Geospatial Assessment of Urban Air Pollution Using Multi-Source Remote Sensing and GIS: A Case Study of Nashik City, India

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Abstract

Rapid industrialization and unplanned urbanization have increased air pollution levels across Indian cities, posing serious environmental and health challenges. This research presents a geospatial assessment of air pollutant behaviour across Nashik city by integrating multi-source remote sensing datasets and real observation datasets from Sentinel-5P, NASA POWER, and CPCB ground observations within a GIS-based analytical framework. Using ward-level mapping and spatial overlays, the study examines the distribution of key pollutants - $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO - and their relationship with environmental and anthropogenic parameters, including land use, road networks, wind direction, temperature, and vegetation density. The results consistently reveal high concentrations of $PM_{2.5}$, ranging from a minimum of 52.4 µg/m³ to a maximum of 73 µg/m³, and PM_{10}, a minimum of 87.3 µg/m³ and a maximum of 121.5 µg/m³, particularly along high-traffic corridors and industrial zones, which exceed the WHO standards. Correlations with meteorological and vegetative factors further highlight the influence of urban form and climatic conditions on pollutant dispersion. This integrated approach demonstrates how multi-source remote sensing and GIS tools can be effectively employed to identify emission hotspots, support evidence-based policy formulation, and strengthen urban environmental management strategies for sustainable development.

1. Introduction

Air pollution remains one of the most critical environmental challenges affecting urban populations worldwide, particularly in developing countries such as India (UN, 2021). The rapid increase of industrial growth, urban development, and heavy reliance on fossil fuels has intensified the emission of air pollutants, leading to complex interactions among urban environments, weather conditions, and human activities. Approximately 80% of the world's energy consumption still comes from fossil fuels, resulting in a continuous release of particulate matter and gaseous pollutants that significantly degrade air quality (Soliman, 2025). The identification and quantification of pollution sources, along with the associated health risks, are essential for formulating effective pollution control policies (Chen, 2025). The World Health Organization (WHO) and numerous epidemiological studies have repeatedly demonstrated a connection between exposure to fine particulate matter ($PM_{2.5}$) and an increased risk of cardiovascular, respiratory, and metabolic diseases (Anderson, 2009; Wolf, 2022).

India is facing a severe air quality crisis within a larger global context. Cities like Delhi, Mumbai, and Pune often report pollutant levels that exceed WHO standards. This is mainly due to vehicle emissions, industrial activities, and uncontrolled construction. The Health Effects Institute (2024) states that air pollution is the second leading cause of premature death in India, responsible for about one in ten deaths. The Central Pollution Control Board (CPCB) and the National Clean Air Program (NCAP) recognize the urgent need to reduce particulate matter (PM_{10} and $PM_{2.5}$) levels by 20-30% by 2025. However, many Indian cities still lack detailed information on how pollutants are distributed and behave, which is necessary for effective planning and reduction efforts. Clean air action plans were prepared to achieve a 40% decrease in PM10 pollution by 2026 compared to the 2017 annual averages, or to meet national standards (Guttikunda, 2016). New Delhi, the Capital of India, frequently exceeds WHO standards for PM2.5. The average concentration is approximately 205 µg/m³, and it is one of the most polluted cities globally (Khan, 2023).

Traditional air quality monitoring relies on having a few ground-based stations that provide high temporal but low spatial coverage. On the other hand, remote sensing and geospatial innovations today provide unprecedented means to observe, map, and model atmospheric pollutants spatially and temporally. Merging geo-sensors (i.e., Sentinel-5P, MODIS) with NASA POWER and GIS will facilitate multidimensional analysis of various environmental and anthropogenic factors that affect air quality. This geospatial approach facilitates the characterization of emission sources and dispersion patterns, as well as the identification of hotspots in complex cities.

Recent improvements in Earth observation are resulting in greater spatial resolution and accuracy of air quality monitoring, applicable to, among others, urban environmental management, land atmosphere interactions, and climate impact studies (Boogaard, 2012; Nair, 2024) Studies that make use of Sentinel-5P – show that 5P’s newest TROPOMI sensor can capture spatial variability in NO_2 as well as SO_2 and CO. These concentrations follow closely transport network or industrial activity. Combining these data with land-use, meteorological, and vegetation indices derived from remote sensing enables the understanding of pollutant dispersal under different climatic and topographical conditions (EPA, 2012).

Maharashtra is India's economic hub. Hazy Mumbai, Pune, and Nashik AQI levels. The heavy concentration of vehicles, industries, and poor green infrastructure puts these areas at risk for significant air quality degradation (MPCB, 2020). Located in the Mumbai-Pune-Nashik growth corridor, Nashik is emerging as a metropolitan centre. The study examines the relationship between growth and environmental climatic variables in influencing air pollution in Nashik. Despite its moderate size, Nashik is undergoing rapid urbanization. Its growing industrial base and increasing number of vehicles have made it one of Maharashtra’s most polluted cities. The CPCB sets the standards for air pollutants, which are listed in Table 1.

In this context, the present study employs multi-source remote sensing data integrated within a GIS-based framework to analyze the spatial and temporal distribution of key air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO) across Nashik city. The objectives of this study are to map the spatial variability of air pollutants using satellite observations and to validate these findings through ground-based measurements. Examine the relationships between pollutant concentrations and environmental variables, such as temperature, wind flow, vegetation cover, and land use, and identify emission hotspots, interpreting their anthropogenic or climatic drivers. By integrating satellite data, geospatial analysis, and environmental parameters, this study outlines a repeatable geographical framework for air quality monitoring in Indian cities undergoing rapid urbanization. This paradigm is well-suited to the potential applications of remote sensing and spatial information sciences in studying global environmental issues. It offers information that policymakers and urban planners concerned about devising targeted, evidence-based intervention strategies to mitigate pollution and promote sustainable urban development will find helpful.

