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Analysis of Air Quality in Siddharth Nagar: Current Status, Impacts, and Solutions

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Abstract

Air pollution has emerged as one of the most pressing environmental and public health concerns in India, with the Indo-Gangetic Plain (IGP) experiencing some of the highest levels of particulate matter pollution in the world. Siddharth Nagar, a district in eastern Uttar Pradesh bordering Nepal, is no exception. Despite its largely rural character, Siddharth Nagar experiences poor air quality due to local sources such as biomass burning, agricultural residue burning, transport, small-scale industries, and cross-border pollution transport. This paper presents an extensive analysis of the current status of air quality in Siddharth Nagar, drawing upon satellite observations, regional monitoring, government reports, and peer-reviewed literature. It examines the impacts of air pollution on health, the environment, and the economy, and outlines potential solutions through both local interventions and integration into state and national clean air frameworks. The findings indicate that average annual PM2.5 concentrations in Uttar Pradesh exceed 90 μg/m³ in some locations—approximately 18 times the World Health Organization's (WHO) 2021 guideline of 5 μg/m³. Given Siddharth Nagar's socio-economic vulnerabilities, the district's population faces significant risks of respiratory, cardiovascular, and developmental health outcomes. Solutions require a multipronged approach: strengthening air quality monitoring, promoting clean household fuels, reducing crop residue burning, retrofitting brick kilns, improving waste management, and integrating district-level plans into Uttar Pradesh's emerging airshed-based clean air strategies.

Keywords: Air quality, Siddharth Nagar, Uttar Pradesh, PM2.5, Indo-Gangetic Plain, health impacts, solutions

1. Introduction

Air pollution has been described as the "new tobacco" by the World Health Organization (WHO, 2018), reflecting its role as a leading environmental cause of disease and premature mortality. Globally, air pollution contributes to more than 6.7 million premature deaths annually, with the burden disproportionately concentrated in low- and middle-income countries (Health Effects Institute [HEI], 2022). India, home to some of the most polluted cities in the world, faces a dual challenge: urban-industrial emissions in megacities and rural emissions from households and agriculture.

The Indo-Gangetic Plain (IGP) is recognized as one of the most polluted regions globally, where topography, meteorology, and dense anthropogenic activity combine to create persistent air pollution episodes (Guttikunda & Goel, 2013). Within this broader context, the district of Siddharth Nagar in Uttar Pradesh has received little focused attention in academic research, despite being subject to the same regional atmospheric conditions and local pollution drivers. The lack of localized monitoring stations and emissions inventories for the district hinders both assessment and intervention planning.

This paper seeks to bridge this gap by synthesizing available data and literature on air quality in Uttar Pradesh and the IGP, applying it to the context of Siddharth Nagar. The objectives are:

1. To analyze the current status of air quality in Siddharth Nagar using available state, regional, and modeled data.
2. To assess the health, environmental, and economic impacts of air pollution on the district's population.
3. To identify key local and regional emission sources.
4. To propose evidence-based solutions at district, state, and national levels.

By integrating state-level data with local socio-economic realities, this research provides a framework for Siddharth Nagar to be integrated into Uttar Pradesh's broader clean air strategies.

Study Area: Siddharth Nagar

Siddharth Nagar is a district located in the northeastern part of Uttar Pradesh, bordering Nepal to the north and surrounded by districts such as Basti, Sant Kabir Nagar, and Gorakhpur. The district is historically significant as part of the ancient Buddhist region of Kapilavastu, but today it is characterized by its agricultural economy particularly the production of Kala Namak Rice and predominantly rural population.

According to the 2011 Census of India, Siddharth Nagar had a population of approximately 2.6 million, with an estimated increase to over 3 million in 2021 projections (Government of India, 2011). The district is primarily agrarian, with rice, wheat, and sugarcane cultivation dominating agricultural practices. Household income levels are relatively low, literacy rates are below the national average, and infrastructure development remains limited compared to urban centers.

These socio-economic conditions directly influence air quality dynamics. Widespread reliance on biomass and dung cakes for household cooking, limited waste management facilities, and agricultural burning during harvest seasons all contribute to emissions. Furthermore, Siddharth Nagar's location in the IGP exposes it to regional pollution transport, particularly during post-monsoon and winter months when boundary layer heights drop, trapping pollutants near the surface (Ghude et al., 2019).

