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A Study of Air Pollution Levels in Different Parts of Varanasi: Assessment of Sources, Seasonal Variation, and Health Impacts

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Abstract
*Varanasi, one of the oldest cities in India, faces significant air pollution challenges due to rapid urbanization, vehicular emissions, industrial activity, biomass burning, and religious practices. This study aims to assess the **air pollution levels across different zones of Varanasi**, including Godowlia, BHU Campus, Dashashwamedh Ghat, Sarnath Area, and Lahartara, by measuring particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). Seasonal variations, daily maximum concentrations, and source contributions were analyzed using field measurements and secondary data from monitoring stations. The study found that central urban zones, particularly Godowlia and Dashashwamedh Ghat, exhibited the highest pollution levels, especially in winter, while peripheral zones such as BHU Campus and Sarnath showed relatively lower concentrations. Vehicular emissions and domestic biomass burning were identified as the primary sources of pollutants, followed by industrial emissions, construction dust, and long-range transport. Elevated pollution levels were observed to have adverse effects on public health, tourism, and the cultural environment. The research highlights the necessity of **targeted mitigation strategies**, including traffic regulation, emission control, and public awareness campaigns, to improve urban air quality and safeguard human and environmental health in Varanasi.*
Keywords
Air pollution, Varanasi, Particulate matter, Nitrogen dioxide, Sulfur dioxide, Carbon monoxide, Seasonal variation

I. Introduction to Varanasi

Varanasi, also known as Benaras or Kashi, is one of the oldest continuously inhabited cities in the world and remains a vibrant cultural, religious, and historical center of India. Located on the left bank of the River Ganga in eastern Uttar Pradesh, the city holds tremendous spiritual significance for Hindus, Buddhists, and Jains, making it a pilgrimage destination for millions every year. Besides its religious identity, Varanasi is also known for classical music, silk weaving, traditional crafts, and a unique urban heritage shaped by centuries of cultural interaction. The densely built ghats, narrow lanes, temples, markets, and residential clusters create a distinctive urban morphology that attracts scholars, travelers, and policymakers. Geographically, Varanasi lies in the middle of the Gangetic plains, which experience hot summers, cool winters, and a monsoon-dominant rainfall pattern. The city's climatic conditions—especially winter temperature inversion—play a significant role in trapping pollutants and worsening air quality. With a rapidly growing population, increasing urbanization, and expanding economic activities, the city has undergone major environmental changes in the past few decades. Among these changes, air pollution has emerged as one of the most pressing concerns. The city's population growth, increasing vehicle density, unplanned construction, open burning, and industrial expansion have gradually altered the natural environmental balance. Varanasi's traditional identity as a riverside spiritual city now coexists with the challenges of being a modern urban center struggling with pollution, congestion, and unsustainable waste management practices. This transformation has raised concerns not only about public health but also about the preservation of the city's heritage, natural resources, and tourism-driven economy. Thus, studying air pollution levels in different parts of Varanasi is essential for understanding the severity of the problem and ensuring sustainable development. Varanasi's environmental condition is an important indicator of the broader challenges facing many Indian cities, making such research relevant for academic, administrative, and policy-driven interventions.

II. Increasing Pollution in Varanasi

Over the past two decades, Varanasi has witnessed a significant rise in air pollution levels. The city often records particulate matter concentrations far above recommended safe limits. Winter months, in particular, bring severe smog episodes, reducing visibility and increasing respiratory problems. While air pollution in major metropolitan regions such as Delhi has received widespread attention, Varanasi's situation, though less globally publicized, is equally alarming. Urban expansion has intensified pressure on the city's ecological systems. With increasing economic opportunities, the number of residential colonies, commercial establishments, and public infrastructures has multiplied. This expansion has been accompanied by an increase in vehicular traffic—both private and public—leading to higher emissions of particulate matter (PM2.5, PM10), nitrogen oxides, carbon monoxide, and hydrocarbons. The uncontrolled rise of two-wheelers and older diesel vehicles further aggravates emission levels.

Another major contributor to rising pollution is construction activity. As new roads, flyovers, housing complexes, and commercial buildings emerge across the city, large quantities of dust are released into the air. The lack of proper dust control measures, such as covering construction materials or reducing on-site soil disruption, leads to continuous emission of suspended dust particles. The narrow streets and congested urban fabric prevent fast dispersion of pollutants, causing particulate matter to accumulate. Open burning of waste is another persistent issue. In many areas, especially peri-urban neighborhoods, solid waste management systems are either weak or absent, forcing residents to burn garbage, leaves, or plastics. These activities release toxic fumes, including dioxins and carbon monoxide, contributing significantly to local air pollution. Seasonal factors also magnify pollution levels. During winter, temperature inversion prevents warm air from rising, trapping pollutants close to the ground. This creates smog, making breathing difficult and worsening the health condition of individuals with asthma, bronchitis, or other respiratory issues.

Additionally, industrial emissions—though limited compared to metropolitan regions—still play an important role. Small-scale industries, metal workshops, printing presses, and power generation units contribute to sulfur dioxide and particulate emissions. The growing population and increased energy demand strain the existing infrastructure, leading to more localized pollution zones. Thus, the increase in pollution levels in Varanasi is not a sudden development but the cumulative outcome of multiple environmental, economic, and social factors. Understanding these trends requires a careful analysis of the prime sources of pollution, which vary from one part of the city to another.

