Spatial Heterogeneity in the Vegetation Cover–Air Quality Relationship: Evidence from a Zone-Wise Assessment of Ahmedabad, India

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Abstract

Air pollution continues to pose a substantial threat to environmental sustainability and public health in rapid urbanizing cities, highlighting the need for evidence-based and nature-based mitigation strategies. Although urban vegetation has been widely recognized for its capacity to improve air quality, limited research has explored how the influence of vegetation varies across different urban zones or assessed the potential benefits of targeted greening interventions. This study addresses this gap by investigating the relationship between vegetation condition and air quality across the seven administrative zones of Ahmedabad Municipal Corporation (AMC), India.

Monthly Normalized Difference Vegetation Index (NDVI) values were derived from Sentinel-2 satellite imagery using Google Earth Engine, while monthly Air Quality Index (AQI) data were obtained from the National Air Quality Index (NAQI) monitoring network for the period 2021–2025. Correlation analysis was employed to examine the association between NDVI and AQI, followed by zone-wise linear regression modelling to quantify the influence of vegetation condition on air quality. Furthermore, scenario-based sensitivity analysis was conducted to evaluate the potential impact of hypothetical changes in vegetation condition across different administrative zones.

The findings demonstrate a consistent inverse relationship between NDVI and AQI across Ahmedabad, indicating that healthier and denser vegetation is generally associated with improved air quality. However, the magnitude of this relationship varies considerably among zones, revealing significant spatial heterogeneity in vegetation–air quality interactions. The regression models confirmed that the influence of vegetation on air quality is location-dependent, while the sensitivity analysis identified priority zones where improvements in vegetation condition are expected to yield comparatively greater reductions in air pollution. These findings suggest that uniform city-wide greening programmes may not produce optimal environmental outcomes and that spatially targeted interventions are likely to be more effective.

By combining satellite-derived vegetation monitoring, official air-quality observations, zone-wise regression modelling, and sensitivity analysis, this study proposes a practical decision-support framework for prioritizing urban greening initiatives. The proposed methodology provides a scientifically robust and transferable approach for supporting evidence-based urban planning, sustainable environmental management, and nature-based air pollution mitigation in rapidly growing cities.

Keywords: Air Quality Index (AQI); Normalized Difference Vegetation Index (NDVI); Google Earth Engine; Remote sensing; Urban greening; Linear regression; Sensitivity analysis; Sustainable urban planning

Introduction

Urban air pollution has emerged as one of the most critical environmental challenges of the twenty-first century, posing significant threats not only to human health but also to ecological stability and sustainable urban development. Rapid urbanization, industrial expansion, increasing vehicular traffic and changing land-use patterns have substantially intensified atmospheric pollution across cities worldwide. According to the World Health Organization (WHO, 2022), exposure to ambient air pollution is associated with millions of premature deaths annually and contributes to respiratory illnesses, cardiovascular diseases, and reduced quality of life. Consequently, improving urban air quality has become a global priority under the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

India has witnessed unprecedented urban growth over the past few decades, accompanied by increasing environmental pressures. Many Indian metropolitan cities consistently record air-quality levels exceeding the permissible limits prescribed by the National Ambient Air Quality Standards (NAAQS), thereby affecting both environmental sustainability and public health (Central Pollution Control Board [CPCB], 2024). Ahmedabad, one of India's fastest-growing metropolitan cities and the commercial hub of Gujarat, has experienced rapid infrastructure development, population growth, expansion of transportation

networks, redevelopment of residential areas and increasing construction activities. While these developments have accelerated economic progress, they have simultaneously intensified environmental stress, making the city an appropriate case for investigating urban vegetation–air quality interactions.

Among various strategies proposed for mitigating urban air pollution, nature-based solutions have gained increasing attention because of their ecological, economic and social benefits. Urban vegetation functions as a natural environmental regulator by intercepting particulate matter, absorbing gaseous pollutants, moderating urban temperatures, sequestering atmospheric carbon, conserving biodiversity and improving residents' quality of life (Nowak et al., 2014; Escobedo et al., 2011). These multiple ecosystem services have positioned urban greening as an important component of sustainable environmental planning and climate-resilient city development. As sustainable urban management increasingly integrates ecological approaches with environmental policy, the scientific assessment of vegetation–air quality relationships has become an important area of environmental research (Jani & Bhojak, 2025).

Traditionally, urban vegetation has been evaluated using indicators such as green-cover area or tree-canopy extent. However, obtaining reliable, spatially consistent, and temporally comparable green-cover datasets remains challenging, particularly at the administrative-zone level in rapidly expanding cities. In Ahmedabad, comprehensive and continuous zone-wise green-cover data covering the study period were not available from authentic public sources. Therefore, the present study employs the Normalized Difference Vegetation Index (NDVI) as a scientifically accepted proxy for vegetation condition. Derived from satellite reflectance measurements, NDVI represents vegetation health, density and photosynthetic activity rather than merely the physical extent of green spaces (Tucker, 1979; Pettorelli, 2013). Since the capacity of vegetation to mitigate air pollution depends not only on its quantity but also on its physiological condition, NDVI provides a more comprehensive indicator for evaluating vegetation–air quality interactions.

Recent advances in Earth observation technologies and cloud-based geospatial platforms have transformed environmental monitoring by enabling continuous assessment of urban ecosystems at high spatial and temporal resolutions. Google Earth Engine (GEE), integrated with Sentinel-2 satellite imagery, provides an efficient and reproducible platform for extracting vegetation information over large geographical areas. The integration of remotely sensed vegetation indicators with official environmental monitoring data has substantially enhanced the ability of researchers to examine urban environmental processes and support evidence-based planning.

Against this background, the present study investigates the relationship between vegetation condition and air quality across the seven administrative zones of Ahmedabad Municipal Corporation. Unlike many previous studies that primarily examine city-level relationships, this research adopts a zone-wise analytical framework that combines satellite-derived NDVI, official Air Quality Index (AQI) observations, correlation analysis, linear regression modelling and scenario-based sensitivity analysis. This integrated approach enables not only the examination of vegetation–air quality relationships but also the assessment of how hypothetical improvements in vegetation condition may influence air quality across different urban zones. The study seeks to contribute to the growing field of remote sensing–based urban environmental assessment by providing a spatially explicit framework for identifying priority areas where vegetation enhancement may produce greater environmental benefits. The findings are expected to support evidence-based urban greening strategies and assist policymakers in integrating nature-based solutions into sustainable urban planning and air-quality management.