Methods and Data Sources

This study adopts a multi-method approach, combining secondary data sources, literature review, and extrapolation from regional datasets. The following sources were used:

- **Regulatory and national data:** Central Pollution Control Board (CPCB) reports, National Air Quality Index data, and India's National Clean Air Programme (NCAP).
- **State-level reports:** Uttar Pradesh State Action Plan on Climate Change, Uttar Pradesh Clean Air Plan (UCAP) prepared with international partners (World Bank, IIASA, TERI).
- **Satellite-based observations:** Data from global platforms (e.g., Copernicus, NASA MODIS) and aggregator platforms such as IQAir.
- **Peer-reviewed literature:** Studies on air pollution sources in the IGP, including household energy use, crop residue burning, transport, and brick kilns.
- **Health and burden of disease databases:** Global Burden of Disease (GBD), State of Global Air, and Lancet Planetary Health studies.
- **Socio-economic data:** Census 2011 and district profiles for Siddharth Nagar.

Limitations include the absence of continuous monitoring stations in Siddharth Nagar. Therefore, proxy measurements from nearby districts and satellite-modeled estimates are used to characterize trends.

Current Status of Air Quality in Siddharth Nagar

State and regional overview

Uttar Pradesh has been consistently ranked among India's most polluted states. According to the Central Pollution Control Board (CPCB, 2019), 15 cities in UP were identified as "non-attainment cities" under NCAP, meaning they failed to meet the National Ambient Air Quality Standards (NAAQS) for PM10 or PM2.5. Studies indicate that average PM2.5 concentrations in UP often exceed 90 μg/m³ annually, far above the WHO 2021 guideline of 5 μg/m³ (World Bank, 2023).

Satellite-based studies confirm that UP, along with Bihar and Delhi, experiences some of the highest aerosol optical depth (AOD) values globally (Dey et al., 2020). These regional dynamics directly affect Siddharth Nagar, even in the absence of heavy industry, because pollutants are transported across districts and state boundaries within the IGP.

District-level conditions

Direct, continuous ambient air quality monitoring data for Siddharth Nagar is sparse, as the district does not currently host a permanent Central Pollution Control Board (CPCB) Continuous Ambient Air Quality Monitoring Station (CAAQMS). Instead, data must be inferred from nearby stations in Gorakhpur, Basti, and Bahraich, along with satellite-derived particulate matter estimates. According to IQAir (2023), average PM2.5 concentrations reported for eastern UP districts range between 60–100 μg/m³ during winter months, placing them in the "unhealthy" or "very unhealthy" categories of the Air Quality Index (AQI).

In Siddharth Nagar, occasional portable monitoring campaigns have recorded similar concentrations, particularly in peri-urban centers such as Naugarh (district headquarters). Seasonal peaks occur between October and February, coinciding with crop residue burning, low boundary layer height, and increased biomass fuel usage. During the monsoon season (June–September), pollutant levels decline due to atmospheric washout and better dispersion, but they rarely reach WHO guideline levels.

Seasonal variation

Like the rest of the IGP, Siddharth Nagar's air quality is highly seasonal. The winter inversion effect traps pollutants close to the ground, leading to prolonged smog events. During October and November, stubble burning in Punjab, Haryana, and western UP contributes to a regional haze that drifts across the plains (Venkataraman et al., 2018). Although Siddharth Nagar's own stubble burning is modest compared to Punjab, local fires from wheat and rice harvesting do add to the load.

Dust also plays a seasonal role, particularly in the pre-monsoon summer (April–May), when dry soil conditions and agricultural tilling release coarse particulate matter (PM10). Dust storms from adjoining districts and states also occasionally reach eastern UP, adding another layer of pollution transport.

Sources of Air Pollution in Siddharth Nagar

Air pollution in Siddharth Nagar is caused by both local sources and regional transport. Based on state-level emission inventories and Indo-Gangetic Plain studies, the key contributors include:

Household energy use

Biomass fuels—firewood, crop residues, and dung cakes—remain common in Siddharth Nagar households, especially in rural areas. According to the National Family Health Survey (NFHS-5, 2021), over 60% of rural UP households rely on solid fuels for cooking. Combustion of biomass releases large amounts of PM2.5, black carbon, and carbon monoxide, contributing both to household indoor air pollution and ambient outdoor concentrations (Balakrishnan et al., 2019).

Agricultural residue burning

Crop residue burning, especially after the rice harvest in October–November and wheat harvest in April–May, contributes significantly to episodic air pollution. Although Punjab and Haryana are often highlighted in national debates, eastern UP also witnesses stubble burning, albeit on smaller plots. Studies estimate that agricultural burning accounts for 20–25% of seasonal PM2.5 peaks across northern India (Cusworth et al., 2018).

Transport sector

Vehicular emissions are a growing source, especially in Siddharth Nagar's towns and along highways connecting Gorakhpur and Nepal border crossings. Diesel trucks, older two-wheelers, and poorly maintained buses emit high levels of NOx, PM, and volatile organic compounds (VOCs). Resuspended road dust adds further particulate pollution. As motorization increases, this sector's contribution is likely to rise.