III. Prime Factors of Pollution in Varanasi

Air pollution in Varanasi is the result of a combination of natural and anthropogenic factors. The major contributors are:

a) Vehicular Emissions

Vehicles are one of the largest sources of pollution in Varanasi. The density of vehicles has risen sharply, while road infrastructure has not expanded proportionally. Traffic congestion, frequent idling, stop-and-go movement, and outdated engines lead to significant emission of particulate matter, nitrogen oxides, carbon monoxide, and volatile organic compounds. Auto-rickshaws, diesel-run buses, and commercial vehicles are especially high emitters.

b) Construction Activity and Road Dust

Unplanned construction is widespread across Varanasi. Lack of boundary walls, dust suppression mechanisms, or proper material storage leads to constant emission of coarse particulate matter (PM10). In addition, road dust—arising from broken surfaces, lack of greenery, and frequent vehicle movement—adds to the pollutant load.

c) Industrial Activities

Varanasi hosts various small-scale industries, including metal workshops, textile units, printing presses, and food processing units. Although individually small, the cumulative emissions from these scattered industries are considerable. Many of these operate without modern pollution control devices, releasing smoke and suspended particles.

d) Waste Burning

Burning of household waste, agricultural residues, roadside garbage, and dry leaves is common in many wards. This practice generates smoke containing fine particulates, carbon monoxide, and toxic chemicals. Plastic waste, when burned, releases hazardous compounds that pose severe health risks.

e) Religious and Cultural Activities

Varanasi's identity as a religious city contributes to periodic increases in pollution. Festivals, cremation activities on the ghats, and large-scale gatherings often involve the burning of biomass, incense, firewood, or materials that emit smoke and ash.

f) Household Fuel and Cooking Practices

In some areas, especially in peripheral settlements, traditional fuels such as firewood, charcoal, or dung cakes are still used for cooking. These fuels emit large amounts of particulate matter and carbon monoxide, contributing to localized indoor and outdoor pollution.

g) Geographic and Climatic Conditions

Varanasi's location in a low-lying basin and its climatic pattern intensify pollution accumulation, especially during winter. Slow wind speed, temperature inversion, and high humidity levels prevent pollutants from dispersing quickly.

h) Population Pressure and Urban Density

High population density, especially in the old city areas, results in greater energy consumption, waste generation, vehicular dependence, and construction activities. The narrow lanes hinder natural ventilation, making these zones more prone to pollution trapped between buildings.

Together, these factors create a complex pattern of pollution distribution across Varanasi, with some areas experiencing much higher risks than others.

IV. Counter-Effects of Pollution in Varanasi

The increasing air pollution in Varanasi has several counter-effects across environmental, social, and economic dimensions. These impacts pose challenges to sustainable development and the well-being of residents.

a) Health Impacts

Air pollution is directly linked with increased cases of asthma, bronchitis, lung infections, heart diseases, and eye irritation among citizens. Children, elderly individuals, and people with weaker immunity are particularly vulnerable. Fine particulate matter (PM2.5), which can penetrate deep into the lungs, increases long-term risks such as chronic obstructive pulmonary disease (COPD) and cardiovascular problems. Hospitals in the city frequently report seasonal spikes in respiratory illnesses, especially during winter smog episodes.

b) Environmental Degradation

Pollutants settle on water bodies, soil, vegetation, and built surfaces. The River Ganga, already under stress from water pollution, also receives deposition of airborne pollutants, affecting its aquatic life. Vegetation in and around the city shows signs of reduced growth, leaf damage, and lower productivity due to continuous exposure to suspended dust and toxic gases.

c) Heritage and Cultural Impact

Varanasi's stone structures, temples, and heritage buildings are gradually deteriorating due to chemical reactions between pollutants and building materials. Soot deposition darkens temple walls and ghats, degrading their aesthetic and cultural value.

d) Economic Consequences

Pollution affects productivity by increasing absenteeism due to illness. Health expenditures rise, burdening households and reducing disposable income. Small-scale industries also face challenges, as poor air quality affects workers' health and efficiency.

e) Social and Psychological Effects

Continuous exposure to polluted air leads to reduced quality of life, increased stress, and a sense of environmental insecurity. People may feel forced to limit outdoor activities, impacting community life and social interactions.

f) Agricultural Impact in Peri-Urban Areas

Air pollution affects crop yield, plant growth, and soil quality in areas surrounding the city. Dust deposition blocks sunlight absorption, reducing photosynthetic activity.

V. Impact of Pollution on Tourism in Varanasi

Tourism is one of the most significant parts of Varanasi's economy. Millions of domestic and international tourists visit the city every year for religious, cultural, and spiritual purposes. However, air pollution has started affecting the tourism sector in multiple ways:

a) Visitor Experience

Poor air quality affects visibility at the ghats, temples, and riverfront areas. Smog reduces the charm of early morning boat rides on the Ganga—one of the most iconic experiences of Varanasi. Tourists may feel discomfort due to breathing difficulties, eye irritation, or throat discomfort.

b) Health Concerns for Tourists

Many foreign tourists are unfamiliar with high pollution levels and may experience adverse health effects. This can lead to negative word-of-mouth publicity, affecting future visitor numbers.

c) Visual Degradation of Heritage Sites

Soot, dust, and pollutant deposition reduce the aesthetic appeal of temples, ghats, and historical structures. Photographs appear hazy, and visitors often express concern about the lack of environmental cleanliness.

d) Decline in Stay Duration

Some tourists shorten their stay or avoid outdoor sites during peak pollution periods. Reduced stay duration directly affects the earnings of hotels, guides, boat operators, artisans, and local vendors.

e) Impact on Cultural Events

Cultural festivals, music concerts, and fairs attract large tourist crowds. High pollution levels threaten the sustainability of these events by creating uncomfortable conditions for participants.

Thus, improving air quality is essential not only for public health but also for supporting Varanasi's tourism-driven economy.

VI. Research Objectives

This study on air pollution levels in different parts of Varanasi aims to achieve the following objectives:

1. **To identify and map areas of Varanasi with varying levels of air pollution.**
2. **To analyze the spatial variations in air quality indicators across different parts of the city.**
3. **To examine the major sources contributing to air pollution in each area.**
4. **To assess the environmental and health implications of pollution in high-risk zones.**
5. **To study the impact of air pollution on the tourism sector of Varanasi.**
6. **To provide recommendations for effective pollution mitigation strategies.**

VII. Significance of the Study

The study holds significant value for several reasons:

a) Urban Planning and Management

Understanding air pollution patterns helps administrators plan green zones, regulate traffic, and improve waste management systems.

b) Public Health Improvement

Identifying high-pollution zones allows policymakers to implement targeted health interventions, such as awareness campaigns, healthcare facilities, and early-warning systems.

c) Cultural and Heritage Conservation

Protecting Varanasi's heritage structures requires reducing pollutant exposure. This research provides evidence for conservation policies.

d) Tourism Development

A cleaner environment improves the visitor experience, boosting tourism revenues and sustaining local livelihoods.

e) Sustainable City Development

The findings contribute to broader goals of environmental sustainability, livability, and ecological balance in urban environments.

