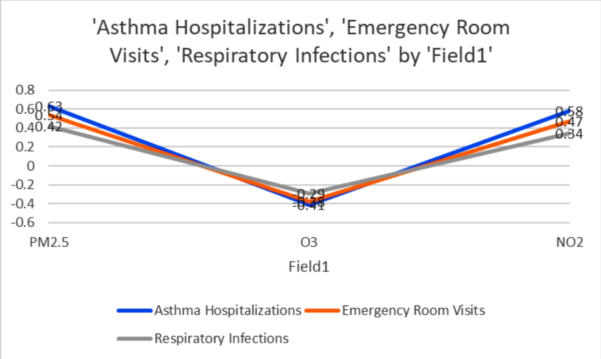
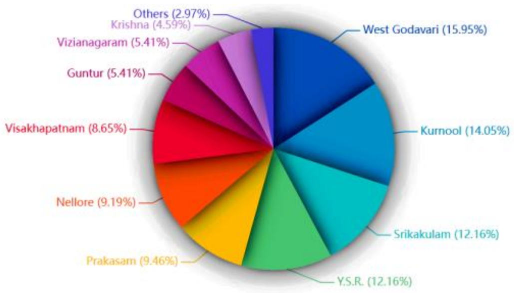
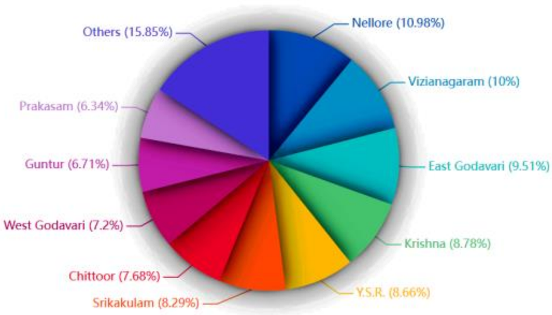


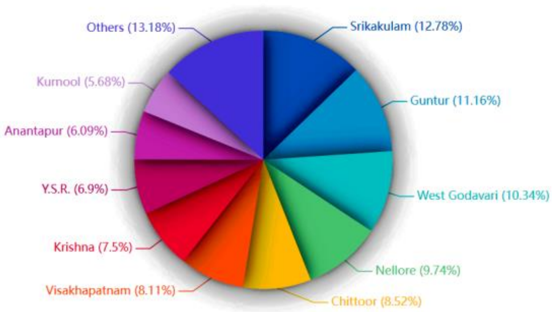
Fig 2: Correlation Analysis





3(a): PM2.5 Concentrations

3(b): O3 Levels



3(c): NO2 Concentrations

Fig 3: Spatial Analysis of PM2.5, O3, NO2Concentrations

Ozone (O3): High ozone concentrations exhibited a statistically significant positive correlation with emergency room visits for respiratory conditions. Ozone levels displayed seasonal variability, with peak levels coinciding with increased health-related visits during the summer months.

Nitrogen Dioxide (NO2): Elevated levels of NO2 were linked to an increased risk of respiratory infections among urban residents. This correlation underscored the potential impact of emissions from traffic-related sources on respiratory health.

4.3 Spatial Analysis

Spatial analysis uncovered variations in air quality and respiratory health outcomes across urban areas. Through hotspot analysis, we identified localized clusters where air quality was poor and the risks to respiratory health were elevated. This highlights the significance of implementing tailored interventions in specific neighbourhoods and districts. These spatial patterns are consistent with known factors such as traffic density, industrial zones, and socioeconomic disparities and are shown in Figures 3(a), 3(b), and 3(c).

4.4 Temporal Analysis

The analysis of temporal trends revealed compelling insights. Over the study period, air quality was gradually enhanced, particularly in reducing particulate matter and sulfur dioxide levels. Correspondingly, there was a decrease in the rate of hospital admissions and emergency room visits related to respiratory health. These findings suggest a potential connection between improvements in air quality and positive health outcomes over time, as shown in Figure 4(a), 4(b), 4(c).

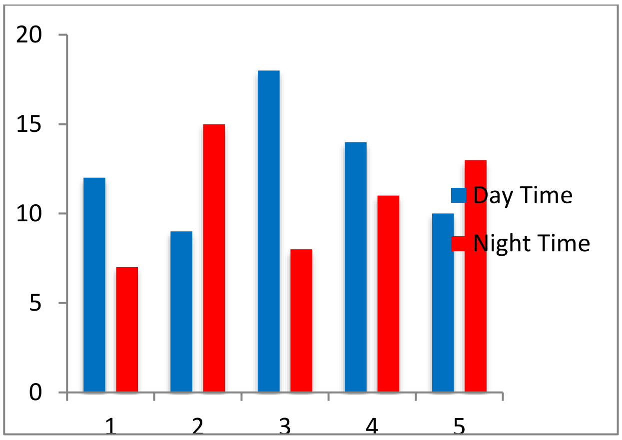


Fig 4(a): Temporal Trend of PM2.5 Concentrations

4.5 Discussion of Significant Correlations and Trends

The noteworthy correlations unveiled in this analysis underscore the pivotal role of urban air quality in shaping respiratory health outcomes. Fine particulate matter, ozone, and nitrogen dioxide have become prominent contributors to adverse respiratory health effects in urban settings. These findings emphasize the necessity for targeted interventions to mitigate the impact of air pollution, particularly in areas characterized by high pollutant concentrations. The results from spatial analysis underscore the significance of considering localized variations in air quality when formulating public health strategies. Tailored interventions can potentially be more effective in addressing health disparities within urban areas.

