Urbanization, Ecological Impact, and Air Quality: Insights from LULC Dynamics in Gandhinagar Using Satellite Data and Geospatial Analysis

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Abstract*—Urbanization is a critical driver of environmental change, significantly impacting air quality and Land Use/Land Cover (LULC) dynamics. This study aims to investigate the relationship between LULC changes and air quality in Gandhinagar, India, utilizing satellite-based datasets from Landsat-8 and Sentinel-5P. The key pollutants, including carbon monoxide (CO), nitrogen dioxide (NO_2), methane (CH_4), sulphur dioxide (SO_2), and formaldehyde (HCHO) were monitored over the years 2018, 2020, 2022, and 2024. The research employs Google Earth Engine (GEE) for comprehensive spatial-temporal analysis, revealing fluctuating pollutant concentrations: CO levels ranged from 0.03432 to 0.04075 mol/m², NO_2 varied between 0.0000709 and 0.0001346 mol/m², CH_4 increased from 1847.42 to 1945.85 ppb, SO_2 fluctuated between 0.0000425 and 0.0004961 mol/m², and HCHO levels ranged from 0.0001352 to 0.0002511 molecules/cm². Notably, the COVID-19 lockdown in 2020 led to a temporary but significant reduction in pollutants compared to pre-lockdown levels: CO dropped by ~7.2%, NO_2 by ~21.4%, SO_2 by ~64%, and HCHO by ~16.8%. These reductions are attributed primarily to decreased human activity rather than changes in LULC, which is validated by the minimal LULC transformation observed during the same period. The results highlight the socio-economic implications of air quality degradation, particularly concerning public health and urban sustainability, aligning with the United Nations Sustainable Development Goals (SDGs), specifically Goal 11 (Sustainable Cities and Communities) and Goal 3 (Good Health and Well-being). The work emphasizes the need for integrated urban planning strategies that incorporate green infrastructure and stricter emission controls. By establishing correlations between LULC dynamics and air quality, this paper provides actionable insights for policymakers and urban planners, contributing to sustainable land management practices and enhancing the resilience of rapidly urbanizing regions like Gandhinagar. This study serves as a model for similar assessments in other urban contexts, promoting a data-driven approach to address the challenges of urbanization and climate change to stabilize the ecological balance.

***Keywords*—Air Quality Index (AQI), geospatial analysis, LULC, Sustainable Development Goals (SDGs), temporal analysis**

I. Introduction

Urbanization is one of the most significant drivers of environmental change, with its impacts being particularly pronounced in the context of air quality and Land Use/Land Cover (LULC) changes. As urban areas expand, it becomes essential to understand the interconnectedness between LULC dynamics and air quality, which is critical for sustainable urban planning and policymaking [1, 2].

Deforestation, a significant driver of LULC changes, profoundly impacts air quality by altering the natural carbon cycle and reducing vegetation that acts as a sink for atmospheric pollutants. Studies have shown that urban expansion and deforestation, often modelled using advanced Geographic Information System (GIS) techniques, disrupt the ecological balance, contributing to increased pollutant concentrations [3]. Moreover, the loss of forest cover exacerbates urbanization impacts on wetlands and other critical ecosystems, further deteriorating air quality [4, 5]. Machine learning techniques have also effectively demonstrated the interconnectedness of LULC changes and environmental degradation, emphasizing the need for sustainable land management practices [6]. Monitoring LULC is a crucial aspect for nations to control urbanization and effectively manage environmental emissions [7, 8]. This shift reduces the capacity of land to absorb water, increasing surface runoff and leading to flooding during heavy rainfall events [9, 10]. Deforestation is another key factor driving LULC changes. Forests, which act as natural carbon sinks, are increasingly being cleared to make way for urban development and agriculture, resulting in significant biodiversity loss and reduced carbon sequestration [11, 12]. In addition, urban sprawl and industrialization have caused a surge in vehicular emissions, industrial pollution, and the release of particulate matter into the atmosphere, further degrading air quality [12, 13].

As a consequence of LULC changes, urban areas have experienced a rise in Land Surface Temperature (LST). Poor air quality from industrialization and vehicular emissions leads to respiratory problems and other health issues in urban populations [13, 14]. Furthermore, the urbanization process and deforestation contribute to the loss of biodiversity, alteration in ecosystems, and a decline in air quality, which

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further intensify the Urban Heat Island effect (UHI) [10, 11]. The interaction of these factors creates pollution hotspots, leading to detrimental environmental and public health consequences [9, 12].

Air pollution is a major environmental issue, driven by various sources, including transportation, industrial activities, and agricultural practices. The rapid urbanization and growing industrial sectors significantly contribute to high pollutant emissions, leading to deteriorating air quality, especially in metropolitan regions [12, 13]. Vehicular emissions are a key contributor to nitrogen oxides and Particulate Matter (PM), which have adverse health impacts on urban populations [15, 16]. Industrial processes, including energy production and manufacturing, release a variety of harmful gases, such as SO_2 and volatile organic compounds, exacerbating air pollution levels [17]. Agricultural activities also play a role in the release of ammonia and CH_4, particularly in regions with extensive livestock farming [18]. Additionally, the phenomenon of UHIs, driven by changes in land use, intensifies the effects of pollution by increasing temperature and trapping pollutants [19, 20]. The burning of fossil fuels, deforestation, and waste management practices further contribute to the degradation of air quality, with significant consequences for both human health and the environment [21, 22]. Efforts to monitor and mitigate air pollution have been focused on improving air quality indices and using remote sensing and GIS technologies to assess the extent and impact of pollution [23].

The introduction of the Google Earth Engine (GEE), coupled with advancements in Artificial Intelligence (AI), Machine Learning (ML), and spatial analysis tools, has revolutionized the monitoring and analysis of LULC changes. GEE serves as a powerful platform for conducting large-scale environmental assessments, seamlessly integrating diverse remote sensing data, including satellite imagery from platforms like Landsat-8, Sentinel, and Moderate Resolution Imaging Spectroradiometer (MODIS). These tools enable the efficient and precise monitoring of changes in LULC, vegetation, urban expansion, and other environmental variables over time [9].

Remote sensing, enhanced by AI and ML algorithms, offers unparalleled capabilities for analysing complex environmental phenomena. For instance, satellite data can be processed using ML models to predict and classify LULC changes with high accuracy. This approach significantly improves our ability to track and forecast environmental parameters such as soil moisture, vegetation coverage, and water quality, which are crucial for understanding the impacts of urbanization on ecosystems [24]. The synergy between AI and ML techniques and satellite-based observations also enhances predictive modelling for air quality, enabling the accurate forecasting of environmental conditions. These models utilize historical and real-time data to generate insights into spatial and temporal patterns of pollution and their broader ecological consequences [11]. Furthermore, spatial analysis tools in GEE provide an integrated environment for conducting multi-scale analyses. By leveraging advanced computational capabilities, researchers can overlay, correlate, and analyse vast datasets, such as topography, urban sprawl, and hydrological patterns, to derive actionable insights. These methodologies empower stakeholders to devise sustainable strategies for managing resources and mitigating the adverse effects of human activities on natural systems. In summary, the integration of remote sensing, spatial tools, and AI/ML techniques within platforms like GEE has become indispensable for comprehensive environmental monitoring, providing scalable, cost-effective, and high-precision solutions to address pressing global challenges.

Furthermore, while this study centers on Gandhinagar, the findings carry broader implications. Many Tier-II and Tier-III Indian cities, and others globally, face similar urban challenges rapid population growth, vehicular emissions, and green space reduction. The methodology and results presented here offer a transferable framework for comparative urban analysis, allowing other regions to adopt, replicate, or adapt these insights. Such cross-city applications can reveal consistent pollutant trends, evaluate urban resilience, and guide context-specific interventions.

While numerous studies have investigated LULC changes, there may be a distinct lack of research specifically addressing the direct impact of these changes on air quality, particularly in regions like Gujarat, India. The existing body of work primarily focuses on land cover classification and environmental monitoring, often isolating these analyses from air quality studies. However, the intricate relationship between LULC shifts and air quality, especially PM and gaseous pollutants, remains underexplored in this regional context [25]. This research gap is significant, as understanding the link between urbanization-driven LULC changes and air quality is critical for rapidly urbanizing areas such as Gujarat. Urban growth often leads to altered vegetation cover, increased impervious surfaces, and higher emissions from industrial and vehicular activities, all of which influence pollutant levels. Yet, the nuanced ways in which these factors interact to impact air quality, public health, and regional climate remain poorly understood [13]. This oversight limits the development of targeted, data-driven strategies for sustainable urban planning and pollution mitigation.