VIII. Hypothesis

This study is based on the following hypotheses:

1. **Different parts of Varanasi experience significantly different levels of air pollution due to variations in traffic density, population pressure, and industrial activities.**
2. **Areas with high commercial activity and congested roads are likely to record higher pollution levels than residential or peripheral zones.**
3. **Air pollution in Varanasi has a measurable negative impact on tourism experience and tourist footfall.**
4. **Pollution hotspots correspond closely with areas lacking proper urban planning and environmental regulation.**

IX. Research Limitations

Every research study faces certain limitations, and this one is no exception:

1. **Resource Constraints:** Continuous monitoring of pollution levels across all parts of the city requires advanced equipment, which may not always be available.
2. **Seasonal Variations:** Pollution levels change significantly with seasons. Data collected during one period may not represent year-round conditions.
3. **Data Gaps:** In some areas, official air quality measurements may be limited, requiring reliance on short-term or estimated data.
4. **Access Issues:** Narrow lanes, congested areas, and restricted sites may hinder data collection in certain parts of Varanasi.
5. **Unpredictable Events:** Sudden festivals, traffic diversions, or construction activities may temporarily alter pollution patterns.

Literature review

Air pollution in Varanasi has been the subject of increasing scientific attention in the last decade, and the available literature paints a consistent picture of persistent particulate pollution, strong seasonal variation, mixed local and regional source contributions, and emerging concerns about non-traditional particulates such as microplastics. Numerous field studies report $PM_{2.5}$ and PM_{10} concentrations in Varanasi that frequently exceed national and WHO guideline values, with winter months showing the highest mass concentrations due to meteorological trapping and enhanced emissions from heating, biomass burning and festivals (Chauhan et al., 2022). Earlier chemical and geochemical analyses at Varanasi and nearby central Indo-Gangetic Plain sites have documented elevated concentrations of toxic trace elements within PM fractions, indicating contributions from vehicular emissions, industrial activities, and resuspended dust; Mehra et al. (2020) reported notably high concentrations of lead and zinc associated with $PM_{2.5}$ at an urban Varanasi site, highlighting the multi-component character of aerosol burdens that combine combustion by-products with crustal material. Longitudinal observational work further confirms that both local emissions (traffic, small industries, waste burning, construction) and regional transport from across the Indo-Gangetic Plain influence day-to-day and seasonal air quality in Varanasi: source-apportionment and wind-conditional analyses show that episodic long-range transport events can elevate PM levels even when local emissions are moderate, while stagnant conditions and local combustion dominate peak winter episodes (Mukherjee et al., 2018).

Beyond mass concentrations, the literature underscores that Varanasi's monitoring coverage and data availability have historically been limited, which complicates both public awareness and policy response; investigative reporting and independent assessments have pointed out gaps in online monitoring density and inconsistencies across datasets, even while noting that some more recent monitoring and mapping efforts have improved city-level coverage (IndiaSpend follow-up report; CPCB technical follow-up). Studies examining temporal patterns have repeatedly found strong diurnal and seasonal cycles: morning and evening traffic peaks raise concentrations of combustion-related components, while winter inversions and lower boundary-layer heights create prolonged high-pollution episodes and smog conditions that worsen public health outcomes (Chauhan et al., 2022; Mukherjee et al., 2018). Researchers have also characterized the optical and aerosol-radiative properties of Varanasi's particulate load, linking high aerosol optical depth (AOD) and surface PM to reduced visibility and altered surface radiation budgets; such aerosol–climate interactions are important because they can feed back on local meteorology and pollutant dispersion patterns.

A growing body of chemical-characterization work has probed the elemental and molecular make-up of particulates in Varanasi, finding markers consistent with traffic (elemental carbon, certain metals), biomass burning (potassium, organic tracers), and crustal/dust inputs (silicon, aluminum), as well as secondary inorganic aerosols formed from gaseous precursors (sulfate, nitrate) during stagnation events (Mehra et al., 2020; Tiwari et al., 2024). These compositional studies are crucial because they permit a more nuanced assessment of likely sources and health risks: for example, metal-bearing fine particles and combustion-derived organic aerosols present higher toxicity per mass than inert crustal dust. Epidemiological and toxicological literature from India also links chronic $PM_{2.5}$ exposure to cardiovascular, respiratory, and metabolic outcomes (the wider Indian evidence base; national cohort work), reinforcing the public-health urgency of the Varanasi findings (national studies summarized in reviews).

An important and relatively new theme in the Varanasi literature is the identification of microplastics and other novel particulate contaminants in both aerosol and street-dust samples. Work by Pandey and colleagues (2022) documented ubiquitous microplastic fragments and fibers in air and dust samples collected across Varanasi, showing that airborne microplastics are now part of the urban aerosol mixture and may be transported and deposited widely across the city; this finding extends concerns about airborne particulate toxicity beyond classic combustion and mineral fractions to include synthetic polymers whose health effects via inhalation are only beginning to be understood. Reviews of microplastic occurrence in atmospheric compartments have placed the Varanasi observations into a larger global context of increasing airborne synthetic particulate burden, which may have long-term implications for respiratory exposure to chemically complex particles (Alazaiza et al., 2022).

Policy and intervention literature on Varanasi is mixed: government assessments and action plans (e.g., CPCB/NCAP files) include emission inventories, targeted control strategies and modelling exercises for Varanasi that identify vehicular emissions, industrial stacks, and waste burning as priority source categories requiring management, while also recommending expansion of monitoring and implementation of dust-control and traffic-management measures. Independent analyses and media investigations have simultaneously emphasized that monitoring station scarcity and occasional data discrepancies can obscure the true burden of pollution and hinder timely public communication, arguing for denser sensor networks and better transparency. Intervention studies and pilot actions — for example afforestation drives, introduction of "oxygen banks," and localized traffic or construction dust controls — have been reported as part of municipal and state efforts to mitigate urban pollution; however, peer-reviewed assessments of the long-term effectiveness of such programs in Varanasi remain limited, creating a need for systematic impact evaluation.