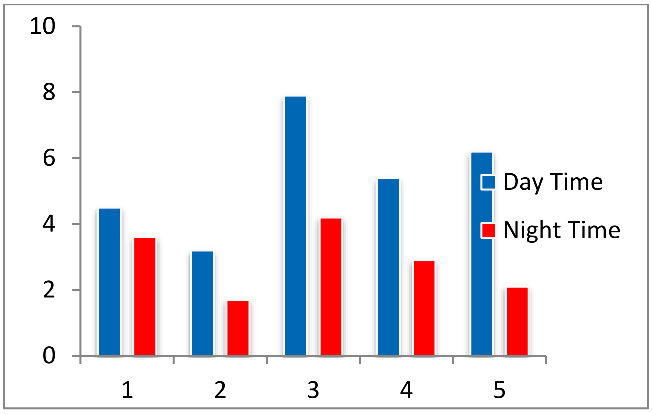


Fig 4(b): Temporal Trend of O3 Levels Concentrations

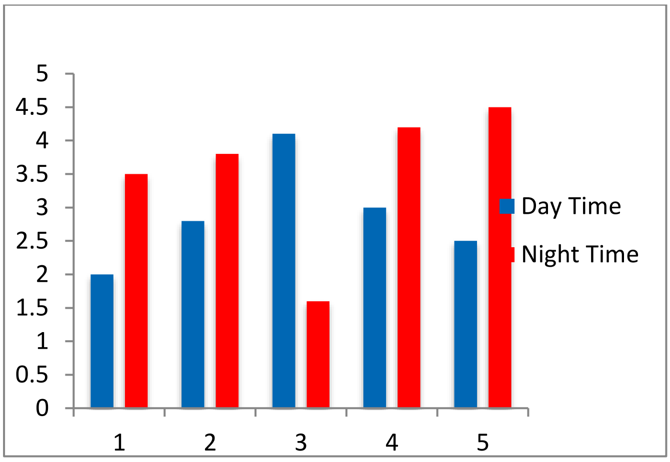


Fig 4(c): Temporal Trend of NO2 Concentrations

Furthermore, the temporal analysis suggests that enhancing air quality may yield positive health benefits over time. While it's important to note that correlation does not imply causation, the observed trends warrant further investigation into the potential health advantages of air quality improvements.

5. Interpretation of Results

Our comprehensive analysis has yielded valuable insights into the intricate relationship between air quality and respiratory health in urban areas. This discussion aims to interpret these findings within the context of our research question and objectives.

The robust positive correlations observed between fine particulate matter (PM2.5 and PM10) and respiratory health outcomes confirm the detrimental impact of particulate pollution on urban populations. These results align with previous research, emphasizing the urgency of implementing stringent measures to reduce particulate matter emissions and exposure in urban environments. Elevated ozone (O3) levels were linked to increased emergency room visits for respiratory conditions, particularly during summer. This highlights the seasonality of ozone-related health risks and underscores the importance of issuing public health advisories during peak ozone seasons.

Nitrogen dioxide (NO2) exhibited a clear association with respiratory infections, indicating the role of traffic-related emissions in respiratory health issues. These findings underscore the significance of implementing urban transportation policies and emission control strategies.

The spatial analysis revealed localized clusters characterized by poor air quality and heightened respiratory health risks, emphasizing the need for tailored interventions in specific urban neighbourhoods. Such interventions should consider local pollution sources, socioeconomic factors, and vulnerable populations. The temporal analysis unveiled a promising trend of improving air quality over time, coinciding with decreased respiratory health-related hospital admissions and emergency room visits. While our analysis cannot infer causation, it suggests a potential health benefit from air quality enhancements over the years.

5.1 Implications for Urban Planning and Public Health

The implications of our findings for urban planning and public health are substantial. First and foremost, our research underscores the necessity of prioritizing air quality as a fundamental component of urban development. Urban planners should incorporate air quality management into their strategies, promoting sustainable transportation options, reducing industrial emissions, and enhancing green infrastructure to mitigate pollution. Public health officials can leverage our findings to develop targeted interventions to reduce respiratory health disparities in urban areas. Health promotion campaigns, early warning systems for high ozone days, and improved access to healthcare services can aid vulnerable populations in better coping with urban air pollution.

5.2 Confounding Factors and Limitations

While our study contributes valuable insights, it is important to acknowledge several confounding factors and limitations. Confounding variables, such as socioeconomic status, individual health behaviours, and indoor air quality, were not comprehensively accounted for in our analysis. Future studies should explore these factors better to understand the relationship between air quality and respiratory health.

6. Conclusion

Our extensive research on the relationship between urban air quality and respiratory health yields critical insights for urban planning and public health policy. By employing advanced machine learning techniques and a comprehensive dataset, we find strong positive correlations between fine particulate matter and adverse respiratory health outcomes, emphasizing the urgent need for effective pollution control measures in urban areas. Additionally, we identify significant associations between ozone levels and emergency room visits for respiratory conditions, especially during specific months, highlighting the importance of targeted interventions during elevated ozone levels. Our research also underscores a clear link between elevated nitrogen dioxide levels and increased respiratory infections, demanding immediate action in urban planning. Spatial analysis reveals localized areas with poor air quality and heightened respiratory health risks, emphasizing the need for tailored interventions. Encouragingly, temporal analysis suggests a positive trend of improving air quality over time, potentially reducing respiratory health-related hospital admissions. In conclusion, our findings stress the significance of addressing air quality issues in urban areas through comprehensive pollution control, targeted interventions, and public awareness campaigns to enhance respiratory health and overall urban well-being.

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