To address this gap, this study integrates earth observation data, advanced analytical tools, and a spatial-temporal approach. It focuses on the Gandhinagar district in Gujarat, utilizing satellite data and geospatial techniques to bridge the existing knowledge divide. Specifically, Landsat-8 imagery and GEE are employed to track and analyse LULC changes over time [26]. Complementing this, Sentinel P-5 and MODIS data provide high-resolution air quality parameters, such as SO_2, NO_2, HCHO, CH_4, and CO, offering a comprehensive understanding of pollutant distribution across different temporal milestones: 2018, 2020, 2022, and 2024. Therefore, the presented work examines the temporal variations in air quality indicators, providing a comprehensive understanding of how pollutant levels have evolved over recent years. To investigate the influence of LULC changes on air pollution, identifying whether these changes exacerbate or mitigate pollution levels and offering critical data to inform regional environmental policies.

II. Study Area

Gandhinagar (refer to Fig. 1), the capital city of Gujarat, India, is situated between 72°37′30″E to 72°41′15″E longitude and 23°09′45″N to 23°15′00″N latitude on the western banks of the Sabarmati River, approximately 23 km north of Ahmedabad. The city spans an area of about 177 km^2 and is characterized by a flat topography with an average elevation of 81 m above sea level [27–29]. Gandhinagar experiences a semi-arid climate, with hot summers, mild winters, and a monsoon season. Monsoon typically occurs from June to September, contributing significantly to the annual rainfall [29].

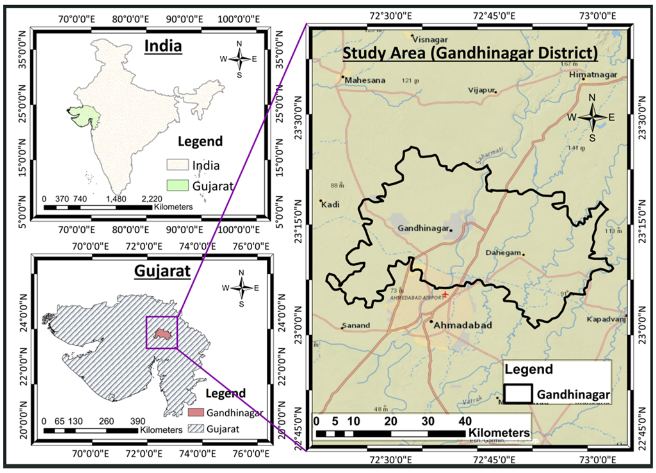


Fig. 1. Area of study of Gandhinagar district.

The soils in Gandhinagar are predominantly sandy loam, exhibiting light grey to brown coloration. These soils are generally low in organic matter and essential nutrients, which can impact agricultural productivity. A study assessing soil characteristics across different land-use systems in the Gandhinagar district found that 79.38% of soil samples were low in available nitrogen, 71.88% were medium in available phosphorus, and 50% were high in available potassium. This nutrient variability necessitates tailored soil management practices to enhance fertility and support sustainable agriculture [30].

Over the past few decades, Gandhinagar has witnessed a steady rise in air pollution levels, reflecting broader trends observed in urbanizing regions of India. For example, the average annual PM2.5 concentration in Gandhinagar increased by approximately 38% between 2010 and 2020, driven by industrial growth, vehicular emissions, and urban sprawl. Recent data from the Central Pollution Control Board (CPCB) indicates that in 2022, Gandhinagar recorded an average Air Quality Index (AQI) of 92 (moderate category) during peak months, with PM2.5 levels exceeding the World Health Organization's (WHO) recommended guidelines by more than 300% in certain zones [31].

One of the primary reasons for this increase is the rise in vehicle ownership in Gujarat, which has grown at an annual rate of 10.3% between 2000 and 2020. This growth contributes significantly to NO_2 and CO emissions, particularly during peak traffic hours. Additionally, Gandhinagar's proximity to Ahmedabad, a major industrial hub, exacerbates air quality issues. Pollutants such as SO_2 and fine particulate matter from industrial emissions in nearby areas often drift into Gandhinagar, worsening its AQI. Geographically, Gandhinagar's flat terrain and low wind speeds during winter months exacerbate pollution by trapping particulate matter close to the surface, leading to localized smog.

Statistical analysis shows a 45% rise in PM10 concentrations and a 28% increase in NO_2 levels in Gandhinagar over the past 15 years [28]. Seasonal fluctuations further influence pollutant levels, with the highest concentrations typically recorded during the winter months due to temperature inversions. For instance, during December and January, PM2.5 levels were recorded at an average of 64 μg/m³, significantly higher than the annual permissible limit of 40 μg/m³ prescribed by India National Ambient Air Quality Standards (NAAQS). The monsoon months, in contrast, see a temporary dip in particulate matter due to wet deposition, but gaseous pollutants like ozone (O_3) often spike due to increased photochemical reactions facilitated by sunlight and moisture.

The geographical location and surrounding land use patterns also contribute to air quality challenges of Gandhinagar. The district's proximity to agricultural zones means it is frequently affected by stubble burning during post-harvest seasons. This practice contributes to sharp, episodic spikes in PM2.5 and PM10 levels. For example, during the stubble-burning season from October to November 2022, Gandhinagar AQI peaked at 176 (unhealthy category), primarily due to fine particulate matter from crop residue fires [SAFAR (System of Air Quality and Weather Forecasting And Research), 2022]. Furthermore, dust from construction activities and unpaved roads adds to the PM burden, particularly in rapidly developing areas.

Rainfall patterns in Gandhinagar are characterized by an average annual precipitation of approximately 800 mm, primarily occurring during the monsoon season. However, inter-annual variability can be significant, affecting groundwater recharge and agricultural activities. A study on groundwater resources in Gandhinagar district highlighted that fluctuations in water levels are influenced not only by rainfall but also by factors such as soil infiltration capacity and land use [28, 29, 32].

III. Materials and Methods

A. Datasets

The datasets used in this study were obtained from satellite-based Earth observation platforms through GEE for the years 2018, 2020, 2022, and 2024. Data on air pollutants, including SO_2, NO_2, HCHO, CH_4, and CO, were acquired from Sentinel-5P. The pollutants were measured as vertically integrated column densities in mol/m² or as column volume mixing ratios in parts per billion (ppb). Moderate-resolution data from MODIS were used to monitor vegetation dynamics and to support the classification of LULC. High-resolution multispectral imagery from Landsat-8 was utilized to create detailed LULC maps. These datasets allowed for an in-depth analysis of changes in pollutant concentrations and LULC over the study period. Different datasets (refer to Table 1) were utilized to analyse the concentration of various pollutants and the LULC in the study area.

Table 1. Dataset information and availability

Sr. No.	Dataset	Dataset Source	Availability	Spatial Resolution
1	SO_2, NO_2, HCHO, CH_4, CO	Sentinel-5P (TROPOMI (TROPOspheric Monitoring Instrument)	July 2018	3.5 to 5.5 km
2	LULC	Landsat-8	2018	30 m

B. Methodology

The shapefile of the area was imported into GEE, where specific JavaScript codes were developed to process pollutant data for the selected years. The pollutant data were analysed to generate outputs in mol/m² or ppb, depending on the type of pollutant. Then, the LULC data extracted from Landsat-8 imagery, with MODIS data were used for training and validation purposes. A supervised classification approach was employed to categorize LULC types, relying on surface spectral reflectance and LST. The classification process was carried out to identify spatial and temporal changes in LULC across the study period. Processed datasets, including pollutant concentrations and LULC classifications, were exported from GEE for visualization in ArcGIS 10.8.3. Thematic maps were generated to represent the distribution of pollutants and the LULC changes. These analyses provided insights into the potential relationships between LULC changes and air quality in the study area, contributing to the understanding of environmental health dynamics. The overall procedure carried out is given in Fig. 2.