The specific objectives of the study are:

- To examine temporal and spatial variations in NDVI and AQI across Ahmedabad Municipal Corporation zones during 2021–2025.
- To evaluate the relationship between vegetation condition and air quality using zone-wise statistical analysis.
- To assess the sensitivity of AQI to hypothetical changes in NDVI across different administrative zones.
- To identify priority zones where vegetation enhancement initiatives may generate the greatest air-quality benefits.

By integrating remote sensing, environmental monitoring, regression and sensitivity analysis, the study contributes to the growing literature on urban environmental sustainability and provides practical insights for policymakers seeking to incorporate nature-based solutions into urban air-quality management and sustainable urban development.

2. Literature Review and Research Gap

Urban air pollution has emerged as one of the most critical environmental challenges associated with rapid urbanization, industrialization, increasing vehicular emissions, and changing land-use patterns. Exposure to poor air quality has been linked to respiratory illnesses, cardiovascular diseases, ecosystem degradation, and reduced urban livability. Consequently, improving urban air quality has become a major objective of sustainable urban development and environmental management strategies worldwide (Khan et al., 2022).

Among various mitigation approaches, urban vegetation has received considerable attention as a nature-based solution for improving environmental

quality. Trees, parks, urban forests, and green corridors contribute to pollutant removal through interception, deposition, absorption, and dispersion processes. Vegetation also regulates urban microclimates, reduces dust resuspension, and enhances ecological resilience. As a result, urban greening initiatives are increasingly being integrated into sustainable city planning frameworks to address air pollution and climate-related challenges (Vashist et al., 2024).

Advances in remote sensing have significantly enhanced the ability to monitor vegetation dynamics across space and time. The Normalized Difference Vegetation Index (NDVI) has emerged as one of the most widely used indicators for quantifying vegetation cover due to its consistency and applicability across different geographical contexts. NDVI has been extensively applied in studies investigating urban greenness, ecological health, land-use change, urban heat islands, and environmental quality. In developing-country contexts, where consistent long-term vegetation datasets are often unavailable, NDVI serves as a reliable proxy for assessing urban vegetation cover and facilitating spatial comparisons (Sharma et al., 2023).

A growing body of literature has examined the relationship between vegetation cover and air quality. Studies conducted across Asia, Europe, and North America generally report a negative association between vegetation density and air pollution levels, indicating that greener urban environments tend to experience improved air quality conditions (Khan et al., 2022). Similar observations have been reported in several Indian cities, where urban vegetation has been associated with reduced concentrations of particulate matter and enhanced environmental quality. However, researchers have also noted that the magnitude of this relationship varies considerably across urban settings due to differences in traffic intensity, industrial emissions, urban morphology, built-up density, meteorological conditions, and land-use composition (He et al., 2022).

Despite the growing literature on vegetation–air quality interactions, important limitations remain. Many studies continue to rely on city-wide averages or regional-scale assessments that implicitly assume a spatially uniform relationship between vegetation and air quality. Such approaches often overlook intra-urban variability and fail to capture localized environmental dynamics. Recent studies have emphasized that environmental conditions can differ substantially within the same city and that the effectiveness of vegetation in mitigating air pollution may vary across urban zones characterized by different land-use patterns, population densities, transportation networks as well as industrial activities (He et al., 2022; Verghese & Nema, 2023).

Understanding these spatial differences is particularly important in rapidly urbanizing Indian cities. Ahmedabad represents a relevant case due to its rapid urban expansion, industrial development, transportation growth, and persistent air-quality concerns. Although previous studies have investigated air pollution and environmental conditions in Ahmedabad and other Indian metropolitan regions, comprehensive assessments integrating multi-year Air Quality Index (AQI) observations with zone-wise vegetation indicators remain limited. Furthermore, relatively little attention has been given to examining how sensitive air quality conditions are to changes in vegetation cover within different urban zones.

Research Gap

The existing literature reveals three important gaps. Firstly, most studies examine vegetation–air quality relationships at city-wide or regional scales, while limited attention has been given to intra-urban spatial heterogeneity within rapidly growing cities. Secondly, few investigations have evaluated how the strength of the vegetation–air quality relationship varies across different urban zones characterized by distinct environmental and land-use conditions. Thirdly, although correlation-based assessments are common, limited research has quantified the sensitivity of air quality to changes in vegetation cover, particularly within the context of Indian metropolitan regions.

To address these gaps, the present study conducts a zone-wise assessment of Ahmedabad using Air Quality Index (AQI) data and satellite-derived Normalized Difference Vegetation Index (NDVI) estimates for the period 2021–2025. Unlike conventional city-level analyses, the study investigates the spatial heterogeneity of vegetation–air quality interactions and quantifies the sensitivity of AQI to changes in vegetation cover across different urban zones. The findings are expected to contribute to the growing body of knowledge on urban environmental sustainability while providing evidence-based insights for urban greening strategies and air-quality management in rapidly urbanizing cities.

3. Materials and Methods

3.1 Study Area

Ahmedabad, located in the western Indian state of Gujarat, is one of the fastest-growing metropolitan regions in the country. The city has experienced rapid urbanization, industrial expansion, infrastructural development, and increasing vehicular traffic over the past two decades. These developments have intensified environmental concerns, particularly with respect to deteriorating air quality and changing urban green spaces.

Ahmedabad experiences a semi-arid climate characterized by hot summers, a monsoon season extending from June to September, and relatively mild winters. The city comprises diverse land-use categories, including residential, commercial, industrial, and transportation corridors, distributed across multiple administrative zones. Owing to these spatial variations in urban characteristics, Ahmedabad provides an appropriate setting for

investigating intra-urban differences in the relationship between vegetation cover and air quality. The present study was conducted across seven administrative zones of the Ahmedabad Municipal Corporation (AMC), namely West, South, North, Central, East, North-West, and South-West Zones.

3.2 Data Sources

Table 1.