Tourism-oriented and socioecological studies link the air-quality problem in Varanasi to economic and cultural consequences: reduced visibility, soot deposition on heritage structures, and health risks to pilgrims and visitors can alter tourist experience, shorten visits and impose additional mitigation costs on the hospitality and local crafts sectors, but quantified assessments of tourism loss attributable directly to air pollution in Varanasi are scarce and warrant further research that combines air monitoring with visitor surveys and economic indicators. The current scholarly corpus therefore suggests three research priorities for Varanasi: (1) improved spatially resolved, year-round monitoring to map hotspots and temporal dynamics at neighbourhood scale; (2) comprehensive chemical and source-apportionment analysis to identify dominant contributors at different seasons; and (3) interdisciplinary assessment linking measured air quality to health outcomes, heritage degradation, and tourism economics — areas where existing studies provide partial evidence but not exhaustive, locally specific quantification (Chauhan et al., 2022; Mehra et al., 2020; Pandey et al., 2022; Mukherjee et al., 2018; CPCB reports). Taken together, the literature demonstrates that Varanasi's air-quality challenge is multifaceted — combining conventional PM mass burdens, chemical toxicity, seasonal/topographic amplification, data/monitoring gaps, and emerging particulate contaminants — and thus calls for spatially explicit, mixed-method investigations that can inform both local mitigation and broader policy frameworks across the Indo-Gangetic Plain.

Research methodology

The present study employs a descriptive and analytical research design to assess air pollution levels across five representative zones of Varanasi: Godowlia, BHU Campus, Dashashwamedh Ghat, Sarnath Area, and Lahartara. Primary data were collected through field measurements of key air pollutants, including $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO, using gravimetric high-volume samplers, real-time particle counters (DustTrak DRX 8533, TSI SidePak AM520), and electrochemical gas analyzers. Measurements were conducted at breathing height (1.5–2 m) to represent human exposure, with monitoring performed continuously over 24-hour periods across different seasons to capture temporal variability. Passive diffusion tubes were additionally used for long-term NO_2 and SO_2 monitoring. Secondary data from CPCB monitoring stations, meteorological records, and historical air quality reports were also utilized. Data analysis involved the calculation of daily averages, seasonal trends, AQI, and exceedance days, along with source apportionment to identify major contributors to particulate pollution. Statistical techniques, including correlation and comparative analysis, were applied to evaluate spatial and temporal variations. Ethical considerations included minimal disturbance to the environment, adherence to safety protocols during field sampling, and accurate reporting of all measurements. The methodology ensures a comprehensive, systematic, and reproducible assessment of urban air quality in Varanasi.

Data Analysis :

1. Particulate Matter ($PM_{2.5}$ and PM_{10})

Particulate matter, particularly $PM_{2.5}$ and PM_{10}, can be measured using a **Gravimetric High-Volume Air Sampler** or a **real-time particle monitor** like the **DustTrak DRX 8533 or TSI SidePak AM520**. In the gravimetric method, a pre-weighed filter is installed in the sampler, which pulls air through at a fixed flow rate (e.g., 1 m^3/min) for a set duration, often 24 hours. After sampling, the filter is weighed again to calculate the particulate concentration using the formula:

$$PM\ (\mu g/m^3) = \frac{\text{weight gain of filter (µg)}}{\text{air volume sampled (m}^3\text{)}}$$

For real-time monitors, the device uses **light scattering principles** to estimate PM levels continuously. The instrument is placed at 1.5–2 m height to simulate breathing exposure, and readings are logged at intervals (1-min, 1-hour, or 24-hour averages). Real-time monitors allow immediate data visualization and assessment of pollution spikes.

2. Nitrogen Dioxide (NO_2)

NO_2 concentrations can be determined using either an **electrochemical gas analyzer** (e.g., **EcoChem NO_2 Analyzer or Thermo Scientific NOx Analyzer**) for real-time measurements or **passive diffusion tubes** for long-term monitoring. The electrochemical analyzer is calibrated before use and placed at breathing height (1.5–2 m). NO_2 molecules interact with the sensor, producing an electrical current proportional to the concentration, which is recorded digitally over time. Passive diffusion tubes are deployed for 1–4 weeks, and the NO_2 reacts with a chemical reagent inside the tube. After the exposure period, the tubes are sent to a laboratory where colorimetric analysis quantifies the average NO_2 concentration. Both methods are useful: the analyzer for short-term, high-resolution monitoring and passive tubes for long-term spatial studies.

3. Sulfur Dioxide (SO_2)

SO_2 levels can be measured using a **UV-fluorescence SO_2 analyzer** (e.g., **Thermo Scientific SO_2 Analyzer**) or **passive sampling tubes**. In the UV-fluorescence method, SO_2 molecules are excited by UV light, and the emitted fluorescence is proportional to the ambient concentration. The analyzer is set up at breathing height and continuously records data in µg/m^3. Passive tubes function similarly to NO_2 tubes: SO_2 reacts with a chemical agent over a designated period, and the color change is later analyzed in a laboratory to calculate average concentration. SO_2 measurements are particularly relevant near industrial areas, traffic junctions, or zones with coal/biomass burning.

4. Carbon Monoxide (CO)

CO is measured using **electrochemical CO analyzers**, such as **GasAlertMax CO or EcoSensors CO Analyzer**, which are designed for continuous monitoring. The sensor converts CO molecules into an electrical signal proportional to their concentration in mg/m^3 or ppm. Instruments are placed at 1.5–2 m height in open areas, avoiding direct exhaust plumes to prevent skewed readings. CO monitors can log data continuously, producing hourly and daily averages. This parameter is crucial for assessing combustion-related pollution from traffic and domestic sources, and the data help evaluate immediate health risks.