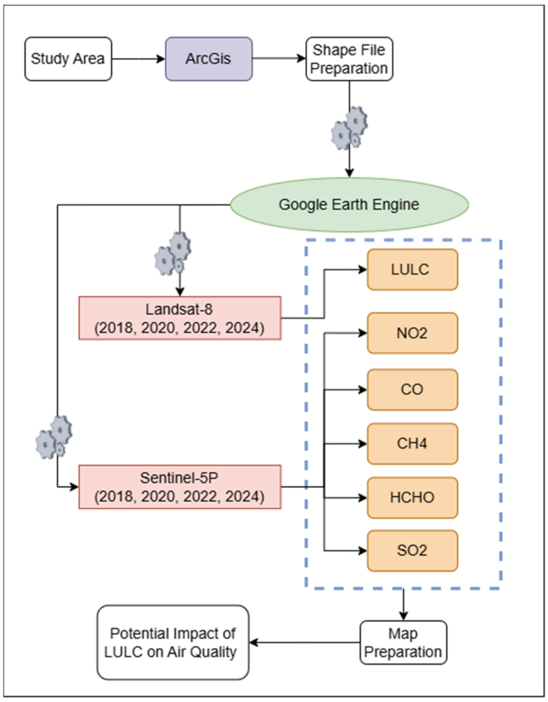
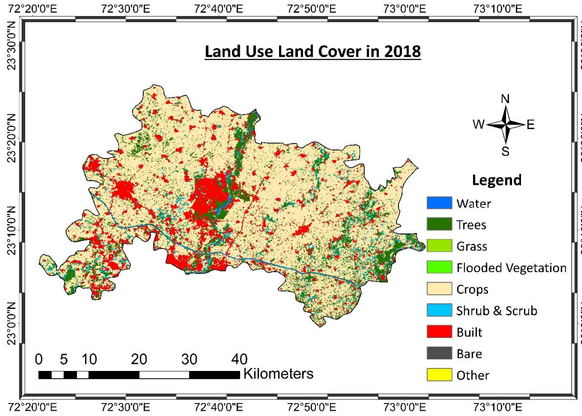


Fig. 2. Overall methodology.

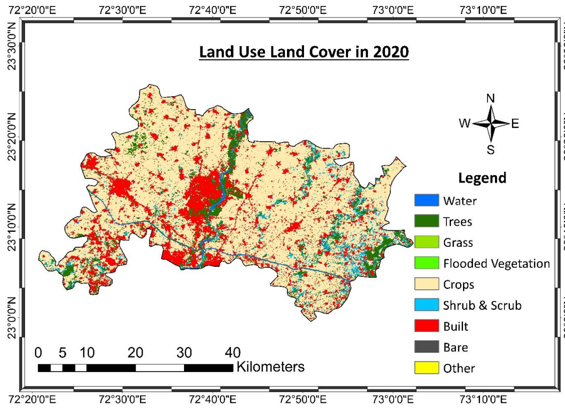
IV. Results

A. LULC Analysis

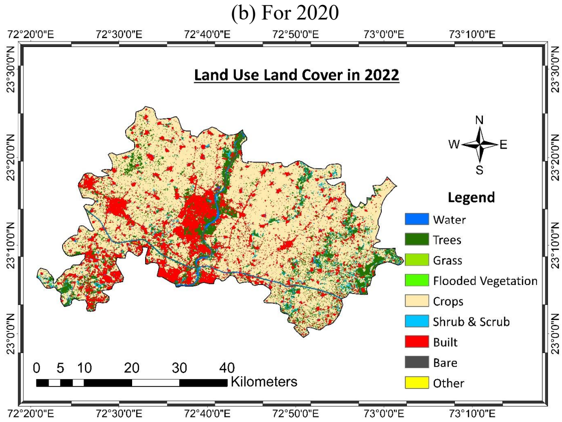
Fig. 3 presents the LULC changes from 2018 to 2024. Between 2018 and 2024, a significant change in LULC can be seen, mainly due to urbanization. Built-up areas (shown in red) have been increasing steadily, with the most significant growth around major urban centers, encroaching on vegetation and bare land. In 2018 (Fig. 3a), vegetation, including trees, grass, and crops, was the dominant the land cover, but it has been gradually declining over the years as urban areas expanded. By 2024 (Fig. 3d), a significant proportion of agricultural and green zones had been transformed into built-up areas, indicating the continued impacts of urbanization. Bare land (shown in grey) also declined substantially as they were converted into urban zones, which further transformed the landscape of the region.



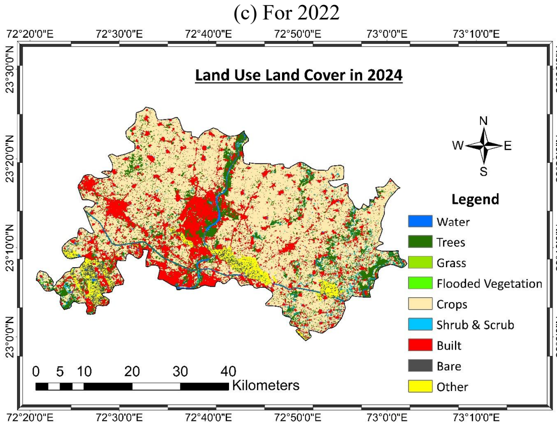
(a) For 2018



(b) For 2020



(c) For 2022



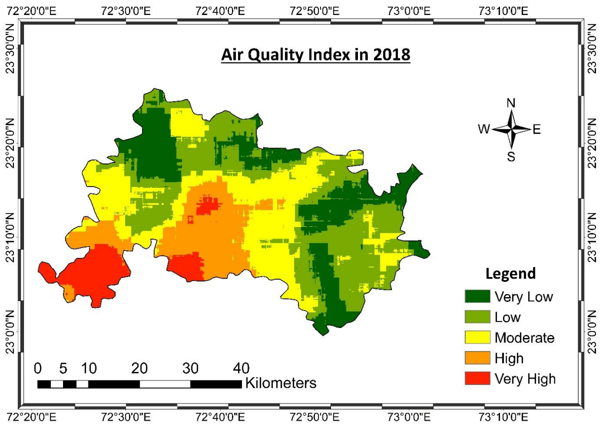
(d) For 2024

Fig. 3. LULC of Gandhinagar. (a) LULC in 2018; (b) LULC in 2020; (c) LULC in 2022; (d) LULC in 2024.

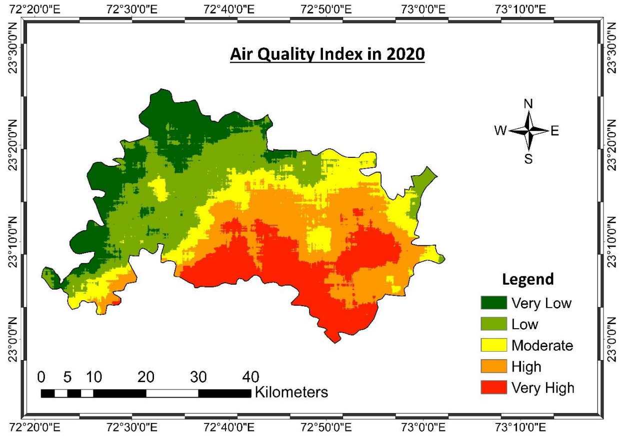
Water bodies (shown in blue) showed modest growth from 2018 to 2022, possibly as a result of conservation efforts or climatic influences but stabilized by 2024. Vegetation cover was estimated to have decreased by around 2% to 3%, and bare land was seen to have decreased much more over six years. Changes in shrub, scrub, and snow/ice areas were minimal, being almost constant during the period. These trends demonstrate persistent urban spread in this region at the price of natural and agricultural land while pointing out the increasing need for sustainable planning that balances development with ecological protection.