Variable	Source	Temporal Resolution	Spatial Resolution	Study Period	Purpose
Air Quality Index (AQI)	National Air Quality Index (NAQI), Central Pollution Control Board (CPCB), Government of India	Monthly	Monitoring stations aggregated to AMC zones	2021-2025	Assessment of air quality conditions
NDVI	Sentinel-2 imagery processed using Google Earth Engine	Monthly composites	10 m	2021-2025	Assessment of vegetation condition and density
Administrative Boundaries	Ahmedabad Municipal Corporation (AMC)	Static	Seven administrative zones	Study period	Zone-wise aggregation and analysis
Statistical Analysis	Descriptive statistics, Correlation Analysis, Regression Analysis, Sensitivity analysis	Monthly observations	Zone-wise	2021-2025	Evaluation of vegetation–air quality relationships

The study utilized two primary datasets: Air Quality Index (AQI) data and vegetation data represented by the Normalized Difference Vegetation Index (NDVI). The study period extended from January 2021 to December 2025.

AQI data were obtained from monitoring stations operating under the National Air Quality Index (NAQI) framework administered by the Central Pollution Control Board (CPCB), Government of India. Monthly AQI observations were compiled for the selected monitoring stations located within Ahmedabad.

Vegetation information was derived from satellite imagery using NDVI. NDVI values were extracted through Google Earth Engine (GEE) using Sentinel-2 satellite imagery and subsequently aggregated at the zone level.

3.3 AQI Data Collection and Processing

Monthly AQI observations for Ahmedabad were obtained from official monitoring stations operating under the National Air Quality Index programme. The collected AQI records were verified and organized to ensure consistency throughout the study period.

The monitoring stations were assigned to their corresponding administrative zones based on geographic location. Zone-wise AQI values were subsequently generated through aggregation of station-level observations. This procedure enabled the development of a spatially comparable AQI database representing the seven AMC zones from 2021 to 2025. The use of official AQI records ensured reliability and authenticity of the air quality data employed in the analysis.

3.4 NDVI Data Acquisition and Processing Using Google Earth Engine

NDVI data were obtained using Google Earth Engine, a cloud-based geospatial processing platform providing access to extensive satellite image archives and analytical capabilities.

Sentinel-2 multispectral imagery was employed for the analysis owing to its high spatial resolution (10 m) and suitability for urban vegetation monitoring. Ahmedabad Municipal Corporation zone boundaries were used to delineate the study area.

Satellite observations covering the period from January 2021 to December 2025 were processed. Images affected by excessive cloud contamination were excluded from the analysis to ensure data quality. Monthly cloud-free composite images were generated to minimize atmospheric disturbances and temporary cloud effects.

NDVI was calculated using the standard equation:

$$NDVI = (NIR - Red) / (NIR + Red)$$

where NIR represents near-infrared reflectance and Red represents red-band reflectance.

NDVI is a dimensionless vegetation index with values ranging from −1 to +1. Negative values generally represent water bodies and non-vegetated surfaces, values close to zero indicate built-up or barren areas, whereas higher positive values represent increasing vegetation density and healthier vegetation.

3.5 Zone-Wise NDVI Estimation

A zonal statistical approach was employed to obtain representative NDVI values for each administrative zone of Ahmedabad.

Following NDVI calculation at the pixel level, the mean NDVI value of all pixels within each zone was computed for every month of the study period. This process generated a continuous monthly NDVI dataset for all seven AMC zones from January 2021 to

December 2025.
The resulting NDVI values represented the overall vegetation condition of each zone during a particular month. Higher NDVI values indicated healthier and denser vegetation, while lower values suggested sparse vegetation, built-up dominance, or reduced vegetation density.

3.6 Justification for the Use of NDVI

The present study was initially conceptualized to investigate the relationship between urban green cover and air quality across Ahmedabad. However, authentic, spatially consistent, and temporally comparable green-cover datasets at the zone level were not readily available for the entire study period.
Conventional green-cover estimates generally quantify the extent of vegetated area but do not adequately capture vegetation condition, density, or seasonal dynamics. In contrast, NDVI provides a continuous measure of vegetation vigor, density, and photosynthetic activity derived directly from satellite observations.
Unlike percentage green-cover estimates, NDVI captures subtle temporal variations in vegetation condition and reflects characteristics that influence pollutant interception and deposition processes. Since the effectiveness of vegetation in improving air quality depends not only on the quantity of vegetation but also on its health, density, and physiological activity, NDVI was considered a more appropriate indicator for examining vegetation–air quality interactions.
Furthermore, NDVI has been widely adopted in studies related to urban air quality, urban heat islands, carbon sequestration, ecological health, and vegetation dynamics, thereby facilitating comparison of the present findings with existing scientific literature.

3.7 Integration of AQI and NDVI Datasets

The zone-wise AQI and NDVI datasets were integrated to establish a spatially and temporally consistent analytical database.
For each administrative zone, corresponding monthly AQI and NDVI observations were matched for the period 2021–2025. The resulting dataset enabled investigation of the relationship between vegetation condition and air quality across Ahmedabad while accounting for intra-urban spatial differences.

3.8 Statistical Analysis

Descriptive and inferential statistical techniques were employed to evaluate vegetation–air quality relationships across the study area.

3.8.1 Descriptive Analysis

Descriptive statistics were used to summarize variations in AQI and NDVI across different zones. Mean values and temporal patterns were examined to identify differences in environmental conditions within Ahmedabad.

3.8.2 Correlation Analysis

Karl Pearson's correlation coefficient was employed to assess the direction and strength of association between NDVI and AQI across the seven zones.
A negative correlation coefficient indicated that higher vegetation density was associated with lower AQI values and consequently improved air quality conditions.

3.8.3 Regression Analysis

To quantify the influence of vegetation condition on air quality, simple linear regression analysis was performed separately for each administrative zone. Monthly NDVI values were considered the independent variable, whereas monthly AQI values were treated as the dependent variable. Separate regression models were developed to estimate the extent to which variations in vegetation condition explain changes in air quality across different zones.
The regression model used in the study is represented as:

$$AQI = \beta_0 + \beta_1(NDVI) + \varepsilon$$

where:
AQI = Air Quality Index (dependent variable)
NDVI = Normalized Difference Vegetation Index (independent variable)
β_0 = Intercept
β_1 = Regression coefficient
ε = Random error term
The regression coefficient (β_1) was used to determine the direction and magnitude of the influence of vegetation condition on air quality, while the coefficient of determination (R^2) was used to evaluate the proportion of variation in AQI explained by NDVI. The regression equations obtained for each zone subsequently served as the basis for the scenario-based sensitivity analysis.