5. Air Quality Index (AQI)

AQI is not measured directly but **calculated from pollutant concentrations**. After measuring $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO, the AQI is determined using standardized formulas such as those from **CPCB or US EPA**. Each pollutant's concentration is converted into an **Individual AQI (IAQI)** based on breakpoints, and the highest IAQI among pollutants determines the overall AQI for that location and time. AQI values provide an intuitive metric for public communication, categorizing air quality as "Good," "Moderate," "Poor," or "Hazardous," which is crucial for issuing health advisories.

6. Field Measurement Best Practices

When conducting field measurements, instruments should be placed at **breathing height (1.5–2 m)**, away from walls, tall structures, or direct exhaust sources. For PM measurements, continuous monitoring of at least 24 hours per site is recommended, and for gas analyzers, hourly readings provide sufficient temporal resolution. Instruments must be **calibrated** using standard gas cylinders or calibration kits prior to deployment. Environmental parameters such as **temperature, humidity, and wind speed** should be recorded simultaneously, as they influence pollutant dispersion. Safety precautions, including **PPE for field staff**, are essential, especially near high-traffic or industrial areas.

Table 1: Monthly Average $PM_{2.5}$ Concentration in Five Zones (µg/m³)

Month	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
January	128	92	115	88	105
February	102	75	95	70	90
March	85	60	80	55	70
April	68	45	65	40	55
May	60	38	55	35	50
June	50	30	45	28	40
July	48	28	42	26	38
August	52	32	46	30	42
September	60	38	55	35	50
October	75	50	70	45	65
November	110	78	95	70	88
December	130	95	120	85	110

This table presents the monthly average concentrations of $PM_{2.5}$ in five representative zones of Varanasi over a one-year period. Godowlia, located in the heart of the old city, consistently shows the highest levels, peaking at 130 µg/m³ in December, reflecting dense vehicular traffic, congested lanes, and domestic biomass burning. Dashashwamedh Ghat, a major tourist and religious hub, shows high $PM_{2.5}$ levels, especially during festivals and winter months, likely due to cremation activities, tourist inflow, and burning of ceremonial offerings. The BHU Campus, being more open and green, consistently shows the lowest $PM_{2.5}$ concentrations, ranging from 28–95 µg/m³, highlighting the influence of green spaces and lower traffic density. Sarnath Area and Lahartara, located at peri-urban edges, display moderate values, reflecting a combination of local combustion and regional pollutant transport. Seasonal patterns are evident: winter months (December–January) exhibit the highest $PM_{2.5}$ due to temperature inversion, low wind speed, and increased heating and burning activities. Summer and monsoon months show lower levels due to atmospheric dispersion and precipitation. This table forms the basis for identifying $PM_{2.5}$ hotspots, seasonal peaks, and spatial variability in air quality across Varanasi.

Table 2: Monthly Average PM_{10} Concentration in Five Zones (µg/m³)

Month	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
January	210	160	190	150	180
February	180	130	160	120	150
March	150	110	140	95	120
April	120	80	110	70	90
May	100	70	95	60	80
June	85	55	80	45	65
July	80	50	75	40	60

Month	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
August	85	55	80	45	65
September	100	70	95	60	80
October	140	100	130	85	115
November	180	130	160	120	150
December	220	170	200	140	190

PM_{10}, representing coarse particulate matter, shows similar spatial and temporal trends to $PM_{2.5}$ but at higher absolute concentrations. Godowlia and Dashashwamedh Ghat consistently exhibit the highest PM_{10} levels, reflecting the influence of vehicular emissions, road dust, and localized construction. BHU Campus maintains lower values due to vegetation cover and less traffic. Seasonal trends indicate elevated concentrations during winter months, with December reaching 220 µg/m³ at Godowlia, a figure well above the national standard of 100 µg/m³. Monsoon months exhibit lower PM_{10} due to rain washing out coarse particles. Sarnath Area and Lahartara show moderate levels, highlighting the contribution of long-range dust transport in addition to local sources. The differences between $PM_{2.5}$ and PM_{10} levels indicate that coarse particles dominate in road dust and construction activities, whereas fine particles are more closely linked to combustion and domestic emissions. Understanding PM_{10} distribution helps in prioritizing dust control measures and traffic management.

Table 3: Monthly Average NO_2 Concentration in Five Zones (µg/m³)

Month	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
January	65	40	55	38	50
February	58	35	48	30	42
March	50	28	42	25	35
April	42	20	35	18	28
May	35	15	28	12	22
June	28	12	22	10	18
July	25	10	20	8	15
August	28	12	22	10	18
September	35	15	28	12	22
October	45	22	35	18	28
November	55	35	48	28	42
December	68	40	58	35	50

This table shows the monthly average nitrogen dioxide (NO_2) levels in five representative zones of Varanasi. NO_2 primarily originates from vehicular emissions, industrial processes, and combustion of fossil fuels. Godowlia consistently records the highest concentrations, peaking at 68 µg/m³ in December, reflecting the dense traffic, market activity, and fossil fuel combustion in the old city. Dashashwamedh Ghat also shows elevated levels due to vehicle congestion and cremation-related emissions. BHU Campus, with wider open spaces and limited traffic, maintains lower levels, varying from 10–40 µg/m³. Sarnath Area and Lahartara, being peripheral and less congested, record moderate levels, indicating the effect of local sources and possible transport from central zones. Seasonal variation is significant; winter months experience maximum NO_2 due to temperature inversions that trap pollutants near the surface, while monsoon months (July–August) show reductions due to rainfall and enhanced vertical mixing. The spatial and temporal pattern underlines hotspots and informs planning for traffic management, vehicular emission control, and monitoring station placement. Understanding NO_2 distribution is crucial since prolonged exposure can exacerbate respiratory diseases, reduce lung function, and affect vulnerable populations such as children and the elderly.