B. *Air Quality Assessment*

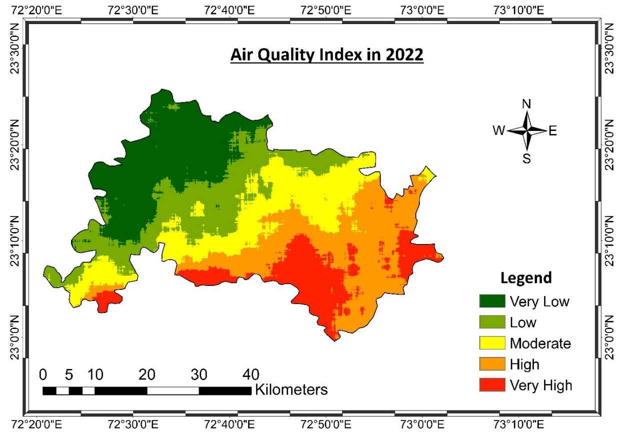
Fig. 4 showcases the spatiotemporal variation of the AQI in Gandhinagar. The assessment of air quality in Gandhinagar over the years 2018 to 2024 provides valuable insights into the spatiotemporal variations in pollutant levels and their implications for environmental health. Air pollutants such as CO, NO_2, CH_4, SO_2, and HCHO serve as key indicators of urbanization, industrial activity, and combustion processes. Monitoring these parameters reveals the interplay between human activities and natural processes, providing a foundation for understanding emission trends, identifying critical pollution sources, and formulating mitigation strategies. The dynamic patterns of these pollutants underscore the importance of sustained efforts in emission control, technological advancements, and policy interventions to safeguard public health and maintain ecological balance in the region. Table 2 summarizes the percentage change in air pollutant concentrations from 2018 to 2020 and then from 2020 to 2024. Notably, NO_2 dropped by 21.4%, highlighting a strong correlation between reduced anthropogenic activity and improved air quality. However, a rebound was seen in most pollutants by 2024.



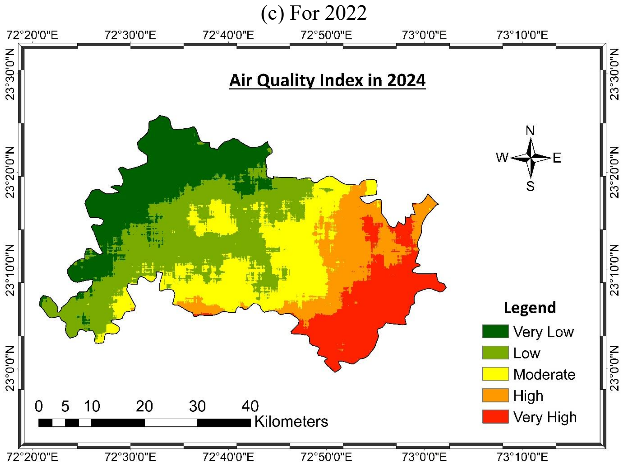
(a) For 2018



(b) For 2020



(c) For 2022



(d) For 2024

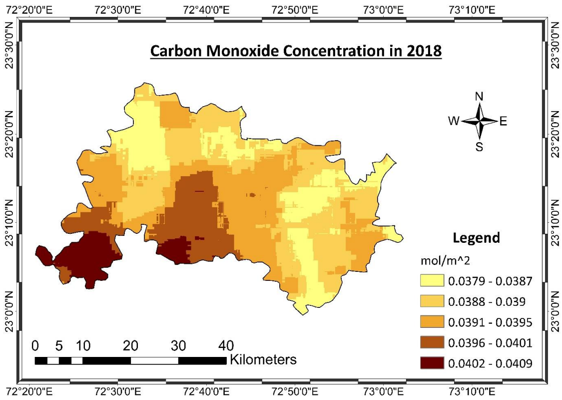
Fig. 4. Spatiotemporal variation of AQI. (a) AQI in 2018; (b) AQI in 2022 (c) AQI in 2020; (d) AQI in 2024.

Table 2. Percentage change in air quality parameters

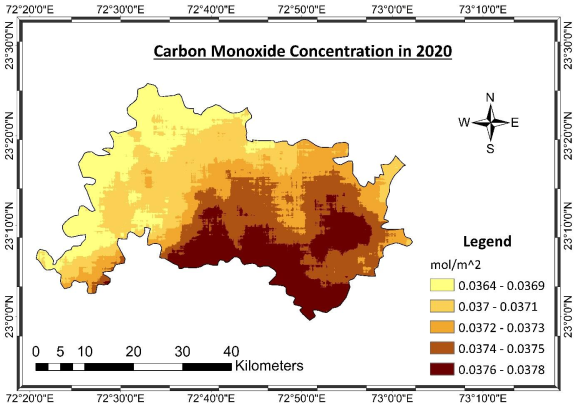
Pollutant	2018 Value	2020 Value	% Change (2018–2020)	2024 Value	% Change (2020–2024)
CO (mol/m²)	0.04075	0.03781	−7.2%	0.03914	+3.5%
NO_2 (mol/m²)	0.0001346	0.0001059	−21.4%	0.0001194	+12.7%
SO_2 (mol/m²)	0.0004961	0.0001788	−64.0%	0.0002251	+25.9%
HCHO (mol/cm²)	0.0002511	0.0002088	−16.8%	0.0002320	+11.1%
CH_4 (ppb)	1886.93	1913.99	+1.4%	1945.85	+1.7%

1) *Carbon monoxide*

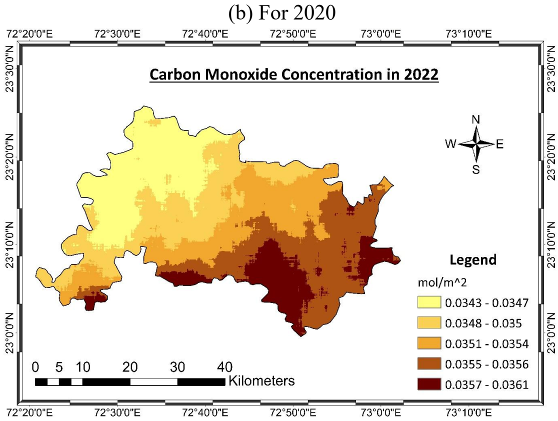
The CO levels in Gandhinagar reflect a fluctuating but overall stable trend over the period from 2018 to 2024 (Fig. 5). In 2018 (Fig. 5a), the CO concentration ranged from a minimum of 0.03789 mol/m² to a maximum of 0.04075 mol/m², indicating moderate emissions from vehicular traffic and industrial activities. By 2020 (Fig. 5b), there was a slight reduction in CO levels, with values ranging between 0.03654 mol/m² and 0.03781 mol/m², suggesting a temporary improvement possibly due to emission control measures or reduced activity. However, this decline continued in 2022 (Fig. 5c), where the minimum value dropped to 0.03432 mol/m² and the maximum to 0.03610 mol/m², reflecting a lower presence of incomplete combustion sources. In 2024 (Fig. 5d), there was a slight rebound in CO concentration, with levels increasing to a minimum of 0.03717 mol/m² and a maximum of 0.03914 mol/m², possibly attributed to renewed industrial growth or higher transportation demands. This pattern highlights the dynamic nature of CO emissions in Gandhinagar, necessitating continuous monitoring and policy interventions to mitigate the impact of incomplete fuel combustion on local air quality and temperature regulation.