Sr. No	Pollutants	Time Period	National Ambient Air Quality Standards (NAAQS)	
			Industrial, Residential, Rural & Other areas	Ecologically Sensitive Areas
1	Sulphur Dioxide (SO_2) -µg/m³	Annual	80	80
2	Nitrogen Dioxide (NO_2) -µg/m³	Annual	80	80
3	Particulate Matter (PM_{10})-µg/m³	Annual	100	100
4	Particulate Matter ($PM_{2.5}$)-g/m³	Annual	60	60
5	Ozone (O_3) -µg/m³	8 hrs.	100	100

Table 1 : Standards for Air Pollutants, (Source: CPCB)

This research centers around the dispersion of air pollution in the city of Nashik, a rapidly growing and urbanized area of great historical and cultural significance. The aim of this research is to ascertain the location of concentrated sources of air pollution, particularly major pollutants such as $PM_{2.5}$, PM_{10}, NO_2, SO_2 and CO. This will be achieved through the analysis of various maps and data pertaining to traffic density and patterns, landuse, windflow, temperature, and green cover, as well as near-market comparisons between wards in terms of pollution distribution. This analysis will highlight the wards that are most adversely affected by air pollution, the reasons for this, and how these effects are exacerbated by both natural and local conditions, as well as human factors. Finally, and most importantly, the research will provide practical suggestions to urban planners and authorities, which will both improve air quality and promote healthier and more sustainable development throughout the city of Nashik.

2. Background Study

Maharashtra is a major Indian state renowned for its leading role in economic development. It is popularly referred to as the country’s economic engine, as it has the potential for strong and sustained economic growth. However, due to the high pace of growth, natural resources and urban amenities are being severely damaged whereas road transport significantly drives economic growth and development, it also brings significant environmental consequences (Fernald, 1999). The state faces several environmental challenges, including the shrinking of green spaces, worsening air quality, contaminated water sources, increasing solid waste in cities, uneven access to basic urban services, rising concerns about urban poverty, and noticeable regional disparities. These issues have become widespread across Maharashtra, reflecting the environmental cost of its development. (MPCB, 2020) and (Times, 2025). Nashik city is situated on the banks of the Godavari River, holds significant religious, historical, and cultural importance in India. It is one of the four places of the Kumbh Mela, and has for centuries attracted pilgrims and tourists. Nashik, due to its strategic location in the triangle of development between Mumbai, Pune, and Nashik, has become an important township in recent years. This development has brought with it serious environmental problems. The transportation sector is the primary source of air pollution. Additionally, domestic, commercial, and industrial activities also contribute to it. It is reported that more than 70-80% of air pollution in large cities in developing countries is attributed to greenhouse gas emissions from many worn-out vehicles, combined with poor vehicle maintenance, inadequate road infrastructure, and substandard fuel quality. The key air pollutants are: particulate matter ($PM_{2.5}$ & PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O3) (Zhou, 2017). Particulate Matter (PM), which originates from transportation (exhaust brake/tire wear), combustion industry, construction/demolition, and wind erosion, is one of the major sources of air pollution. Nitrogen dioxide or NO_2 is created during combustion in power plants, automobiles, ships, and heating systems. When sulfur-rich fossil fuels are burned in homes, power plants, and automobiles, sulfur dioxide (SO_2) is released. Carbon monoxide (CO) is mostly produced by combustion in gas-powered cars and industrial processes. Ozone: Associated with the automobile industry and solvents produced when NOx and VOCs react in sunlight (EPA, 2012) and (UNEP, 2021).

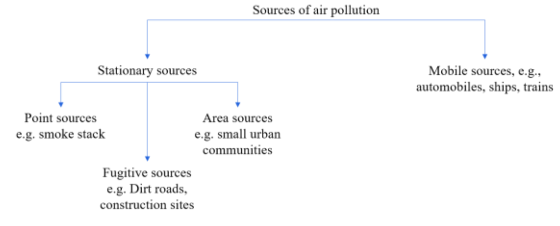

Figure 1 Sources of air pollution (Source: NMC, ESR 2019)

Figure 1 illustrates how air pollution sources are broadly categorized into natural and anthropogenic (human-made) origins. Anthropogenic sources dominate and are categorized into transport, industrial activities, and area-based emissions, such as construction and biomass burning, highlighting the complex and interconnected origins of pollution.

3. Study Area

Nashik is one of the holiest locations for Hindus worldwide, situated on the banks of the Godavari River. According to tradition, Lord Rama, the King of Ayodhya, established Nashik

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as his residence during his 14-year exile, thereby endowing the city with a rich historical heritage. At the same spot, Lord Laxman chopped Shurpnakha's nose at Lord Rama's request, giving the town the name Nasik. The city of Nashik has cultural, social, historical, and mythical significance. According to data from the 2011 census, Nashik Municipal Corporation has a population density of 5556 per square kilometer. Figure 2 shows the study area region and municipal boundary, along with the wards; there are 44 wards in the Nashik Municipal Corporation. The village of Kamathwade has the most excellent gross density, with 250.13 people per hectare. The town of Dadhegaon has the lowest gross density, at 4.22 people per hectare. Given its superb location in the Mumbai-Pune-Nashik Golden Triangle, Nashik is a rapidly rising region with enormous growth potential. According to the 2011 census, 14,86,053 people lived in the Nashik Municipal Corporation region. This was an increase from 10,77,236 people in the 2001 census. This represents a 37.95% rise in population during the decade from 2001 to 2011. Similarly, the population in 1991 was 7,33,000, showing a 46.96% increase over the previous decade. As of 2024, Nashik city has 44 wards and covers a total area of 266.35 square kilometers. (MPCB, 2020)

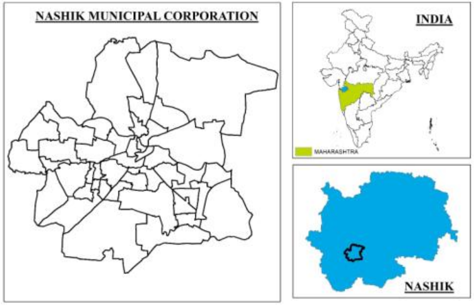

Figure 2 Geographical scope of the study area, delineating the 44 administrative ward boundaries of the Nashik Municipal Corporation. Situated within the Mumbai-Pune-Nashik growth corridor

Nashik has a mild and pleasant climate, and the city experiences four distinct seasons throughout the year. From December to February is the cold season, while from March to May is the hot season. June to September is the monsoon season, and October to November is the post-monsoon season. Rainfall averages between 600 and 700 mm annually, with June and July seeing the highest amounts. The lowest recorded temperature was between 4°C and 50°C in January, while the highest was between 40°C and 45°C in May. Throughout the south-west monsoon season, the region is very humid. The air is often dry throughout the winter and summer months after the monsoon. The summer season is the driest period of the year, with relative humidity between 30% and 35% in the afternoons.