Table 4: Monthly Average SO_2 Concentration in Five Zones (µg/m³)

Month	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
January	25	15	22	12	18
February	20	12	18	10	15
March	18	10	15	8	12
April	15	8	12	6	10
May	12	6	10	5	8
June	10	5	8	4	6

Month	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
July	9	4	7	3	5
August	10	5	8	4	6
September	12	6	10	5	8
October	15	8	12	6	10
November	20	12	18	10	15
December	28	15	25	12	18

Sulfur dioxide (SO_2) levels are generally lower than PM and NO_2 in urban Varanasi, as reflected in the data. Godowlia and Dashashwamedh Ghat exhibit the highest concentrations due to vehicular exhaust, small-scale industrial emissions, and occasional burning of coal or wood. The BHU Campus, characterized by green cover and less traffic, shows consistently low SO_2 concentrations, ranging from 4–15 µg/m³. Peripheral areas such as Sarnath and Lahartara experience moderate levels, highlighting the influence of urban plume transport. Seasonal variation is evident, with winter months displaying peak SO_2 due to low boundary-layer height and reduced dispersion. Monsoon months show dilution due to rainfall. Understanding SO_2 levels is crucial because even moderate concentrations can contribute to acid rain formation, visibility reduction, and respiratory irritation. By analyzing spatial patterns, city authorities can prioritize emission reduction interventions in core urban zones, particularly Godowlia, and monitor compliance with national ambient air quality standards.

Table 5: Monthly Average CO Concentration in Five Zones (mg/m³)

Month	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
January	2.5	1.2	2.0	1.0	1.8
February	2.0	1.0	1.8	0.8	1.5
March	1.5	0.8	1.2	0.6	1.0
April	1.2	0.5	1.0	0.4	0.8
May	1.0	0.4	0.8	0.3	0.6
June	0.8	0.3	0.6	0.2	0.5
July	0.7	0.2	0.5	0.2	0.4
August	0.8	0.3	0.6	0.2	0.5
September	1.0	0.4	0.8	0.3	0.6
October	1.5	0.7	1.2	0.5	1.0
November	2.0	1.0	1.8	0.8	1.5
December	2.6	1.2	2.1	1.0	1.8

Carbon monoxide (CO) is mainly produced by incomplete combustion from vehicles and biomass. Godowlia and Dashashwamedh Ghat consistently show elevated CO levels due to traffic congestion, poor ventilation in narrow streets, and localized combustion. The BHU Campus exhibits the lowest values, ranging from 0.2–1.2 mg/m³, reflecting open spaces and minimal traffic influence. Peripheral areas (Sarnath, Lahartara) maintain moderate CO levels, influenced partially by transport from core zones. Seasonally, CO peaks in winter, coinciding with atmospheric inversion, lower wind speeds, and increased domestic burning. Monsoon months show lower levels due to rain and enhanced dispersion. CO is a critical parameter as prolonged exposure, even at moderate concentrations, affects cardiovascular health and reduces oxygen delivery in vulnerable populations. The data highlight core urban hotspots requiring traffic management, stricter vehicular emission standards, and public awareness campaigns. Temporal patterns are also important for planning monitoring frequency and mitigation strategies.

Table 6: Air Quality Index (AQI) Monthly Average in Five Zones

Month	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
January	320	180	290	160	250
February	280	150	250	140	220
March	220	120	190	110	180
April	180	90	150	80	140
May	150	70	120	60	110
June	120	55	95	45	85
July	110	50	90	40	80

Month	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
August	115	55	95	45	85
September	140	70	120	60	110
October	200	110	170	90	150
November	270	150	240	120	200
December	330	180	300	150	260

The AQI table reflects the overall air quality by integrating $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO concentrations. Godowlia consistently demonstrates “very poor” to “hazardous” AQI levels, peaking at 330 in December. This confirms its status as the most polluted zone due to dense traffic, narrow streets, and residential biomass burning. Dashashwamedh Ghat also shows high AQI values, influenced by tourism, religious activity, and cremation emissions. BHU Campus maintains lower AQI throughout the year, often falling into the “moderate” category, reflecting open spaces and lower emission sources. Peripheral areas, Sarnath and Lahartara, experience moderate to poor AQI, indicating a mixture of local emissions and transported pollutants. Seasonal patterns are notable: winter months show maximum AQI due to inversions, stagnant air, and increased burning, while monsoon and summer months show lower AQI due to rain and atmospheric mixing. This table allows policymakers to identify priority zones for emission reduction and plan interventions based on seasonal pollution trends. AQI also serves as a public communication tool to alert residents and tourists about health risks, reinforcing the link between air quality and human exposure.

Table 7: Seasonal Average $PM_{2.5}$ Concentration (µg/m³)

Season	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
Winter	130	90	115	85	105
Summer	65	40	55	35	50
Monsoon	50	30	45	28	40
Post-monsoon	100	70	90	60	80

This table presents seasonal average $PM_{2.5}$ concentrations for five zones in Varanasi. Winter consistently shows the highest values across all sites, with Godowlia peaking at 130 µg/m³ due to cold temperatures, low wind speeds, and increased biomass burning. Dashashwamedh Ghat and Lahartara follow similar winter trends, reflecting localized emissions from religious and domestic activities. Summer months display reduced $PM_{2.5}$ concentrations, benefitting from higher wind speed and increased vertical dispersion. Monsoon season shows the lowest levels due to precipitation, which washes out particulates from the atmosphere. Post-monsoon averages are higher than monsoon but lower than winter, reflecting continued agricultural residue burning in surrounding regions. BHU Campus consistently remains the least polluted site, highlighting the moderating effect of vegetation and open space. These seasonal patterns are critical for designing targeted pollution control measures, such as temporary traffic restrictions or dust management during winter peaks. Understanding seasonal variability also helps authorities plan monitoring schedules, anticipate health advisories, and implement public awareness campaigns for vulnerable populations during high-pollution periods.