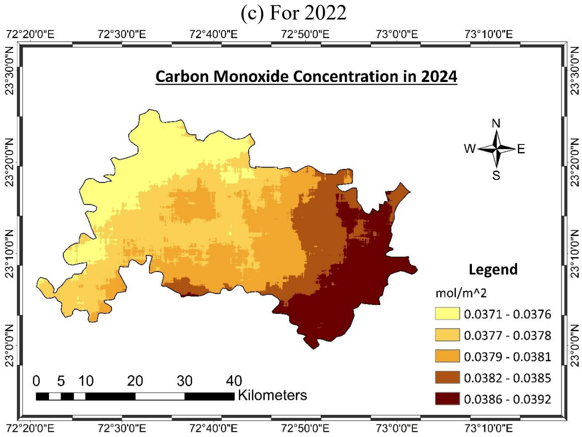
(a) For 2018



(b) For 2020



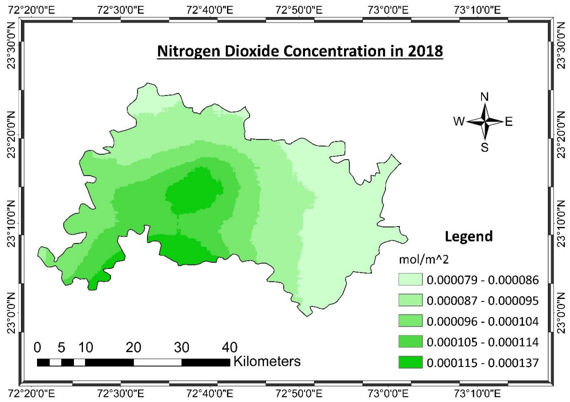
(c) For 2022



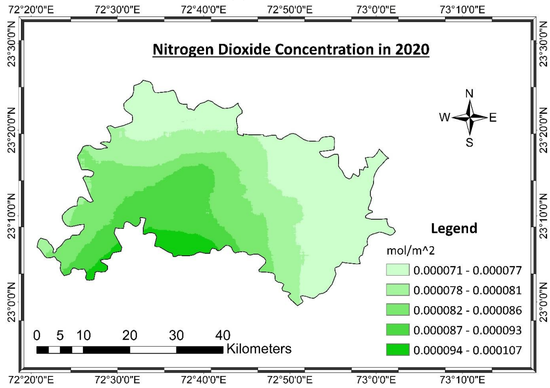
(d) For 2024

Fig. 5. Spatiotemporal variation of CO concentration. (a) CO in 2018; (b) CO in 2020; (c) CO in 2022; (d) CO in 2024.

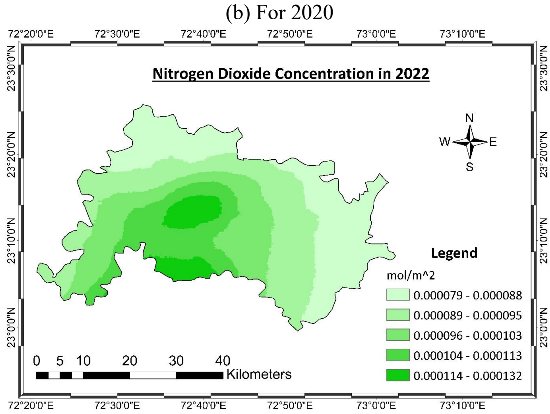
2) Nitrogen dioxide



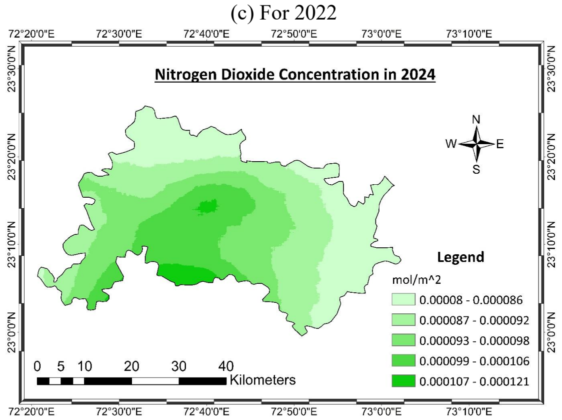
(a) For 2018



(b) For 2020



(c) For 2022



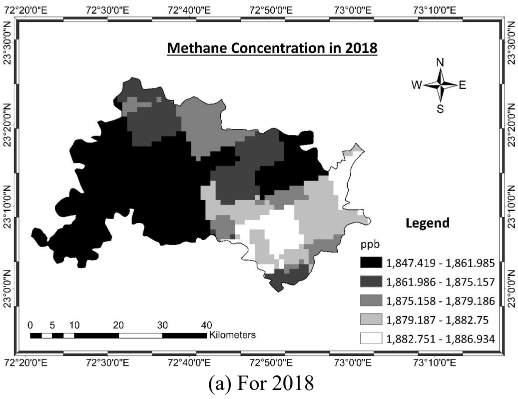
(d) For 2024

Fig. 6. Spatiotemporal variation of concentration (a) NO_2 in 2018; (b) NO_2 in 2020; (c) NO_2 in 2022 (d) NO_2in 2024.

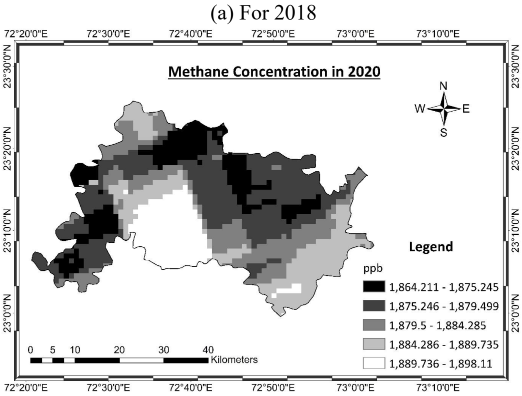
The NO_2 levels in Gandhinagar reveal a dynamic pattern of fluctuation from 2018 to 2024, reflecting the influence of industrial activities, vehicular emissions, and local energy production. In 2018 (Fig. 6a), NO_2 concentrations ranged between 0.0000789 mol/m² and 0.0001346 mol/m², indicating moderate levels attributed to urban development and combustion processes. By 2020 (Fig. 6b), a notable decline in maximum NO_2 concentration to 0.0001059 mol/m² was observed, likely due to reduced industrial activities and transportation during the COVID-19 pandemic, with a corresponding minimum of 0.0000709 mol/m². Post-pandemic recovery in 2022 (Fig. 6c) resulted in an increase to 0.0001296 mol/m², approaching pre-pandemic levels. However, by 2024 (Fig. 6d), a slight decrease in NO_2 levels (max 0.0001194 mol/m²) suggests a stabilization trend, potentially driven by cleaner energy adoption and stricter emission regulations. This overall trend underscores the importance of sustained efforts in emission control to manage NO_2 levels and mitigate their environmental and health impacts in Gandhinagar.

3) Methane CH_4

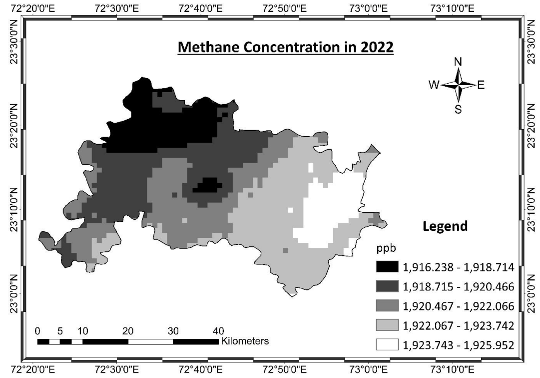
In Gandhinagar, the concentration of CH_4 has shown a progressive increase from 2018 to 2024, indicating rising anthropogenic influence and environmental stress. In 2018 (Fig. 7a), the minimum CH_4 value was recorded at 1847.42 ppb, with a maximum of 1886.93 ppb, suggesting relatively moderate emissions. By 2020 (Fig. 7b), the values increased to a minimum of 1897.44 ppb and a maximum of 1913.99 ppb, reflecting a notable uptick, likely driven by intensified urbanization and industrial activities. This trend continued in 2022 (Fig. 7c), with CH_4 levels ranging between 1916.24 ppb and 1925.95 ppb, highlighting the sustained rise in emissions. The latest data for 2024 (Fig. 7d) shows the highest recorded CH_4 levels, with a minimum of 1935.14 ppb and a peak at 1945.85 ppb. This consistent escalation suggests increasing contributions from agricultural, vehicular, and industrial sectors, which could potentially exacerbate air quality issues and influence regional climate patterns. Gandhinagar's steady CH_4 growth aligns with broader regional trends, warranting attention towards mitigation strategies to curb emissions.