4. Methodology, Data Collection and Sources

4.1 Methodological Workflow

The methodology of this study consists of four primary steps: data collection, preprocessing, spatial analysis, and validation. The first step involves collecting data. The multi-source datasets were derived from Sentinel-5P satellite products, NASA POWER meteorological databases, and CPCB ground monitoring stations. Additionally, records from the Nashik Municipal Corporation and satellite imagery were utilized to compile further spatial layers, such as land use, road networks, vegetation density, and ward boundaries. Stage 2: Data Preprocessing. Satellite datasets were accessed and filtered using Google Earth Engine for the duration of the study. Atmospheric pollutant variables (NO_2 , SO_2 , CO, PM_2 .5, and PM_{10}) were extracted and converted into spatial raster layers. Meteorological variables such as temperature, wind direction, and wind speed were also processed. Each dataset was clipped to the boundaries of Nashik municipality after being converted to a common coordinate system. The third stage involves spatial analysis. ArcGIS Pro was utilized to merge raster datasets and conduct overlay analysis for spatial examination at the ward level. To identify potential sources of emissions and pollution hotspots, maps depicting pollutant concentrations were generated and compared with environmental layers including road networks, land use patterns, vegetation density, and points of interest. Validation is the fourth step, to assess consistency CPCB ground monitoring data and satellite-derived pollutant values were compared. The dependability of the spatial patterns obtained from remote sensing observations was guaranteed by this validation step.

The information needed for this study is obtained by reviewing various development authorities and contacting the board members of the particular authority whose data is not available online or in any other source. This data-gathering method was employed to determine the study area boundaries, and specific data were manually digitized using the ArcGIS georeferencing tool. However, to collect data on different air pollution parameters, there are numerous dataset providers. For India, the Central Pollution Control Board (CPCB) and the State Pollution Control Boards (SPCBs) are responsible for collecting air pollution data from various locations throughout the country. Many data providers, such as NASA, Copernicus Sentinel 5p, and ISRO, can provide pollution and weather data datasets. Every source provides up-to-date real-time data, but CPCB and SPCB deliver the data in the form of a CSV file only, whereas NASA and Copernicus provide both the raster file and the CSV file of the data. As was previously mentioned, the process of gathering information that any organization or authority has already published is known as inventory data collection. Collecting inventory data enables the use of existing information to serve as the foundation for the study. The data is collected from various sources, including the governing body, the planning authority, NASA, Copernicus, CPCB, and SPCB, as well as from published literature and verified publication documents.

For this study, various data were collected from different sources. The data were collected from the respective urban development authorities, municipal corporations, and their Development plans, Master plans, which are the study area boundaries for Nashik city. The remaining datasets of air pollutants are collected from NASA Power Data catalogs, Copernicus Sentinel-5P, and the Central Pollution Control Board (CPCB). All these datasets were cross-checked with each other to identify errors and remove false data. The Air pollutants like Particulate Matter (PM 2.5 & PM 10), Carbon Monoxide (CO), Sulfur Dioxide (SO_2), and Nitrogen Dioxide (NO_2) datasets for Nashik city have been collected from the NASA Air Quality Dataset, Copernicus Sentinel 5P datasets, and the Central Pollution Control Board (CPCB). All spatial datasets were processed and analyzed using ArcGIS Pro and Google Earth Engine (GEE). Satellite products from Sentinel-5P, including the pollution datasets NO_2, SO_2, CO, and $PM_{2.5}$ & PM_{10}, have been acquired. Additionally, meteorological parameters are obtained from NASA POWER. These data were integrated with CPCB ground station data to generate spatial interpolations and validate pollutant concentrations. The process ensures consistency and facilitates future development through open-source platforms. While meteorological variables from NASA POWER were processed using seasonal averages (winter: - October-January, summer: - February-May, monsoon: - June-September), the satellite-derived pollutant datasets used in this study were combined into annual mean composites for the year 2024. In order to minimize short-term variability and highlight long-term spatial patterns of pollutant concentration throughout Nashik city Sentinel-5P atmospheric products were accessed via the Google Earth Engine platform and averaged temporally and this data is validated against CPCB observation station values.

5. Remote Sensing and Geospatial Data Analysis of Existing Air Pollution Scenario in Nashik City with Climatic and Anthropogenic Sources

Conducting an in-depth analysis of the existing air pollution scenario concerning the road network, wind speed and direction, temperature, point of interest, land use map, and tree density map in Nashik city. How air pollutants behave and whether they are emitted within the town or across the border must be analyzed ward by ward. The city of Nashik has 44 wards, as shown in Figure 3.

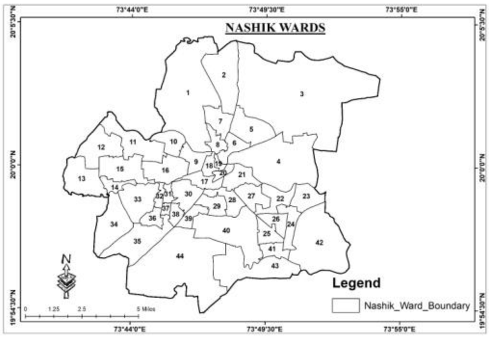

Figure 3 Nashik Wards

5.1 Overview of Environmental and Anthropogenic Influences

This section critically evaluates the spatial distribution of key air pollutants $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO across Nashik city using geospatial overlays with environmental and anthropogenic source maps. Key hotspots and dispersion patterns are identified by integrating pollutant distribution data with the road network, land use types, point of interest locations, wind speed and direction, vegetation cover, and temperature variations to understand pollution dynamics in an urban Indian context.