3.8.4 Scenario-Based Sensitivity Analysis

The regression equations developed for each administrative zone were further used to perform a scenario-based sensitivity analysis. Hypothetical changes of −10%, −5%, +5%, and +10% in NDVI were introduced to estimate the corresponding changes in AQI while keeping all other components constant. Eventually, this approach enabled the assessment of the relative sensitivity of different zones to changes in vegetation condition and facilitated the identification of priority areas where urban greening initiatives are likely to produce greater improvements in air quality.

3.9 Methodological Framework

The methodological framework implemented in this study comprised the following stages:

- Collection of monthly AQI data from National AQI monitoring stations.
- Acquisition of Sentinel-2 imagery through Google Earth Engine.
- Generation of monthly cloud-free composite

images.
- Calculation of NDVI using Sentinel-2 spectral bands.
- Extraction of zone-wise mean NDVI values using zonal statistics.
- Aggregation of AQI observations according to AMC administrative zones.
- Integration of AQI and NDVI datasets.
- Descriptive statistical analysis.
- Correlation analysis.
- Regression analysis.
- Sensitivity analysis.
- Interpretation of spatial heterogeneity in vegetation–air quality relationships across Ahmedabad.

3.10 Research Hypothesis

Null Hypothesis (H_0):

There is no statistically significant negative correlation between vegetation condition (measured using the Normalized Difference Vegetation Index (NDVI)) and Air Quality Index (AQI) across the administrative zones of Ahmedabad.

Alternative Hypothesis (H_1):

There is a statistically significant negative correlation between vegetation condition (measured using the Normalized Difference Vegetation Index (NDVI)) and Air Quality Index (AQI) across the administrative zones of Ahmedabad.

4. Results

4.1 Temporal Trends in AQI and NDVI (2021–2025)

In order to understand the broader environmental context of Ahmedabad, annual average NDVI and AQI values were examined for the period 2021–2025 as mentioned in Table 1. Although year-to-year variations were not substantial but noticeable fluctuations were observed in both vegetation condition and air quality.

Table 2. Year-wise Average AQI and NDVI Across Ahmedabad

Year	Average NDVI	Average AQI
2021	0.1869	101.57
2022	0.1766	123.68
2023	0.1785	109.00
2024	0.1839	114.35
2025	0.1865	104.89

It is revealed from the collected data that 2022 was the least favourable year from an environmental viewpoint. During this year, Ahmedabad recorded its lowest average NDVI (0.1766) along with the highest average AQI (123.68). Such conditions suggest reduced vegetation condition and comparatively poorer air quality. On the contrary, 2021 exhibited the highest NDVI (0.1869) and the lowest AQI (101.57). This reflects healthier vegetation and better air quality.

Following the decline observed in 2022, the average NDVI gradually increased during the subsequent years, reaching 0.1865 in 2025. A relating improvement in air quality was also observed, although the trend was not uniform since AQI increased slightly in 2024 before declining again in 2025. These fluctuations indicate that while vegetation condition may influence air quality, annual AQI is also affected by multiple interacting factors, including meteorological conditions and human caused emission sources however NDVI or green cover does contribute. It is largely interpretated that the observed temporal pattern suggests that years with comparatively healthier vegetation condition, as represented by higher NDVI values, generally coincided with lower AQI levels. Although this observation does not establish causality, it indicates that vegetation condition may contribute to improved urban environmental quality, warranting further statistical examination.

The preliminary trends observed in Table 1 suggest a potential inverse association between vegetation condition and air quality. As NDVI is widely used as a proxy for urban green cover, the findings indicate that healthier vegetation may be associated with improved air quality. However, this observation is descriptive in nature and requires statistical validation through correlation and regression analyses, which are presented in the subsequent sections.

Therefore, the annual city-wide averages serve only as background information whereas the subsequent analyses focus on the zone-wise relationship between NDVI and AQI to provide a more detailed understanding of how vegetation condition influences air quality across Ahmedabad.

4.2 Zone-wise Variation in Vegetation Condition (NDVI) and Air Quality (AQI)

To examine the spatial variability in vegetation condition and air quality, the mean NDVI and AQI values were calculated for each of the seven administrative zones of Ahmedabad during the study period. The results reveal considerable differences in environmental conditions across the city. This indicates that vegetation distribution and air quality are not spatially uniform.

Table 3. Zone-wise Mean AQI and NDVI

Zone	Mean AQI	Mean NDVI
West	105.78	0.167
South	117.73	0.198
North	105.37	0.208
Central	128.87	0.106
East	109.07	0.184
North-West	91.20	0.213
South-West	120.38	0.201

As presented in Table 3, considerable variation was observed in both vegetation condition and air quality across Ahmedabad. The Central Zone recorded the highest mean AQI (128.87) and the lowest mean NDVI (0.106), indicating comparatively poorer vegetation condition and greater environmental stress. This zone is characterised by dense commercial establishments, mixed residential development, heavy vehicular movement, and limited availability of open green spaces, all of which may contribute to elevated air pollution levels.

In contrast, the North-West Zone exhibited the lowest mean AQI (91.20) and the highest mean NDVI (0.213), suggesting comparatively healthier vegetation and better air quality. The North Zone also demonstrated relatively favourable environmental conditions, recording a high mean NDVI (0.208) together with a comparatively lower AQI (105.37). These findings indicate that areas with healthier vegetation generally tend to experience better air quality.

The South-West Zone displayed a relatively high NDVI (0.201) but also recorded a comparatively high AQI (120.38). Similarly, the South Zone exhibited moderate vegetation condition (NDVI = 0.198) while maintaining relatively elevated AQI levels (117.73). These observations suggest that vegetation alone does not determine urban air quality. Industrial activities, ongoing construction, infrastructure development, vehicular emissions, and other anthropogenic sources are also likely to influence pollution levels within these zones.

All in all, an inverse spatial pattern between vegetation condition and air quality across Ahmedabad is revealed by descriptive analysis. However, the relationship is not uniform across all administrative zones which means that local land-use characteristics and emission sources may moderate the influence of vegetation on air quality. Therefore, correlation analysis was subsequently performed to statistically evaluate the strength and direction of the relationship between NDVI and AQI across the seven administrative zones.