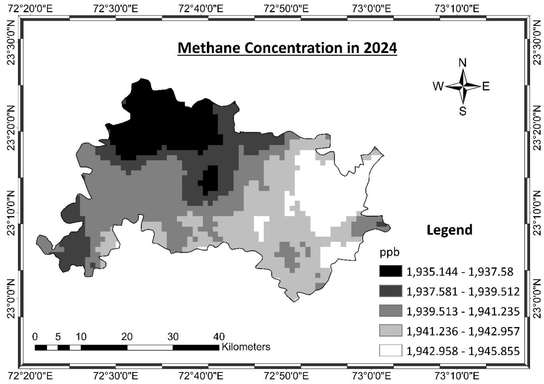
(a) For 2018



(b) For 2020



(c) For 2022

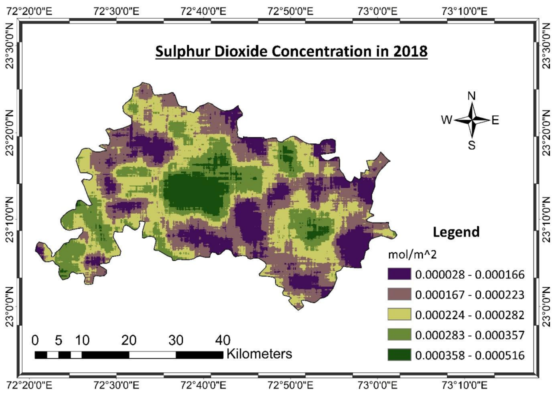


(d) For 2024

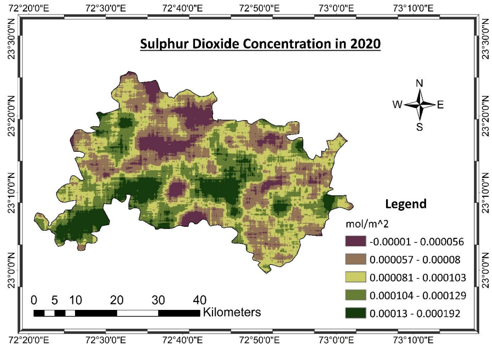
Fig. 7. Spatiotemporal variation of CH_4. . (a) CH_4 in 2018; (b) CH_4 in 2020 (c) CH_4 in 2022; (d) CH_4 in 2024.

4) Sulphur dioxide

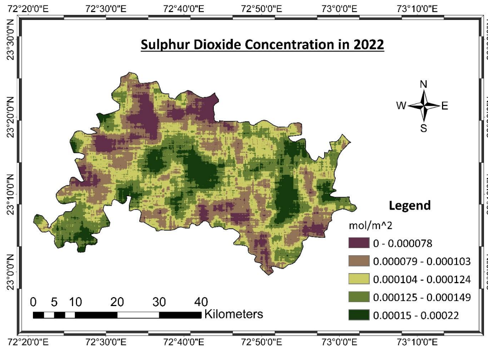
SO_2 levels in Gandhinagar show a fluctuating trend from 2018 to 2024, reflecting the influence of industrial activity and fossil fuel combustion. In 2018 (Fig. 8a), SO_2 concentrations ranged from 0.0000425 mol/m² to 0.0004961 mol/m², indicating a relatively high peak likely driven by power generation and vehicular emissions. A significant drop in 2020, with a maximum value of 0.0001788 mol/m², suggests reduced industrial operations and transportation, possibly linked to pandemic restrictions (Fig. 8b). However, by 2022 (Fig. 8c), SO_2 levels rebounded, with the maximum rising to 0.0002042 mol/m², reflecting the resumption of industrial activities. In 2024, the upward trend continued with a maximum of 0.0002251 mol/m², pointing to ongoing urban development and energy production (Fig. 8d). The persistent rise in SO_2 concentrations highlights the need for stricter emission controls and cleaner energy alternatives to mitigate the environmental impacts of sulphur dioxide in the Gandhinagar region.



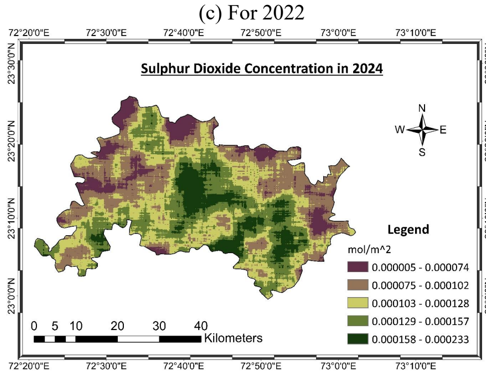
(a) For 2018



(b) For 2020



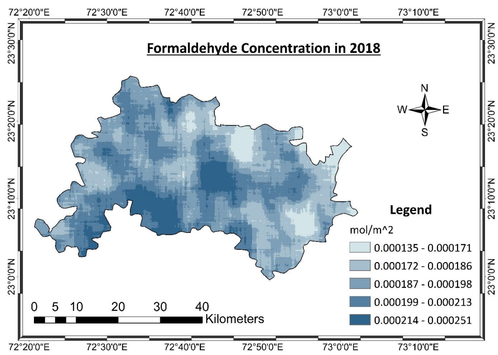
(c) For 2022



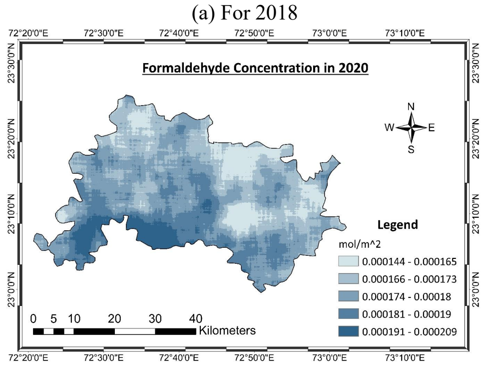
(d) For 2024

Fig. 8. Spatiotemporal variation of SO_2. concentration (a) SO_2 in 2018; (b) SO_2 in 2020; (c) SO_2 in 2022; (d) SO_2 in 2024.

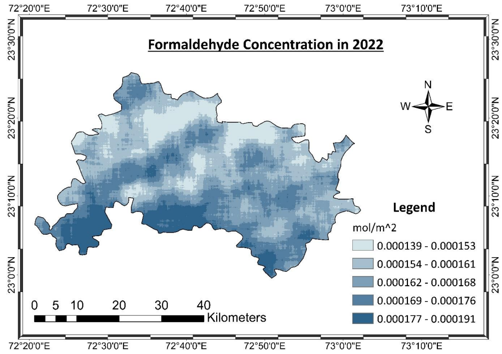
5) *Formaldehyde*



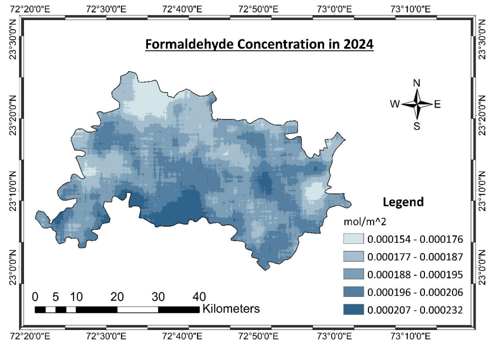
(a) For 2018



(b) For 2020



(c) For 2022



(d) For 2024

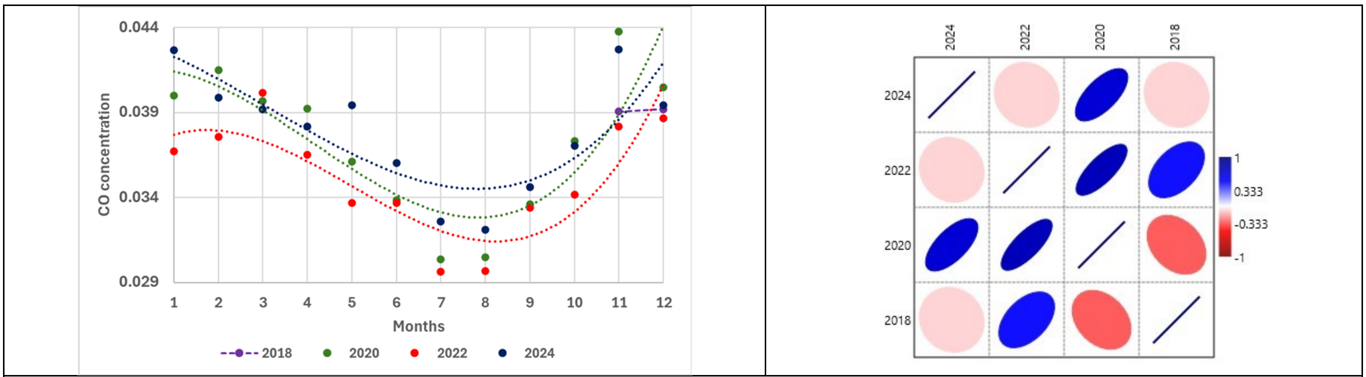
Fig. 9. Spatiotemporal variation of formaldehyde concentration. (a) formaldehyde in 2018; (b) formaldehyde in 2020; (c) formaldehyde in 2022; (d) formaldehyde in 2024.