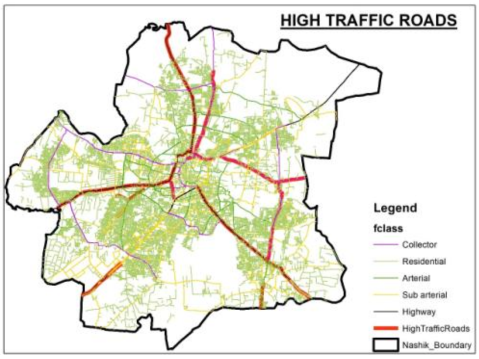

Figure 4 Road Network

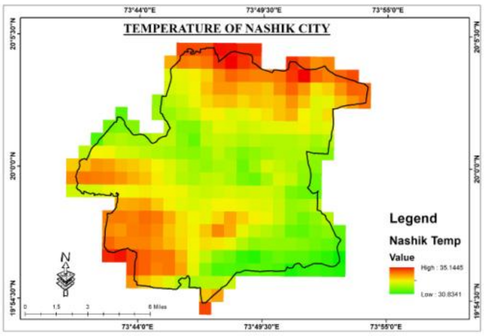

Figure 5 Temperature Map of Nashik City

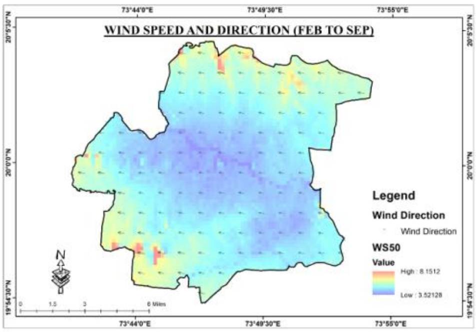

Figure 6 Wind Speed and Direction Map of Nashik City from October to January

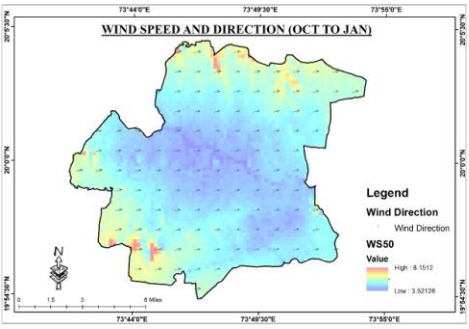

Figure 7 Wind Speed and Direction Map of Nashik City from January to October

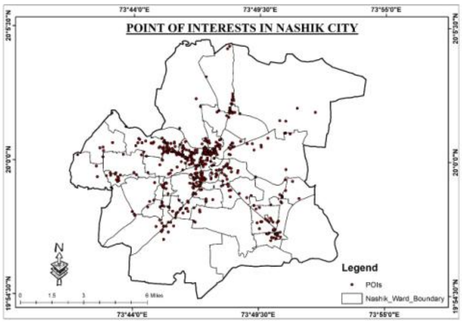

Figure 8 Points of Interest

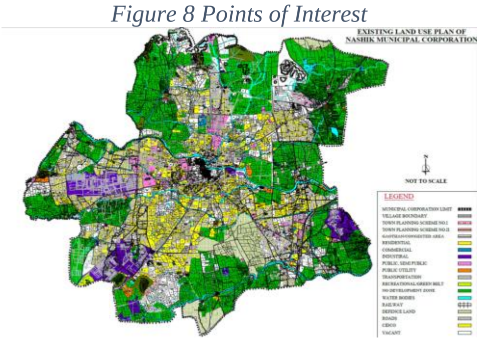

Figure 9 Land Use Map of Nashik City

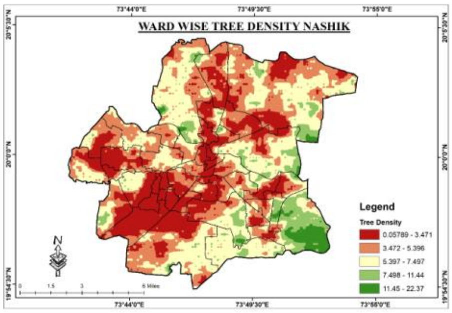

Figure 10 Ward Wise Tree Density Map of Nashik City

Figures 4, 5, 6, 7, 8, 9, and 10 are the environmental and anthropogenic maps of Nashik city, used to analyze the behaviour, reasons, and major sources of air pollutant emissions in a particular area.

5.2 Spatial Distribution of Particulate Matter (PM 2.5 and PM 10)

Particulate matter is small airborne particles from natural and artificial sources. It can enter homes through cracks in walls.

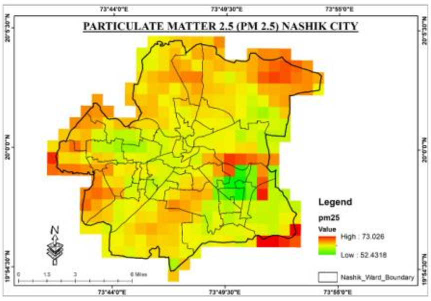

Figure 11 Spatial distribution of annual average $PM_{2.5}$ concentrations across Nashik municipal wards derived from integrated satellite and ground observations