4.3 Relationship Between NDVI and AQI

Table 4.

Zone	Correlation Coefficient (r)	Interpretation
West	−0.828	Very strong negative
South	−0.572	Moderate negative
North	−0.602	Moderate negative
Central	−0.737	Strong negative
East	−0.617	Moderate negative
North-West	−0.756	Strong negative
South-West	−0.800	Very strong negative

As presented in Table 4, negative correlation coefficients were observed across all seven administrative zones, indicating an inverse relationship between vegetation condition and air quality. In general, higher NDVI values were associated with lower AQI values. This clearly suggests that areas with healthier vegetation tended to experience comparatively better air quality.

The West Zone exhibited the strongest negative correlation ($r = -0.828$), closely followed by the South-West Zone ($r = -0.800$). These findings indicate a very strong inverse association between NDVI and AQI. Strong negative correlations were also observed in the North-West ($r = -0.756$) and Central ($r = -0.737$) zones, suggesting strongly that vegetation condition has a substantial association with air quality in these areas.

Thereafter,moderate negative correlations were observed in the East ($r = -0.617$), North ($r = -0.602$), and South ($r = -0.572$) zones. Although the strength of the association was comparatively lower in these zones, the consistently negative coefficients indicate that improved vegetation condition was generally associated with reduced air pollution across all administrative zones.

It can be clearly understood by the study that such correlation analysis provides statistical evidence of an inverse relationship between NDVI and AQI throughout Ahmedabad. Based on the statistical significance of the correlation coefficients ($p < 0.05$), the null hypothesis (H_0) was failed to be accepted and therefore it provides evidence in support of the alternative hypothesis (H_1), which states that a statistically significant negative correlation exists between vegetation condition and air quality across the administrative zones of Ahmedabad. However, correlation analysis alone does not quantify the extent to which changes in vegetation condition influence AQI. Therefore, linear regression analysis was subsequently performed to estimate the magnitude of

this relationship

4.4Regression Analysis

Zone	Regression Coefficient (β_1)	R^2	p-value	Interpretation
West	-640.65	0.686	<0.001	Strong negative relationship; NDVI explains 68.6% of AQI variation.
South	-327.94	0.327	<0.001	Moderate negative relationship; vegetation explains 32.7% of AQI variation.
North	-440.46	0.362	<0.001	Moderate negative relationship; NDVI explains 36.2% of AQI variation.
Central	-1153.34	0.543	<0.001	Strongest vegetation effect among all zones; NDVI explains 54.3% of AQI variation.
East	-501.41	0.381	<0.001	Significant negative relationship; vegetation explains 38.1% of AQI variation.
North-West	-416.76	0.572	<0.001	Strong negative relationship; NDVI explains 57.2% of AQI variation.
South-West	-624.81	0.640	<0.001	Strong negative relationship; NDVI explains 64.0% of AQI variation.

To further examine the relationship between vegetation condition and air quality, simple linear regression analysis was carried out for each administrative zone. While the correlation analysis established the existence of an inverse relationship, regression analysis quantified the extent to which changes in NDVI were associated with changes in AQI.

The regression coefficients were negative across all seven administrative zones, confirming that higher NDVI values were consistently associated with lower AQI levels. In other words, improvements in vegetation condition were generally accompanied by better air quality, although the magnitude of this relationship varied from one zone to another.

The Central Zone recorded the largest regression coefficient (β_1 = −1153.34), indicating the strongest association between vegetation condition and AQI among all zones. This finding is noteworthy because the Central Zone also had the lowest mean NDVI and the highest mean AQI. It is studied that environmental improvements in this densely developed part of the city could yield substantial benefits if vegetation condition is enhanced alongside effective emission-control measures.

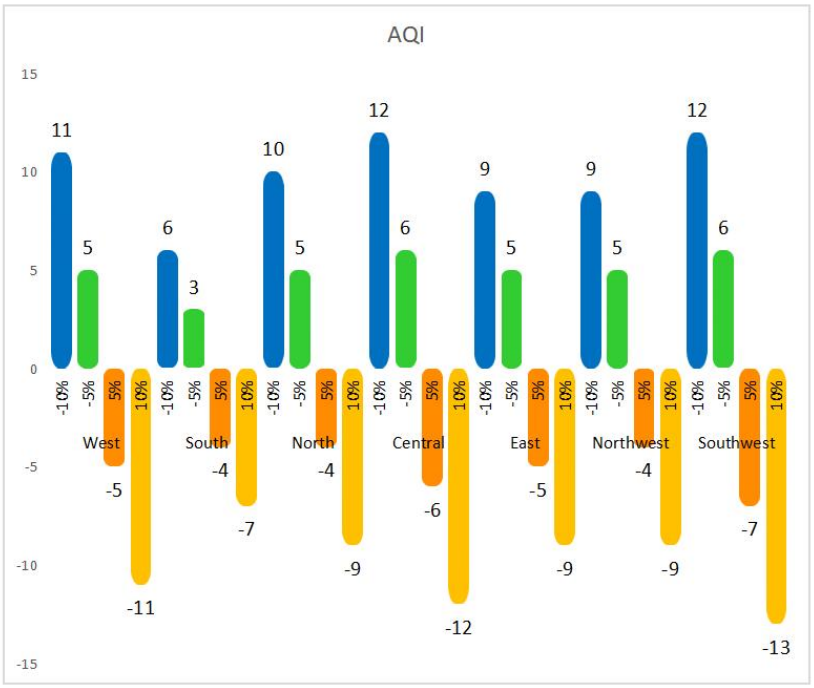
The West (β_1 = −640.65) and South-West (β_1 = −624.81) zones also exhibited strong negative regression coefficients, reflecting a substantial association between vegetation condition and air quality. In contrast, the South Zone showed the smallest regression coefficient (β_1 = −327.94). This comparatively weaker relationship may be attributed to the influence of industrial activities, construction, traffic emissions, and other local pollution sources that continue to affect air quality despite the presence of vegetation.