Formaldehyde (HCHO) levels in Gandhinagar from 2018 to 2024 indicate a dynamic pattern influenced by industrial, vehicular, and domestic emissions. In 2018 (Fig. 9a), HCHO concentrations ranged from 0.0001352 to 0.0002511 molecules/cm², reflecting elevated emissions likely associated with urbanization and petrochemical activities. By 2020 (Fig. 9b), a slight decrease in maximum values to 0.0002088 molecules/cm² was observed, potentially linked to reduced economic activities and transportation during the COVID-19 pandemic. However, the minimum concentration increased marginally to 0.0001441 molecules/cm², suggesting continuous low-level emissions from domestic and small-scale sources. In 2022 (Fig. 9c), HCHO levels declined further, with a maximum of 0.0001910 molecules/cm², pointing to improved air quality or enhanced emission control measures. The trend reversed in 2024 (Fig. 9d), with the maximum value rising to 0.0002320 molecules/cm², reflecting renewed industrial growth and urban expansion. The consistent fluctuations in HCHO levels highlight the importance of monitoring volatile organic compounds to mitigate air pollution and associated health risks in Gandhinagar.

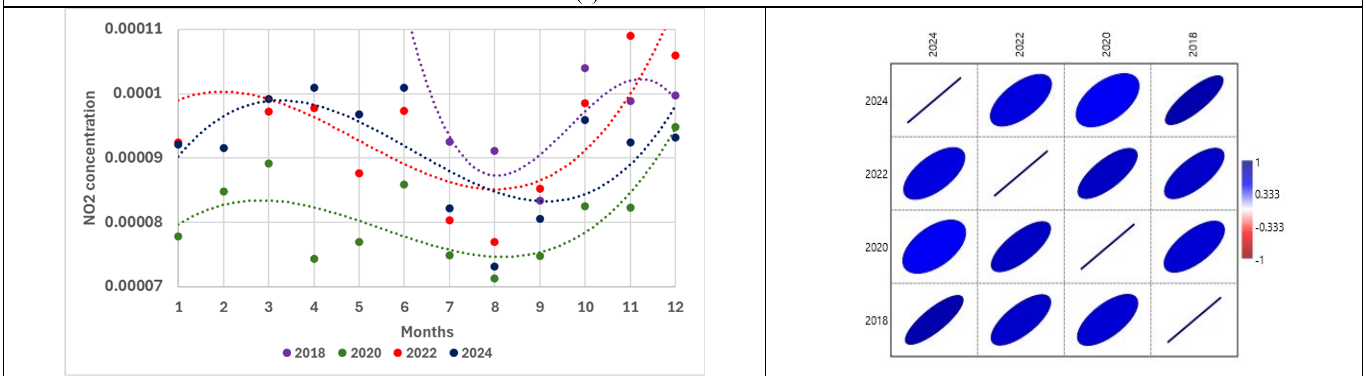
C. *Co-Relation between LULC Classes and Pollution Parameters*

This study examines the correlation between LULC changes and air pollutants, specifically HCHO, SO_2, CH_4, NO_2, and CO, in Gandhinagar, India, from 2018 to 2024 (refer to Fig. 10) at two-year intervals. Using multi-temporal remote sensing data, the analysis reveals that urbanization, vegetation dynamics, and industrial activities significantly impact pollutant concentrations. Seasonal trends indicate that CO levels are lowest during the monsoon months (June-August) due to atmospheric cleansing, while NO_2 and CH_4 concentrations peak in winter (October-January), driven by smog formation, pollution accumulation, and reduced atmospheric dispersion. These seasonal patterns underscore the critical role of meteorological conditions and anthropogenic factors in influencing air quality.

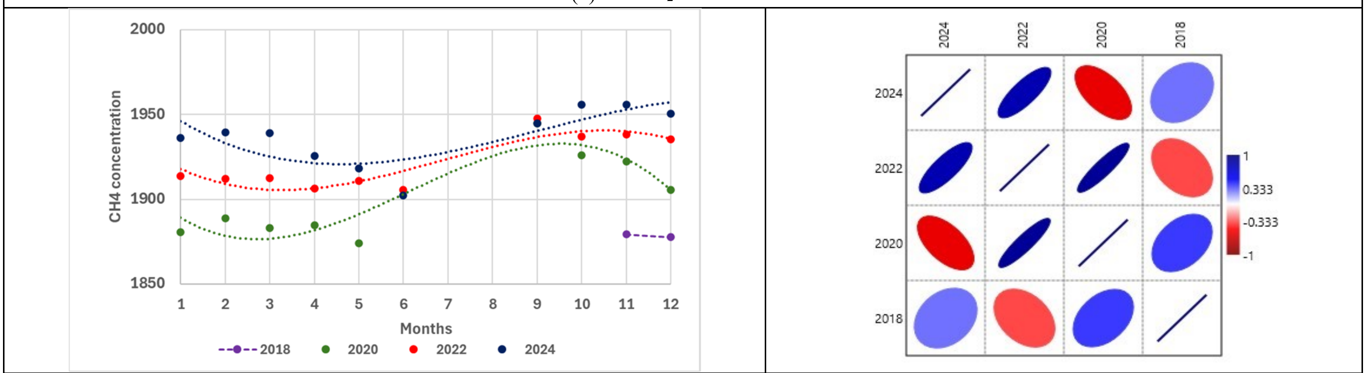
The findings highlight a strong relationship between LULC transformations and pollutant levels. Increasing urbanized areas, characterized by rising built-up land, correspond with elevated NO_2 levels, particularly during winter, as vehicular emissions and atmospheric stability amplify pollution. Regions with reduced vegetation display higher NO_2 and SO_2 concentrations, while areas with sustained or enhanced vegetation cover show a significant decline in CO levels, especially during monsoons. These trends emphasize the role of green spaces in mitigating pollution and the complexities of CH_4 trends due to varied emission sources. This study underscores the need for sustainable urban planning, preservation of green spaces, and proactive mitigation strategies to balance development and environmental health in rapidly growing cities like Gandhinagar.