The observed $PM_{2.5}$ and PM_{10} values reflect the distribution of their concentration across Nashik City, as shown in Figures 11 and 12. They reveal a significant spatial disparity in PM concentration, with values ranging from approximately 52.4 $\mu g/m^3$ to over 73 $\mu g/m^3$ for $PM_{2.5}$ and from 87.3 $\mu g/m^3$ to 121.5 $\mu g/m^3$ for PM_{10}. These levels are critically high compared to the World Health Organization’s recommended 15 $\mu g/m^3$ threshold for 24-hour mean exposure. The primary sources of particulate matter 2.5 are Area sources, which are responsible for the emission of more PM $_{2.5}$. Within this, paved and unpaved roads account for a larger share of the total emissions, followed by domestic emissions. In the Panchavati division of Nashik city, $PM_{2.5}$ emissions are higher from Both Paved and Unpaved Road dust. There are two types of domestic: 1. Slums, 2. Non-Slum. In slums, residents use LPG, Coal, Kerosene, and Wood for their daily needs, whereas in non-slums, they use LPG and Wood. The CIDCO division of Nashik city has more $PM_{2.5}$ emissions from domestic sources. Ward numbers 1, 2, 3, 4, 5, 12, 13, and 34 have higher particulate matter 2.5 and 10 emissions, reaching 73 and 121 $\mu g/m^{3,}$ respectively. The city core has paved and well-maintained roads, resulting in lower $PM_{2.5}$ and PM_{10} levels compared to other areas. The wards 22 and 26 have very low emissions of $PM_{2.5}$ and PM_{10}. In the Panchavati division, more open burning is happening. Figure 4. shows high PM2.5 and PM10 levels along major corridors like NH-60. This connects traffic emissions to poor air quality in crowded areas. It highlights the importance of transport planning in reducing pollution.

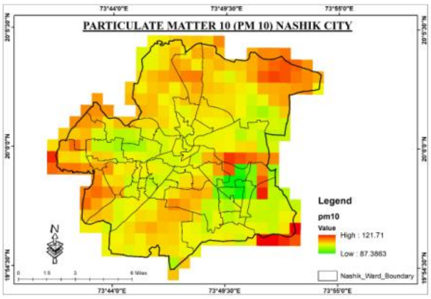

Figure 12 Ward Wise PM 10 of Nashik city

As shown in Figures 6 and 7, Meteorological parameters, including wind speed and direction, have a profound influence on the dispersion and accumulation of particulate matter. The analysis of seasonal wind speed and direction reveals that Nashik experiences predominantly north-westerly winds from February to September and northerly to northeasterly winds from October to January. These wind patterns exhibit speeds varying from 3.5 to 8.1 m/s, enabling lateral advection of suspended particles. However, several southern and southeastern wards, particularly wards 42 and 43, lie within low-wind-speed pockets, making them susceptible to stagnation. From the wind rose diagram for the months of February to September, dominant south-west winds likely carry pollutants towards the north-east, causing visible dispersion plumes in that direction, especially for PM_{10}. However, in low-wind zones, PM accumulates due to poor dispersion, leading to localized air stagnation. The wind speed and direction map, as well as the PM map, indicate that areas with low wind speeds correspondingly have low $PM_{2.5}$ and PM_{10} values. These conditions restrict the dispersion of pollutants and enable the accumulation of airborne particles within the near-surface atmosphere. Such stagnation zones become particularly hazardous during the winter months, when atmospheric temperature inversion occurs, where cooler air near the ground is trapped beneath a warmer layer, effectively sealing pollutants in the breathable layer of the urban atmosphere. Figure 5 shows that Nashik’s temperature (30.8°C to 35.1°C) influences particulate behaviour. Higher temperatures in the northern and western areas promote photochemical reactions that boost PM2.5 formation. Although thermal volatilization may lower particulates locally, secondary aerosol formation takes over. Figure 8 shows many points of interest in the central wards (20, 21, 30) with moderate pollution. Proper planning and vegetation help lower emissions, but high human exposure continues due to focused daily activities.

5.3 Spatial Distribution of Nitrogen Dioxide (NO_2)

NO_2 is a byproduct of high-temperature combustion processes, with the transportation sector being the most significant contributor in urban areas.

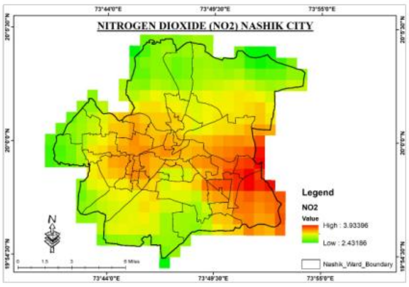

Figure 13 Ward-wise Nitrogen Dioxide of Nashik City

Figure 13 shows that the central business districts and high traffic corridors, especially those close to essential intersections and industrial points of interest, have the highest NO_2 concentrations. In line with roads, the map shows distinct linear patterns that support vehicle emissions as the primary source. Nitrogen Dioxide (NO_2) concentrations in Nashik exhibit a clear central to south-east pollution belt, with higher values exceeding 3.9 µg/m³ in wards 23, 42, 43, 24, 25, 26, and portions of wards 27 and 4. These zones contrast the relatively low NO_2 levels in northern and northwest fringes (Wards 1, 2, and 3). This gradient illustrates the strong effects of land use types, vehicle and combustion-based emissions, and urban density on NO_2 dispersion. Nitrogen Dioxide predominantly arises from vehicular traffic, diesel generators, domestic fuel burning, and industrial thermal activities. In Nashik city, the wards exhibiting high NO_2 concentrations are spatially aligned with zones of transportation corridors, as shown in Figure 4, a map of the high-traffic-volume road network. For instance, wards 23, 42, and 43 are key arterial zones where major roads converge and urban congestion is pronounced. These emission line sources are further exacerbated by frequent idling at junctions and high densities of two - and four-wheelers, which are known to emit large quantities of NO and NO_2 due to incomplete combustion. Figure 9 shows high levels of NO_2 in mixed land-use wards (21, 30, 31, 42) because of fuel combustion from industries, generators, and cooking. A thermal power plant in ward 42 increases emissions. Low wind speeds from October to January make it harder for the pollutants to disperse, trapping NO_2 in the urban canopy and extending exposure in dense neighbourhoods. Figure 10 shows a reverse connection between tree density and NO_2 levels. Wards with less vegetation (wards 30, 31, 32, & southeast ring) have higher concentrations, while greener areas (3, 4, 5) have lower levels. Vegetation helps disperse and absorb pollutants, though thick canopies may hold gases. Ward 42 has high NO_2 comes from its thermal power plant.