The coefficient of determination (R^2) varied across the administrative zones, indicating differences in the proportion of AQI variation explained by NDVI. The highest explanatory power was observed in the West Zone (R^2 = 0.686), where vegetation condition accounted for 68.6% of the variation in AQI. Similarly, relatively high explanatory power was observed in the South-West (64.0%), North-West (57.2%), and Central (54.3%) zones. Lower R^2 values were recorded in the South (32.7%), North (36.2%), and East (38.1%) zones. The studied data suggests that additional environmental and anthropogenic factors also contribute to air-quality variation in these areas.

All regression models were statistically significant ($p < 0.001$), providing strong evidence that the observed relationships were unlikely to have occurred by chance. These findings reinforce the results of the Pearson correlation analysis and demonstrate that vegetation condition is a significant predictor of air quality across Ahmedabad. However, the variation in regression coefficients and R^2 values also highlights that the effectiveness of urban greening differs across administrative zones, emphasizing the need for location-specific environmental planning rather than a uniform city-wide approach.

4.4 Sensitivity Analysis of AQI to Changes in NDVI

Sensitivity analysis was conducted to estimate the potential impact of changes in vegetation condition on air quality across the seven administrative zones. Using the regression coefficients obtained from the linear regression models, hypothetical scenarios representing + or - 10% changes in NDVI were developed to assess the corresponding changes in AQI. The analysis provides an indication of how improvements or reductions in vegetation condition could influence air quality under existing environmental conditions.



The results revealed substantial differences in AQI responsiveness across zones (Table 5). This shows that the environmental benefits associated with urban vegetation are not spatially uniform within the city. The Central Zone and South-West Zone exhibited the highest sensitivity to changes in NDVI. A hypothetical 10% decline in NDVI in these zones corresponded to increases of approximately 12–13 AQI units, whereas a 10% improvement in NDVI was associated with reductions of similar magnitude. These findings suggest that even modest improvements in vegetation condition within these zones may yield meaningful air-quality benefits.

In contrast, the South Zone demonstrated comparatively lower sensitivity, with similar changes in NDVI resulting in smaller variations in AQI. This observation implies that factors other than vegetation, such as traffic congestion, industrial emissions, localized pollution sources, or built-up density, may exert a stronger influence on air quality within this part of the city.

Largely, the sensitivity analysis complements the correlation findings by demonstrating that although healthier vegetation is associated with improved air quality across Ahmedabad, the magnitude of this benefit varies considerably among zones. Consequently, uniform greening initiatives may not generate equivalent outcomes throughout the city. Instead, environmental interventions should be prioritized in areas where air quality exhibits greater responsiveness to vegetation improvements.

Interesting Findings

Two findings from the sensitivity analysis bring particular attention.

First, the Central Zone, which recorded the highest average AQI and the lowest mean NDVI, also emerged as one of the zones most responsive to changes in vegetation condition. This suggests that the environmentally most vulnerable part of Ahmedabad may also possess substantial potential for improvement through targeted greening interventions.

Second, the South-West Zone exhibited the largest potential reduction in AQI associated with improvements in NDVI. This indicates that investments aimed at enhancing vegetation quality and density in this zone could generate comparatively greater air-quality benefits than similar interventions elsewhere.

These observations highlights the importance of adopting evidence-based and zone-specific urban greening strategies rather than implementing generalized city-wide approaches. The findings provide a practical framework for policymakers to identify priority areas where vegetation enhancement initiatives may contribute most effectively to improving urban air quality.

5. Discussion

The present study demonstrated a significant inverse relationship between vegetation condition (NDVI) and AQI across all seven administrative zones of Ahmedabad. Both the correlation and regression analyses confirmed that healthier vegetation is generally associated with improved air quality. However, the strength of this relationship varied considerably among the zones, indicating that vegetation alone does not determine urban air quality and that local land-use characteristics and emission sources also influence environmental conditions.

5.1 Relationship Between Vegetation Condition and Air Quality

The present study confirms a statistically significant inverse relationship between vegetation condition (NDVI) and air quality (AQI) across all seven administrative zones of Ahmedabad. It has been

consistently showed by correlation analysis and linear regression that areas with healthier vegetation generally experienced lower levels of air pollution. The rejection of the null hypothesis (H_0) further supports the existence of a significant negative association between NDVI and AQI.

Vegetation contributes to urban environmental quality through multiple ecological processes, including the interception of particulate matter, absorption of gaseous pollutants, moderation of surface temperatures and improvement of the local microclimate (Nowak et al., 2014; Escobedo et al., 2011). The present findings are consistent with these mechanisms and reinforce the importance of maintaining healthy urban vegetation as part of long-term air-quality management.

However, the relationship was not equally strong across all administrative zones. This variation confirms that urban air quality is influenced by a combination of vegetation condition and local emission sources. Urban greening therefore cannot be viewed as a standalone solution but as one component of a broader environmental management strategy.

5.2 Spatial Variability of the NDVI–AQI Relationship Across Ahmedabad

Although all zones exhibited negative NDVI–AQI relationships, the strength of these relationships varied considerably across Ahmedabad. Such spatial variability suggests that the influence of vegetation on air quality is not uniform throughout the city.

The Central Zone emerged as the most environmentally stressed area, recording the highest average AQI and the lowest NDVI values among all zones. The evident vegetation-air quality relationship observed in the Central Zone may be attributed to its dense urban fabric, characterized by a concentration of commercial establishments, residential neighbourhoods, and high traffic volumes. Such highly built-up environments generally possess limited open spaces and fragmented vegetation. Such conditions make the ecological functions of existing green spaces particularly important. Consequently, it is understood that even modest improvements in vegetation condition may contribute substantially to pollutant interception, temperature regulation, and overall improvements in ambient air quality.

The observed spatial differences may also reflect variations in land-use patterns, population density, transportation infrastructure, industrial activity and the distribution of urban green spaces. Similarly, the comparatively weaker vegetation-air quality relationship observed in the South Zone may be associated with the presence of industrial estates and manufacturing activities, where emissions from industrial processes, freight movement, and associated anthropogenic sources contribute substantially to ambient air pollution. Under such conditions, vegetation alone may explain a smaller proportion of AQI variability, indicating that emission control measures should complement urban greening initiatives in industrial areas.

Therefore, while vegetation plays an important role in influencing air quality, its effectiveness is mediated by local urban characteristics and emission sources. These findings highlight the necessity of adopting spatially differentiated environmental management strategies rather than relying on uniform city-wide interventions.