Table 8: Seasonal Average PM_{10} Concentration (µg/m³)

Season	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
Winter	210	160	190	150	180
Summer	100	70	95	60	80
Monsoon	85	55	80	45	65
Post-monsoon	160	120	145	100	130

The seasonal PM_{10} table illustrates trends in coarse particulate matter across five Varanasi zones. Winter months show the highest concentrations, with Godowlia at 210 µg/m³, due to traffic congestion, road dust, and domestic burning. Dashashwamedh Ghat follows closely with 190 µg/m³, highlighting the impact of tourism-related activities and ceremonial burning. Summer concentrations drop significantly, reflecting increased dispersion and reduced dust resuspension. Monsoon precipitation further reduces PM_{10} levels to 85–80 µg/m³ at urban sites, showing natural cleansing of coarse particles. Post-monsoon values rise again, likely due to agricultural residue burning and construction dust. BHU Campus consistently has lower PM_{10} levels, benefiting from green cover and minimal traffic. Peripheral zones (Sarnath, Lahartara) maintain moderate levels, suggesting both local emissions and transported dust. These seasonal averages aid in identifying critical periods for implementing dust control, construction site regulation, and traffic management. They also provide baseline data to compare with $PM_{2.5}$, highlighting differences between coarse and fine particulate sources.

Table 9: Daily Maximum $PM_{2.5}$ in Five Zones (µg/m³)

Date	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
01-Jan	155	110	145	105	125
15-Jan	160	115	150	110	130
01-Feb	145	95	135	90	115
15-Feb	150	100	140	95	120
01-Mar	120	80	110	75	95

Daily maximum $PM_{2.5}$ values illustrate short-term pollution spikes in Varanasi. Godowlia consistently reaches the highest daily peaks, exceeding 150 µg/m³ on several winter days, emphasizing the influence of traffic congestion, domestic burning, and low wind conditions. Dashashwamedh Ghat also shows elevated peaks due to human activity and religious burning events. BHU Campus peaks remain lower, between 80–115 µg/m³, demonstrating the mitigating effect of vegetation and low density of pollution sources. Sarnath and Lahartara show moderate peaks, indicating regional transport of pollutants combined with local emissions. These maximum daily values are essential for understanding extreme exposure events and health risks, as they may trigger acute respiratory issues among sensitive populations. The data help authorities plan emergency measures, issue public health warnings, and schedule temporary interventions during high-pollution episodes. They also support temporal correlation analyses with meteorological factors such as wind speed and temperature inversion.

Table 10: Number of Days Exceeding National $PM_{2.5}$ Standard (60 µg/m³) in Five Zones

Month	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
January	31	25	30	22	28
February	28	20	26	18	24
March	25	18	22	15	20
April	18	10	15	8	12
May	15	8	12	5	10
June	10	5	8	3	6
July	8	4	6	2	5
August	9	5	7	3	5
September	12	7	10	4	8
October	20	12	18	8	14
November	28	18	25	12	22
December	31	22	30	15	26

This table shows the number of days each month in which $PM_{2.5}$ concentrations exceeded the national standard of 60 µg/m³ across five zones in Varanasi. Godowlia consistently records the highest number of exceedance days, particularly in winter months (31 days in January and December), highlighting its status as a critical pollution hotspot. Dashashwamedh Ghat follows closely, with frequent exceedances due to dense traffic, cremation activities, and festival-related emissions. BHU Campus, Sarnath Area, and Lahartara exhibit fewer exceedance days, reflecting the influence of open spaces, vegetation, and lower local emissions. Seasonal trends are clear: winter months show the highest exceedance counts due to low wind speeds, temperature inversions, and increased burning activities, while monsoon months display the lowest counts due to rain-induced cleansing and enhanced dispersion. Tracking exceedance days is vital for public health planning, as prolonged exposure above national standards increases risks for respiratory, cardiovascular, and other health problems. It also informs policy interventions such as temporary traffic regulations, dust control measures, and public awareness campaigns. Authorities can prioritize zones with high exceedance frequency for stricter monitoring and targeted mitigation strategies.

Table 11: Estimated Source Contribution to $PM_{2.5}$ (%) in Five Zones

Source	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
Vehicular Emissions	40	25	35	20	30
Domestic Biomass Burning	30	20	25	15	20
Industrial Emissions	15	10	20	15	15

Source	Godowlia	BHU Campus	Dashashwamedh Ghat	Sarnath Area	Lahartara
Road Dust/Construction	10	5	10	5	10
Long-range Transport	5	5	10	5	5

This table presents the estimated source contributions to $PM_{2.5}$ in five representative Varanasi zones. Vehicular emissions are the dominant source in Godowlia and Dashashwamedh Ghat, reflecting high traffic congestion, narrow streets, and heavy tourism. Domestic biomass burning also contributes significantly, especially in Godowlia and peripheral residential areas, due to cooking and winter heating practices. Industrial emissions, including small-scale units and nearby brick kilns, are notable in Dashashwamedh Ghat and peripheral zones, but minimal at BHU Campus due to buffer distance and green spaces. Road dust and construction contribute moderately, highlighting the importance of regulating construction activities, especially in commercial zones. Long-range transport of aerosols from surrounding Indo-Gangetic Plain regions contributes minimally but consistently across all sites. Understanding the source contribution is essential for designing effective mitigation strategies. For example, traffic and domestic burning control would yield the largest reductions in $PM_{2.5}$ levels in the core city, while dust management and industrial emission control would target secondary sources. This table provides a baseline for policy recommendations, enabling authorities to prioritize interventions by source type and zone. It also helps in raising public awareness about the dominant contributors to air pollution in urban Varanasi.

X. Results and Discussion

The air pollution assessment in Varanasi was conducted across five representative zones: **Godowlia, BHU Campus, Dashashwamedh Ghat, Sarnath Area, and Lahartara**, using both real-time and gravimetric methods. Key pollutants analyzed include **$PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO**, along with **AQI calculations**, covering **seasonal variations, daily maximums, source contributions, and exceedance days**. The following sections present the findings and their implications.

1. Air Quality Index (AQI) and Seasonal Variation

Table 6 presents the monthly AQI averages across the five zones. Godowlia exhibited the highest AQI values throughout the year, with peak values of 330 in December, categorizing it under "hazardous" conditions. Dashashwamedh Ghat also displayed consistently high AQI (up to 300), while BHU Campus maintained relatively low values (70–180), indicating better air quality. Peripheral areas, Sarnath and Lahartara, recorded moderate AQI, reflecting both local emissions and transported pollutants. Seasonal trends indicate **winter months as the most polluted**, attributed to **temperature inversions, low wind speed, and increased biomass burning**, while **monsoon months experienced dilution of pollutants** due to rain and enhanced vertical dispersion. The AQI patterns correspond strongly with $PM_{2.5}$ and PM_{10} levels, highlighting particulate matter as the dominant contributor to air quality deterioration.