5.4 Spatial Distribution of Sulfur Dioxide (SO_2)

Figure 14 illustrates the spatial distribution of sulfur dioxide (SO_2) in Nashik, revealing distinct hotspots in the city's northernmost (Ward 3) and southernmost (Wards 43 and 44) zones with concentration peaks as high as 2.0 µg/m³. In contrast to the central and eastern regions, where levels sharply decline, these values are noticeably higher. The concentrations of SO_2 seem to be higher in industrial areas, especially in the industrial belts of the northwest and east. These hotspots, which include small-scale factories and processing facilities, are in line with industrial POIs. According to the master plan, both hotspot zones correlate with industrial zones from a land-use perspective, especially the large-scale industrial clusters in Satpur-Gonde (north) and Ambad (west). The emission pattern is consistent with the point source characteristics of SO_2, which are primarily caused by the burning of fossil fuels in boiler operations and thermal processes, such as those using coal, diesel, and furnace oil. The connection to human sources is strengthened by the overlap of the southern clusters with CIDCO industrial zones.

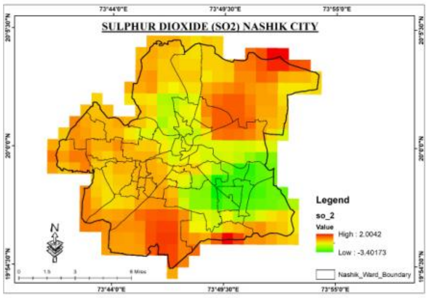

Figure 14 Ward-wise Sulfur Dioxide of Nashik City

The temperature map indicates more thermal conditions in the north and southwest regions. Higher temperatures typically enhance vertical dispersion, yet paradoxically, in Nashik, SO_2 levels remain high. This anomaly is attributed to intensive local emissions overpowering thermal uplift, particularly during winter, when temperature inversions trap pollutants closer to the surface. From February to September, northwest winds carry SO_2 eastward. In winter, winds shift southward, spreading pollutants toward residential areas (wards 26 - 29). Sparse tree cover in hotspot areas (ward 2&43) reduces SO_2 absorption. Even though industrial zones are far from points of interest, wind-driven pollution poses a risk to nearby residential areas that lack plant cover.

5.5 Spatial Distribution of Carbon Monoxide (CO)

Figure 15. CO concentration map for Nashik shows that the eastern (Wards 3, 4, 22, 23) and southeastern (Wards 25, 26, 43, 44) belts have higher values (up to 10.235 µg/m³) while the western and central zones (Wards 10, 13, 15, 16) have progressively lower concentrations.

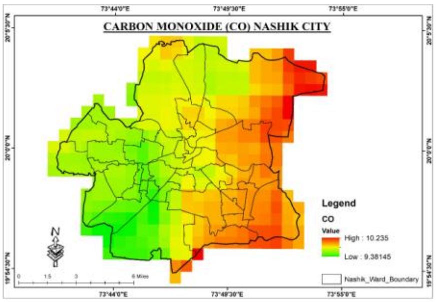

Figure 15 Ward Wise Carbon Monoxide of Nashik City

Vehicle combustion, particularly in congested areas, and incomplete burning of fossil fuels in residential and commercial activities are the main causes of CO emissions in urban settings. The land use map confirms that the high-density residential, commercial, and transportation zones in eastern Nashik are closely aligned with CO hotspots, indicating that these areas are the primary contributors. Localized emissions from stoves, generators, and idling cars are further intensified by the POI map, which also shows groups of restaurants, business centers, and public events.

The CO map illustrates how temperature affects various aspects. According to the temperature map, higher ambient temperatures in the northeast and southern zones (above 34°C) can promote atmospheric buildup and decrease CO solubility, particularly in stagnant conditions. Poor dispersion and pollutant accumulation are caused by low wind speeds (3.5–4.5 m/s) in the same zones, especially during winter and early mornings when inversion layers are common. The tree density map reveals that most CO-intensive zones suffer from very low canopy coverage (below 3.5 units). This lack of vegetative cover contributes to poor pollutant interception and minimal phytoremediation potential. In contrast, Western wards with richer greenery exhibit lower

CO levels due to better natural diffusion and absorption. Hence, CO hotspots in Nashik stem from the intersection of line-source vehicular emissions, high population density, thermal stagnation, and sparse green infrastructure, especially in Wards 22, 25, and 44. These areas require priority intervention through traffic decongestion, tree plantation, adoption of clean fuels, and real-time monitoring.

6. Validation and Comparative Assessment of Central Pollution Control Board (CPCB) Data

The data on air pollution parameters collected from different sources, like Sentinel 5P, NASA Power, and world AQI data, are validated with the data of the Central Pollution Control Board (CPCB) and the Maharashtra Pollution Control Board (MPCB) to know the accuracy of the collected datasets used for this study. The station-wise pollution data collected from the Central Pollution Control Board for Nashik city is shown in Table 2.

Station Name	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
Gangapur Road, Nashik - MPCB	84	86	6	26	12
Hirawadi, Nashik - MPCB	34	56	3	4	18
MIDC Ambad, Nashik - MPCB	63	82	2	3	25
Pandav Nagari, Nashik - MPCB	33	112	6	4	17

Table 2 Station-Wise Pollution Data, (Source: CPCB)

Station Name	$PM_{2.5}$	PM_{10}	SO_2	NO_2	CO
Gangapur Road, Nashik - MPCB	73.02	81.39	2.0	3.93	9.38
Hirawadi, Nashik - MPCB	36.51	51.10	1.21	3.05	9.32
MIDC Ambad, Nashik - MPCB	61.30	88.00	-2.1	0.15	10.2
Pandav Nagari, Nashik - MPCB	36.00	121.7	1.86	1.25	9.85

Table 3 Observed Pollutants Data at those Station Locations from Sentinel - 5P

As shown in Table 3 and Figure 16, at Gangapur Road, Nashik, the annual exceedance of Particulate Matter 2.5 and 10 is approximately 90%, with a maximum concentration of 84 µg/m³. AQI varied between unhealthy in winter and moderate to harmful for the sensitive group in other months. The 24-hour average of NO_2 also exceeds the standards at this location and the wards. Likewise, at Pandav Nagari, the concentrations exceeded the annual average and 24-hour average of PM_{10}; at MIDC Ambad, the 24-hour average of carbon monoxide was surpassed.