In addition to this, it is observed that rapid urbanization, redevelopment of old residential societies, expansion of commercial infrastructure, road widening, BRTS, Metro constructions and other continuous construction activities have changed the urban landscape of Ahmedabad in recent years. These developments may contribute not only to increased particulate emissions but also to the removal of mature trees and reduction of urban green spaces. Such changes can weaken the ecological capacity of the urban environment to regulate air quality, thereby reinforcing the importance of conserving existing vegetation alongside new plantation initiatives.

5.3 Comparison with Previous Research

The results obtained in Ahmedabad are broadly consistent with findings reported in previous national and international studies. Several investigations conducted in major Indian cities have documented negative relationships between vegetation cover and air pollution levels, demonstrating the environmental benefits associated with urban greenery.

International studies have similarly reported that higher vegetation density, often measured using NDVI, is associated with lower concentrations of atmospheric pollutants. It is understood that study conducted in cities across China, Europe and North America has shown that urban vegetation contributes to pollutant removal, microclimatic regulation, and improvements in environmental quality.

However, the present study extends this body of knowledge by providing a zone-wise assessment of the NDVI–AQI relationship within Ahmedabad over a five-year period. Unlike many earlier studies that focus primarily on overall city-level relationships, the current research demonstrates substantial intra-urban variability in both vegetation condition and air-quality outcomes. The inclusion of sensitivity analysis further strengthens the contribution by quantifying the potential air-quality benefits associated with hypothetical changes in vegetation condition.

Consequently, the study contributes new empirical evidence from a rapidly urbanizing Indian city and provides insights that may be relevant for urban environmental planning in comparable metropolitan regions.

5.4 Policy and Planning Implications

The sensitivity analysis provides important practical implications for urban environmental management in Ahmedabad. The results indicate that improvements in vegetation condition do not generate uniform air-quality benefits across all zones. Instead, certain areas

exhibit substantially greater responsiveness to changes in vegetation.

A particularly noteworthy finding is that the Central Zone, despite recording the poorest environmental conditions, also demonstrated one of the highest levels of responsiveness to vegetation improvements. Similarly, the South-West Zone exhibited the largest projected reductions in AQI under vegetation enhancement scenarios. These observations suggest that targeted greening initiatives in environmentally vulnerable zones may produce disproportionately large environmental benefits. Sustainable urban development requires integrated environmental strategies that combine ecological conservation with long-term planning objectives (Jani & Bhojak, 2025).

From a policy perspective, the findings support the integration of urban greening strategies into broader air-quality management frameworks. Tree plantation programs, green corridors, roadside vegetation, urban forests, and the protection of existing green spaces may contribute to improving environmental quality when strategically implemented in highly responsive zones.

The results also emphasize that urban greening should not be limited to plantation drives alone. Equal importance should be given to the conservation of existing mature trees, which provide immediate ecological services such as pollutant removal, carbon sequestration, temperature moderation, and habitat support. The removal of healthy mature trees for redevelopment of residential societies, commercial construction, road widening, and infrastructure expansion should be strictly regulated and permitted only where no feasible alternative exists. Wherever tree removal is unavoidable, compensatory plantation using native species, together with long-term monitoring of tree survival, should be made mandatory to preserve the ecological balance of the city.

It is understood by the findings that urban greening strategies should be integrated with broader urban planning and air-quality management policies. Since the effectiveness of vegetation enhancement varies across administrative zones, environmental interventions should be prioritized in areas exhibiting greater responsiveness to improvements in vegetation condition. Such a targeted approach would enable more efficient utilization of available resources while maximizing environmental and public health benefits.

6. Conclusion

The present study examined the relationship between vegetation condition and air quality across the seven administrative zones of Ahmedabad using monthly NDVI and AQI data for the period 2021–2025. Therefore, the findings establish a statistically significant inverse relationship between NDVI and AQI. Therefore it can be said that healthier vegetation is generally associated with better air quality. The null hypothesis was therefore failed to be accepted, supporting the existence of a significant negative relationship between vegetation condition and air quality.

The analysis also revealed considerable spatial variation across Ahmedabad. The Central Zone emerged as the most environmentally vulnerable area, recording the highest average AQI and the lowest vegetation condition. In contrast, the North-West Zone maintained comparatively healthier vegetation together with better air quality. Regression analysis further demonstrated that the influence of vegetation on AQI was not uniform across the city, while the sensitivity analysis showed that improvements in vegetation condition are likely to produce greater environmental benefits in some administrative zones than in others.

These findings underline an important aspect of urban environmental planning. Increasing vegetation alone cannot completely resolve air pollution, particularly in areas affected by heavy traffic, industrial activities, commercial concentration and continuous construction. Urban greening should therefore be implemented alongside effective measures to control anthropogenic emissions.

Overall, the study demonstrates that vegetation enhancement can play a meaningful role in improving urban environmental quality when supported by scientific planning and long-term conservation efforts. More importantly, the results highlight the need to move beyond uniform plantation drives and adopt zone-specific greening strategies based on local environmental conditions. Such an approach can assist municipal authorities in developing more effective and sustainable air-quality management policies for rapidly growing cities like Ahmedabad.

7. Recommendations

Based on the findings of the present study, it is recommended that urban greening initiatives be implemented through a zone-specific approach rather than relying solely on uniform city-wide plantation targets. Priority should be accorded to environmentally vulnerable zones where vegetation enhancement is expected to produce greater improvements in air quality. In addition, the conservation of existing mature trees should be accorded equal importance to new plantation initiatives. The indiscriminate removal of trees for redevelopment of residential societies, road widening, infrastructure expansion, and commercial construction should be strictly regulated, as the loss of mature vegetation can substantially reduce the environmental capacity of urban ecosystems to mitigate air pollution. Where tree removal is unavoidable, scientifically planned compensatory plantation using appropriate native species, together with post-plantation monitoring, should be made mandatory to ensure the long-term preservation of urban ecological functions and environmental quality.

7.1 Establish a Priority Greening Zone Programme

for the Central Zone

The Central Zone recorded the highest AQI levels, the lowest NDVI values, and the strongest sensitivity to vegetation change. Consequently, this zone should be designated as Ahmedabad's highest-priority greening area.