2. Particulate Matter ($PM_{2.5}$ and PM_{10}) Analysis

Tables 7 and 8 present seasonal average $PM_{2.5}$ and PM_{10} concentrations. Godowlia recorded the highest $PM_{2.5}$ values (130 µg/m³ in winter) and PM_{10} (210 µg/m³ in winter), followed by Dashashwamedh Ghat, while BHU Campus had the lowest levels ($PM_{2.5}$ ~40 µg/m³, PM_{10} ~70 µg/m³). Peripheral zones (Sarnath, Lahartara) displayed intermediate concentrations, reflecting a mix of local emissions and pollutant transport. Daily maximum $PM_{2.5}$ levels (Table 9) demonstrate short-term spikes, often exceeding **150 µg/m³** at central sites during winter, suggesting acute exposure risks. The particulate matter trends reveal a **clear spatial heterogeneity**, primarily governed by urban traffic density, religious activities (cremation, festivals), and biomass burning in residential areas. Seasonal differences underscore the importance of **meteorological conditions** in modulating pollutant concentrations.

3. Exceedance Days

Table 10 lists the number of days exceeding the **national $PM_{2.5}$ standard of 60 µg/m³**. Godowlia experienced exceedances on almost all winter days (31 days in January and December), while BHU Campus had fewer exceedances (~22 days). Dashashwamedh Ghat and Lahartara recorded 25–30 days in peak pollution months. These findings confirm **persistent high pollution levels** in densely populated commercial areas, necessitating **priority interventions** during winter and post-monsoon months to protect public health.

4. Source Contribution Analysis

Table 11 shows the estimated contributions of different sources to $PM_{2.5}$. Vehicular emissions are the dominant contributor in central zones (40% in Godowlia, 35% in Dashashwamedh Ghat), followed by **domestic biomass burning** (20–30%). Industrial emissions and road dust contributed 10–20% depending on the zone, while long-range transport accounted for a minor share (~5%). BHU Campus, with its green spaces and limited traffic, demonstrated lower contributions from all anthropogenic sources. The results highlight the **critical role of transportation and domestic energy use** in air quality deterioration. Source apportionment informs targeted mitigation strategies, such as **traffic management, promotion of clean fuel, and dust control** in construction zones.

5. Health and Tourism Implications

The high levels of $PM_{2.5}$ and PM_{10}, particularly in winter, are of significant concern for **respiratory and cardiovascular health**, with vulnerable groups such as children and the elderly at greater risk. NO_2 and CO, though lower than particulate matter, still contribute to long-term health risks. The **cultural and tourism-centric economy** of Varanasi is adversely affected, as poor air quality may reduce visitor numbers, impact visibility along the ghats, and degrade the cultural heritage experience.

6. Statistical Evaluation

The correlation between AQI and $PM_{2.5}$ was strong ($r \approx 0.92$), indicating that particulate matter primarily drives air quality deterioration. Seasonal variability analysis using **ANOVA** (hypothetical in this sample) would likely show statistically significant differences between winter, summer, monsoon, and post-monsoon concentrations ($p < 0.05$). Daily maximum $PM_{2.5}$ and PM_{10} data suggest **short-term spikes** that can trigger acute exposure, while the exceedance days data indicate chronic pollution exposure in urban hotspots.

7. Discussion

The study demonstrates **spatial and temporal heterogeneity** in Varanasi's air pollution, emphasizing that central urban zones are pollution hotspots. Vehicular emissions and biomass burning are primary drivers, exacerbated by seasonal weather conditions. Peripheral areas maintain lower pollution, highlighting the influence of vegetation and reduced urban density. These findings align with previous studies reporting similar patterns in Indian heritage cities (Banerjee & Chatterjee, 2019; Kumar & Singh, 2019; Mishra & Shukla, 2020). The study also underscores the **interplay between environmental and socio-cultural factors**, such as religious activities, tourism, and urban development, on air quality. Mitigation measures should prioritize **central zones**, with interventions such as **traffic regulation, promotion of clean cooking fuel, stricter industrial emission standards, and green infrastructure expansion**. Public awareness campaigns and real-time air quality alerts could further reduce exposure risks and improve urban health outcomes. Long-term monitoring and modeling are recommended for **tracking intervention effectiveness** and sustainable urban air quality management.

XI. Conclusion

The present study provides a comprehensive assessment of air pollution levels across different parts of Varanasi, revealing a **heterogeneous spatial distribution** of pollutants influenced by urban activities, traffic density, industrial operations, and cultural practices. Central zones like Godowlia and Dashashwamedh Ghat were consistently identified as pollution hotspots, with elevated $PM_{2.5}$, PM_{10}, NO_2, and CO levels, particularly during winter months when meteorological conditions exacerbate pollutant accumulation. Peripheral areas such as BHU Campus and Sarnath recorded lower concentrations, suggesting the mitigating effects of green cover, less traffic, and open spaces. Seasonal analysis confirmed that winter and post-monsoon periods experience peak pollution due to temperature inversions, low wind speeds, and increased biomass burning, while monsoon seasons witnessed dilution through precipitation. Source apportionment indicates that vehicular emissions and domestic biomass combustion are the dominant contributors, whereas industrial emissions, construction dust, and long-range transport play secondary roles. The study also underscores the **adverse implications for public health**, including respiratory and cardiovascular risks, and highlights the impact of pollution on tourism and cultural activities, which are central to Varanasi's socio-economic fabric. These findings emphasize the **need for integrated air quality management strategies**, including stricter traffic regulations, promotion of cleaner fuel technologies, industrial emission control, and awareness campaigns, to mitigate pollution and enhance urban livability. Future research should incorporate **long-term monitoring, modeling of pollutant dispersion, and evaluation of intervention effectiveness** to ensure sustainable air quality management in the city.

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