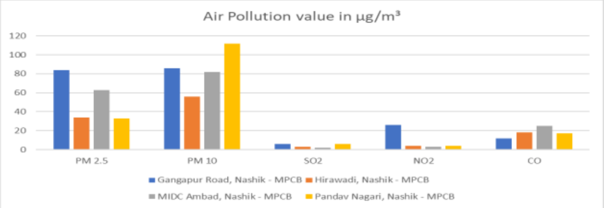

Figure 16 Air Pollution value in µg/m³

These data on air pollution parameters show more similarities with data collected through Sentinel-5P, NASA Power, and AQI data. Thus, satellite data can be used to understand the air pollution scenario of any city.

The spatial scale differences between ward-level administrative boundaries and satellite-derived observations must be acknowledged. The spatial resolutions of Sentinel-5P atmospheric products are generally coarser than the spatial scale of individual urban wards ranging from roughly 3.5 km × 7 km to 5.5 km × 3.5 km. Pollutant concentrations were spatially averaged and incorporated into the GIS framework prior to ward-level overlays in order to overcome this restriction. Previous research has shown that satellite observations are still dependable for identifying larger urban pollution hotspots when combined with ground observations and spatial contextual data despite the possibility of some spatial generalization.

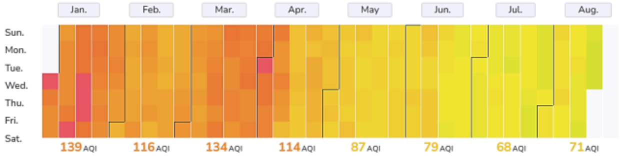

Figure 17 AQI Exceedance Months of Nashik City, (Source: AQI.in)

Figure 17 shows the seasonal variation of AQI in Nashik, with the highest pollution levels in winter. January, February, and March had average AQIs of 139, 116, and 134, often going above the “Unhealthy for Sensitive Groups” limit. The main causes are vehicle emissions, burning biomass, temperature inversions, and stagnant air. The AQI improves starting in April and drops sharply during the monsoon (May to August: 87 to 68) due to better air dispersion and wet deposition. While 60 to 70% of winter and summer days exceeded the limits, only 10% did in the monsoon. This underscores the importance of strict emission control and dust management during winter.

Pollutant	Correlation (r)	RMSE
PM2.5	0.99	5.88
PM10	0.98	6.62
NO2	0.83	3.64
SO2	0.73	11.22
CO	0.78	9.38

Table 4 Statistical validation of satellite-derived pollutant concentrations using CPCB observations

The consistency between satellite derived pollutant estimates and ground-based observations from the Central Pollution Control Board monitoring stations in Nashik was evaluated through a quantitative validation. At the locations of the monitoring stations satellite values were extracted and compared with the concentrations that were observed. Satellite and ground measurements have moderate to strong positive correlations (r = 0.73 – 0.99 depending on the type of pollutant, detailed validation results given in Table 4) according to the statistical analysis. The Root Mean Square Error (RMSE) values stayed comparatively low suggesting that the datasets agreement was reasonable. These findings demonstrate that when combined with data from ground monitoring satellite derived observations can successfully capture spatial patterns of urban air pollution.

7. Discussion and Conclusion

7.1 Discussion

This study provides an integrated ward-level understanding of Nashik’s air pollution dynamics, revealing consistently high $PM_{2.5}$ and PM_{10} concentrations in comparison to WHO guidelines. Additionally, it identifies spatially patterned elevations of NO_2, SO_2, and CO, which are correlated with traffic, industrial activity, and household fuel use. The city is $PM_{2.5}$ and PM_{10} levels ranged from approximately 52.4 µg/m³ to over 73 µg/m³ and 87.3 µg/m³ to 121.5 µg/m³, respectively, which is well above the WHO's 24-hour $PM_{2.5}$ guidelines of 15 µg/m³, indicating a significant and ongoing particulate matter burden. Pollutant hotspots are found in densely populated residential wards with emissions of domestic fuel and road dust along major transportation corridors (such as NH-60 and Nashik-Pune Road) and in industrial areas where SO2 exhibits localized peaks. Whereas SO_2 peaks at about 2.0 µg/m³ in industrial wards, NO_2 exceeds 3.9 µg/m³ in high-traffic corridors and compact urban cores. In eastern and southeastern wards, CO levels can reach as high as 10. 235 µg/m³, especially in places with much traffic. Meteorology further shapes these spatial patterns. Areas with lower wind speeds, particularly in some southeastern wards, exhibit pollutant stagnation, while areas with sparse vegetation cover are associated with higher levels of NO_2 and particulate matter.

These patterns' mechanistic interpretation aligns with recognized urban emission profiles. Along trunk roads and transit corridors, vehicle emissions appear to be the primary cause of NO_2 and CO concentrations, which are then exacerbated by roadway geometry and nearby built-up density, which hinders dispersion. Re-suspended road dust, ongoing construction, and domestic combustion, including LPG, kerosene, coal, and wood, all contribute to particulate pollution, especially in wards with high population densities and little dust control or street sweeping. The combustion of industrial fuels likely causes the SO_2 hotspots. The accumulation of pollutants near sources is facilitated by seasonal weather, particularly in winter, when low wind speeds and possible inversion conditions limit vertical and horizontal mixing. The mitigating role of urban green infrastructure through deposition filtration and microclimate modulation is supported by the inverse relationship between tree canopy and pollutant levels.