Rather than focusing solely on new plantations, municipal authorities should undertake a detailed inventory of available roadside spaces, institutional campuses, vacant public land parcels, and underutilized urban spaces suitable for vegetation enhancement. Increasing vegetation density within this zone is likely to generate the greatest marginal improvement in air quality.

7.2 Develop a High-Impact Urban Forest Initiative in the South-West Zone

The sensitivity analysis demonstrated that the South-West Zone would experience the largest reduction in AQI under vegetation improvement scenarios. This finding suggests that investments in urban forestry within this zone may yield disproportionately large environmental returns.

The Ahmedabad Municipal Corporation should identify suitable locations for the development of urban forests, Miyawaki forests, biodiversity parks, and large green buffers capable of improving air quality while simultaneously enhancing ecosystem services and climate resilience.

7.3 Integrate NDVI Targets into Urban Environmental Planning

Current urban greening programmes are often evaluated using the number of trees planted rather than the actual condition and effectiveness of vegetation. The results of this study demonstrate that vegetation quality is equally important.

The municipal administration should therefore establish annual NDVI-based performance targets for each administrative zone and monitor progress through satellite-based assessments. Such an approach would provide an objective and scientifically measurable indicator of urban greening success.

7.4 Create Green Buffers Along Major Transportation Corridors

Vehicular emissions remain a major contributor to urban air pollution. Green buffers consisting of dense, multi-layered vegetation should be established along major road corridors, traffic intersections, and transport-intensive areas, particularly within environmentally stressed zones.

Priority corridors should be identified using traffic-density and AQI hotspot information so that greening investments are concentrated where pollutant exposure is greatest.

7.5 Incorporate Air-Quality Benefits into Urban Development Approvals

Future urban development projects should include mandatory vegetation plans that specify expected environmental outcomes. Development permissions for large commercial, residential, and institutional projects may require minimum vegetation-performance standards, ensuring that urban expansion does not occur at the expense of environmental quality.

7.6 Establish an NDVI-AQI Monitoring Dashboard for Ahmedabad

A city-level environmental dashboard integrating satellite-derived NDVI and AQI data should be developed to support evidence-based environmental governance.

Such a system would enable continuous monitoring of vegetation condition and air quality across administrative zones, facilitate the identification of emerging environmental hotspots, and support data-driven policy interventions.

7.7 Shift from Plantation-Based to Outcome-Based Greening Policies

The findings indicate that improvements in vegetation condition can contribute to measurable reductions in AQI. Consequently, urban greening policies should be evaluated based on environmental outcomes rather than simply the number of trees planted.

Success indicators may include improvements in NDVI values, reductions in AQI levels, increased canopy density, and enhanced environmental quality within targeted zones.

Overall, the study demonstrates that strategic vegetation enhancement can function as an effective nature-based solution for improving urban air quality. However, the greatest benefits are likely to be achieved when greening interventions are prioritized in zones exhibiting both high environmental stress and high responsiveness to vegetation improvements.

7.8 Strengthen Tree Protection and Compensatory Plantation Policies

Rapid urban redevelopment, infrastructure expansion, road widening projects, and the redevelopment of older residential societies can lead to the removal of mature trees and the gradual reduction of urban vegetation. While urban development remains essential for economic growth and housing needs, environmental considerations must be integrated into redevelopment planning.

Municipal authorities should strengthen tree-protection regulations and ensure that compensatory plantation programmes are implemented effectively and monitored over the long term. Wherever feasible, redevelopment projects should incorporate the preservation of existing mature trees, as established vegetation often provides greater ecological and air-quality benefits than newly planted saplings. Environmental impact assessments for major redevelopment projects should explicitly evaluate potential vegetation loss and propose measures to maintain or enhance local vegetation condition. Given

the findings of this study, maintaining and improving vegetation condition should be considered an integral component of sustainable urban redevelopment in Ahmedabad.

8. Limitations and Future Research

Limitations of the Study

Despite providing valuable insights into the relationship between vegetation condition and air quality in Ahmedabad, the study is subject to certain limitations.

First, the study employed the Normalized Difference Vegetation Index (NDVI) as a proxy for vegetation condition and density. The original objective was to examine the relationship between urban green cover (or tree cover) and AQI. However, reliable, consistent, and zone-wise green-cover statistics for Ahmedabad were not available for the entire study period. Consequently, NDVI derived from Sentinel-2 satellite imagery was utilized as an alternative indicator of vegetation condition.

While NDVI is widely accepted in environmental and remote sensing research and provides information on vegetation health, density, and seasonal variation, it does not directly quantify actual tree canopy cover or the total extent of green spaces. Therefore, the findings should be interpreted as representing the influence of vegetation condition rather than the precise impact of urban tree cover.

Although NDVI was employed as a proxy for vegetation condition due to the absence of consistent, long-term, zone-wise green-cover datasets for Ahmedabad, it provided a reliable and standardized measure for assessing vegetation dynamics using satellite observations. Future studies may integrate detailed tree-canopy inventories or municipal green-cover databases to further refine assessments of vegetation–air quality relationships.

Second, it can be understood that air quality is influenced by multiple factors, including vehicular emissions, industrial activities, meteorological conditions, construction activity, urban morphology, and population density. Although the present study focused on vegetation-air quality interactions, these additional variables were not explicitly incorporated into the analytical framework.

Third, the study was limited to the administrative zones of Ahmedabad Municipal Corporation and may not fully capture environmental dynamics occurring in peri-urban and rapidly expanding suburban areas surrounding the city.

Future Research Directions

Future research may build upon the present study by incorporating direct measures of urban green cover, tree-canopy density, and land-use characteristics as more comprehensive datasets become available. Comparative analysis between NDVI-based vegetation indicators and actual canopy-cover statistics would further improve understanding of the relative importance of vegetation quantity versus vegetation quality in influencing air quality.

In addition, future studies may integrate meteorological variables, traffic density, industrial emission data, and urban built-up characteristics to develop more comprehensive models of air-quality variation. Advanced spatial techniques, including geographically weighted regression and machine-learning approaches, may also provide deeper insights into the complex interactions between urban vegetation and atmospheric pollution.

Finally, extending similar analyses to other Indian metropolitan regions would facilitate comparative assessments and support the development of evidence-based urban greening strategies for sustainable environmental management.

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