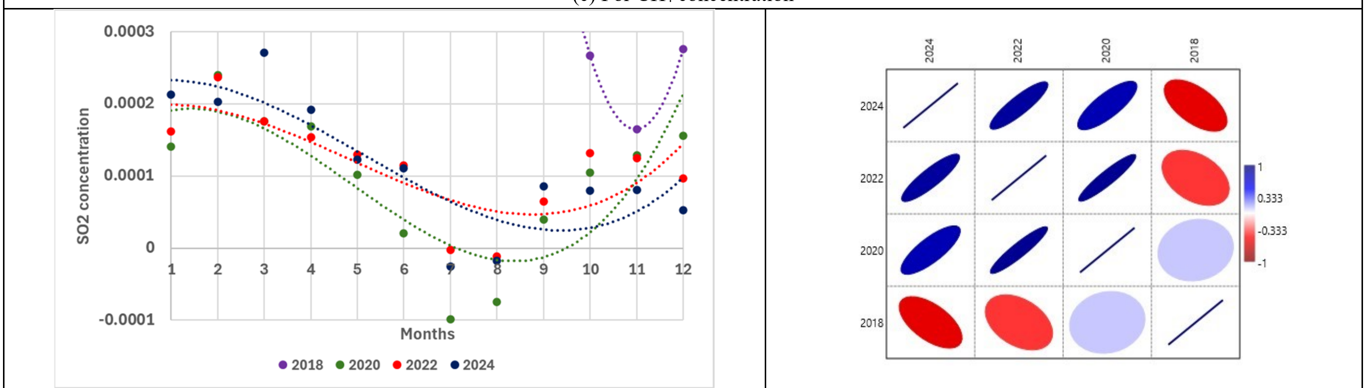
(a) For CO concentration



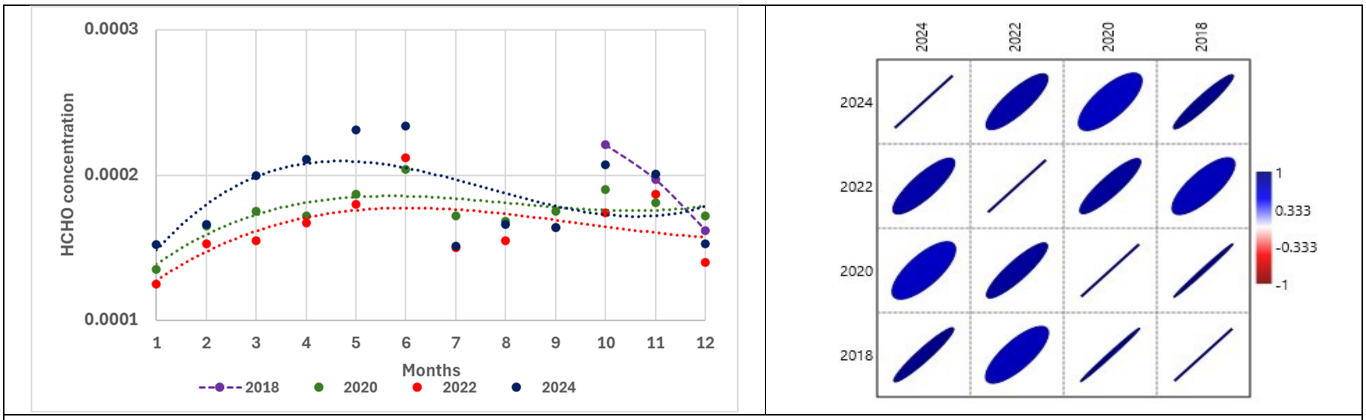
(b) For NO_2 concentration



(c) For CH_4 concentration



(d) For SO_2 concentration



(e) For Formaldehyde concentration

Fig. 10. Co-relation between LULC classes and pollution parameters. (a) with CO concentration; (b) NO_2 concentration; (c) CH_4 concentration; (d) SO_2 concentration; (e) Formaldehyde concentration.

D. *Potential Impact of LULC on Air Quality*

LULC changes significantly influence air quality in Gandhinagar by altering pollutant sources and sinks, as well as atmospheric dispersion mechanisms. Rapid urbanization, evidenced by an increase in built-up areas, directly contributes to higher concentrations of air pollutants such as NO_2 and SO_2 due to increased vehicular emissions, industrial activities, and reduced natural sinks. The expansion of impervious surfaces also exacerbates the UHI, which can stabilize the lower atmosphere and inhibit pollutant dispersion, particularly during winter months, leading to smog formation.

Conversely, vegetation plays a crucial role in mitigating air pollution. Areas with sustained or enhanced vegetation cover act as natural sinks, reducing CO and CH_4 levels through processes such as photosynthesis and soil absorption. However, reductions in green spaces due to urban sprawl diminish this capacity, increasing pollutant concentrations. Seasonal variations further amplify these impacts, as monsoons enhance natural cleansing processes, reducing CO levels, while winter conditions amplify NO_2 and CH_4 accumulation due to low wind speeds and temperature inversions.

In summary, LULC changes directly influence air pollutant dynamics in Gandhinagar, highlighting the need for sustainable land management practices to mitigate adverse air quality impacts and ensure a balanced urban-ecological system.

E. *Potential Impact of Air Quality on Ecology*

Air quality plays a significant role in ecosystems and the stability of biodiversity [33–35]. The impact is significant on plants, wildlife, water systems, soil, and microbial communities, etc. Therefore, understanding the spatiotemporal variation of air quality and its relationship to LULC changes is essential. Reduced photosynthesis can happen due to the increased levels of SO_2 and NO_2. In addition, acid rain can be extremely harmful to plants. Furthermore, heavy metal deposition in soil can lead to significant damage not only to plants but also to other living creatures and organisms. Toxic exposure to air leads to respiratory issues and reproductive issues for humans and wildlife. This is a significant threat to the world. Diversity and distribution of flora and fauna can be a significant threat due to air pollution, water pollution, and other types of anthropogenic activities [36, 37]. Therefore, air quality decline has a substantial impact on the ecological balance of the world thus, the regulations have to be implemented to minimize the adverse scenarios.

V. Discussion

The air quality trends in Gandhinagar from 2018 to 2024 reveal unique challenges compared to other cities in Gujarat and India. While pollutant levels of Gandhinagar remain moderate relative to heavily industrialized regions, the consistent fluctuations across key parameters highlight the increasing anthropogenic pressures on the city. Cities like Ahmedabad, located just 30 km from Gandhinagar, experience far higher pollutant concentrations due to extensive industrial activities, denser vehicular traffic, and a larger urban footprint. Rapid urbanization results in increased pollution levels and altered ecosystems, which can adversely affect both human health and the environment [38–41].

This study's focus on satellite-based monitoring of gaseous pollutants provides a high-resolution, spatially continuous understanding of air quality changes. The use of TROPOMI data from Sentinel-5P allowed for detailed mapping of pollutants that are strongly influenced by land use patterns and human activity [42, 43]. This spatial perspective is crucial in planned cities like Gandhinagar, where urban sprawl and loss of vegetation are occurring rapidly at the periphery.

Furthermore, the COVID-19 lockdown provided a unique "natural experiment," revealing that temporary reductions in industrial activity and traffic led to measurable drops in pollutants such as CO (-7.2%), NO_2 (-21.4%), and SO_2 (-64%). These reductions highlight the potential efficacy of regulatory and behavioral interventions for air quality improvement. While this study centered on Gandhinagar, its methodology and findings can be applied to similar Tier-II cities in India and beyond. The emphasis on remote sensing and geospatial tools supports scalable and cost-effective environmental monitoring essential for cities with limited ground-based infrastructure.

To mitigate future risks, urban planners should adopt green infrastructure strategies, enhance emission regulations, and leverage data-driven forecasting. While particulate matter was beyond this study's scope, the gaseous pollutants monitored here also have significant health and ecological implications, warranting urgent policy attention.

In summary, this work contributes to the growing body of geospatial air quality research by linking land transformation patterns directly to gaseous pollutant behavior offering valuable insights for sustainable urban development.

VI. Conclusions

This study offers a comprehensive spatiotemporal assessment of the relationship between LULC changes and air quality dynamics in Gandhinagar, India. By leveraging satellite-based datasets through Google Earth Engine, we examined variations in key gaseous pollutants CO, NO_2, SO_2, CH_4, and HCHO across 2018, 2020, 2022, and 2024. The results clearly demonstrate how urban expansion and declining vegetation correlate with increased pollutant concentrations, particularly in winter and post-monsoon seasons.

The temporary decline in pollution during the COVID-19 lockdown provides compelling evidence that targeted policy interventions, such as traffic control and industrial regulation, can lead to immediate improvements in air quality. This natural experiment reinforces the value of proactive, not reactive, planning strategies.

From a policy perspective, the study underscores the importance of integrating geospatial monitoring, emission controls, and sustainable land management into urban planning. Innovative approaches such as green infrastructure, emission zoning, and real-time pollutant tracking can help mitigate future risks. The methodologies used here offer a scalable framework applicable to similar mid-sized urban regions across India and globally.

Moving forward, integrating socio-economic indicators and predictive modeling will be critical for anticipating and mitigating environmental pressures. The findings contribute to a growing body of knowledge supporting Sustainable Development Goals, particularly SDG 11 (Sustainable Cities) and SDG 13 (Climate Action), by enabling data-driven strategies to manage the urban-environmental interface.

Nomenclature

CH_4	Methane	**HCHO**	Formaldehyde
CO	Carbon Monoxide	**LULC**	Land Use/Land Cover
COVID-19	Coronavirus Disease 2019	**LST**	Land Surface Temperature
GEE	Google Earth Engine	**MODIS**	Moderate Resolution Imaging Spectroradiometer
GIS	Geographic Information System	**NO_2**	Nitrogen Dioxide
PM	Particulate Matter	**SO_2**	Sulphur Dioxide
TROPOMI	Tropospheric Monitoring Instrument	**AQI**	Air quality index

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

KHJ, MP, HD, and NAS conducted the research; HD analyzed the data; KHJ, NG, and DPP wrote the paper; SKS, UR, and MJ reviewed and revised the paper. All authors had approved the final version.

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