These findings align with multi-city literature from rapidly urbanizing Indian contexts, which reports elevated PM and NO_2 levels associated with traffic density, mixed land uses, and limited dispersion under adverse meteorological conditions. Evidence from North and Western Indian cities with comparable combinations of transportation construction and domestic sources is consistent with the exceedance of WHO particulate thresholds. Prior research on the function of green infrastructure in reducing exposure at the near-road and neighbourhood scale is supported by the correlation between higher pollutant loads and a lack of vegetation. Similarly, source apportionment studies indicate that sulfur emissions from combustion are generally located near manufacturing and thermal processes, which is consistent with the spatial coupling of SO_2 with industrial zones.

In terms of methodology, the study’s integration of remote sensing CPCB/SPCB ground observations and multi-source datasets (e., The Sentinel-5P, NASA POWER) land-use and transport layers and contextual variables at the ward level enhances internal validity through triangulation and cross-validation. Ward-wise analyses and geographic overlay offer operationally appropriate resolution for intervention targeting. However, restrictions must be taken into account. Gridded meteorology and satellite-derived pollutant products may introduce spatial mismatch at the ward scale. The cross-sectional nature limits the generalization to seasons and causal attribution, and the ground monitoring density is still too low for thorough temporal validation. Furthermore, although correlations with wind and tree cover are tenable and pertinent to policy causal pathways (e., the Street canyon effects, certain canopy features, etc), they were not directly measured. The direct quantification of morbidity or mortality burdens attributable to observed concentrations is limited by the study’s failure to establish a connection between exposure profiles and health outcomes. Immediate policies should focus on traffic management, low-emission zones, and cleaner fuels to reduce NO_2 and CO. Controlling PM requires dust reduction and road maintenance. To lower industrial SO_2, we need strict regulation and monitoring. Urban greening, seasonal preparedness, and access to clean energy will further improve air quality and shield residential areas from pollution exposure. Future research should involve ongoing monitoring, identification of pollution sources, and mapping health-related exposure to enhance interventions and evaluate the effects of air quality.

In conclusion, traffic, home combustion, industrial activity, a lack of vegetation, and unfavourable weather all contribute to Nashik’s air quality problems. A targeted policy portfolio for controlling transport emissions, managing dust, ensuring industrial compliance, and promoting strategic urban greening, sequenced to align with seasonal dispersion patterns, is supported by the convergence of multi-source evidence, accurate hotspot localization, and feasible mechanisms. These findings emphasize the significance of location-specific air quality interventions which can change depending on the season. Integrated emission sources should be the primary focus of strategies, rather than isolated controls for individual pollutants. Additionally, the approach integrates observations from CPCB stations with satellite data. To better capture short-term changes and microenvironmental hotspots, future work should incorporate real-time mobile monitoring.

Even though there are benefits to using an integrated geospatial approach, several limitations should be acknowledged. Firstly, the resolution of pollutant observations obtained from satellites is less detailed than the boundaries of administrative wards, which may result in the averaging of spatial data. Secondly, validating data in each ward is limited by the few monitoring stations operated by the CPCB. Thirdly, instead of employing comprehensive source apportionment modelling that would require larger datasets of atmospheric chemistry, the analysis primarily relies on spatial correlations. Future studies could enhance the precision of urban air quality assessments by utilizing mobile monitoring data, higher resolution satellite imagery, and advanced spatial statistical techniques.

7.2 Conclusion

This study demonstrates how the integration of multi-source remote sensing and GIS can be utilized to evaluate and analyze the temporal and spatial dynamics of air pollutants in urban settings. The study effectively mapped and examined the distribution of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO throughout Nashik, India, using data from Sentinel-5P, NASA POWER, and CPCB ground observations. The findings revealed clear spatial patterns associated with environmental and anthropogenic factors, including wind speed, vegetation cover, industrial activity, traffic density, and land-use intensity. Particularly in the eastern and central parts of the city, high concentrations of pollution were consistently observed along major transportation routes and industrial areas. On the other hand, less densely populated and greener areas showed relatively lower concentrations. These results underscore the crucial role of geospatial analysis in regulating urban air quality, confirming a strong spatial correlation between urban morphology, atmospheric dynamics, and pollutant dispersion.

A thorough and repeatable method for comprehending the dynamics of urban air quality is provided by integrating satellite observations with ground-based data in a GIS environment. By identifying emission hotspots, evaluating the effects of land use, and guiding targeted mitigation strategies, this spatially detailed analysis supports well-informed planning decisions. The method used here can serve as a replicable framework for comparable cities that require accurate, fine-scale evaluations of environmental conditions but struggle with data scarcity.

The study emphasizes the policy significance of geospatial monitoring for evidence-based urban planning in addition to its analytical contributions. Local governments can utilize the spatial identification of emission hotspots and their connections to industrial zones and traffic networks to implement targeted interventions, such as green buffer planning, enhanced public transportation, and emission zoning. The findings demonstrate how geospatial data integration can effectively bridge the gap between environmental science and urban governance, fostering the development of more sustainable, healthier, and cleaner cities. By utilizing cloud-based Earth observation platforms, such as Google Earth Engine (GEE), future research can expand this framework to include multi-temporal analysis and near-real-time monitoring. Spatiotemporal precision may be further enhanced by incorporating other datasets such as the normalized difference vegetation index (NDVI), land surface temperature, and satellite-derived Aerosol Optical Depth (AOD). These developments would enable the measurement of long-term trends in air quality, seasonal variability, and climate-pollution interactions at finer spatial resolutions.

This study concludes by highlighting the significance of geospatial technologies and remote sensing as essential instruments for managing, diagnosing, and tracking urban environmental quality. Their integration enables data-driven policymaking, promotes adherence to air quality regulations, and strengthens the scientific basis for achieving climate-resilient and sustainable urban development, leveraging spatial information science to benefit both people and the environment.

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