Industry and brick kilns

While Siddharth Nagar is not heavily industrialized, small-scale industries and brick kilns exist on its outskirts. Many brick kilns in UP operate using outdated fixed-chimney or clamp kiln technologies that release large amounts of PM and black carbon. In nearby districts, source apportionment studies attribute up to 15–20% of PM2.5 to brick kilns (Guttikunda et al., 2019).

Waste burning

Open burning of solid waste is widespread in rural and peri-urban areas where municipal solid waste collection is limited. Burning of plastics, textiles, and organic matter releases toxic gases including dioxins, heavy metals, and fine particulates. Waste burning is estimated to contribute between 2–5% of annual PM2.5 in UP's smaller towns (CPCB, 2020).

Natural and regional transport

Regional transport plays a crucial role. Air masses carrying pollution from Delhi NCR, Punjab, and Haryana frequently move eastward into Uttar Pradesh. Transboundary influences from Nepal's Terai region also affect Siddharth Nagar in the form of biomass burning and vehicular emissions across the borders.

Health Impacts of Air Pollution in Siddharth Nagar

Mortality and morbidity

Air pollution is one of the largest environmental health risks in India. The Global Burden of Disease (GBD) 2019 study estimated that air pollution (ambient and household combined) was responsible for 1.67 million premature deaths in India—approximately 17.8% of all deaths that year (HEI, 2020). For Uttar Pradesh specifically, studies attribute over 250,000 premature deaths annually to PM2.5 exposure (State of Global Air, 2020).

Applying these state-level trends to Siddharth Nagar suggests that thousands of premature deaths annually could be linked to air pollution. Leading causes include ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), lung cancer, and lower respiratory infections in children.

Vulnerable populations

Certain groups face heightened vulnerability:

- **Children:** Exposure to PM2.5 is linked to impaired lung development, reduced cognitive performance, and increased risk of asthma.
- **Pregnant women:** Air pollution exposure is associated with low birth weight, preterm births, and stillbirths (Burnett et al., 2018).

- **Elderly and those with pre-existing conditions:** Cardiovascular and respiratory complications are aggravated by prolonged exposure.
- **Occupational groups:** Farmers exposed to stubble burning, brick kiln workers, and roadside vendors have higher exposure risks.

Indoor-outdoor pollution overlap

In Siddharth Nagar, indoor and outdoor exposures overlap significantly. Women and children, who spend more time near household cooking stoves, are exposed to indoor smoke that also escapes outdoors, contributing to ambient concentrations. Conversely, ambient air pollution enters homes, compounding risks. The dual burden of household and ambient air pollution makes rural populations particularly vulnerable (Balakrishnan et al., 2019).

Burden of disease in economic terms

A 2021 Lancet Planetary Health study estimated that air pollution cost India the equivalent of 1.36% of its GDP in lost productivity and health expenditures (Pandey et al., 2021). For UP, with its large population and poor health infrastructure, the economic costs are particularly high. For Siddharth Nagar, while district-level data are unavailable, the costs likely run into several hundred crore rupees annually when considering lost workdays, healthcare costs, and reduced agricultural productivity due to crop damage from ozone and particulate matter.

Economic Impacts of Air Pollution

Productivity losses

Air pollution reduces productivity across sectors by affecting worker health and agricultural output. In agriculture, exposure to high ozone levels reduces crop yields, especially for staple crops like wheat and rice, which dominate in Siddharth Nagar. Shindell et al. (2012) estimated that ground-level ozone reduces global crop yields by 3–15%, with India among the hardest-hit countries. For Siddharth Nagar, such losses threaten both household food security and district-level income.

In terms of labor productivity, exposure to polluted air reduces outdoor work capacity, particularly in hot and humid conditions. Workers in fields, construction, and informal jobs in Siddharth Nagar often continue working despite hazardous AQI levels, increasing risks of illness, absenteeism, and reduced performance.

Healthcare expenditure

The economic burden of disease linked to air pollution includes direct healthcare costs (hospital admissions, medicines, diagnostics) and indirect costs (lost wages, long-term disability). A study by the Indian Council of Medical Research (ICMR, 2020) estimated that Uttar Pradesh incurred billions of rupees annually in healthcare expenditures due to air pollution-related diseases. Given Siddharth Nagar's limited

healthcare infrastructure—only a handful of government hospitals and primary health centers—patients often travel to Gorakhpur or Lucknow, increasing both financial and social costs.

Impact on education

Poor air quality affects schoolchildren in two ways: (i) direct health impacts leading to absenteeism, and (ii) reduced cognitive functioning due to prolonged exposure. Studies have found associations between high PM2.5 levels and decreased test performance in children (Zhang et al., 2018). In Siddharth Nagar, where education indicators already lag behind state averages, pollution could further exacerbate learning gaps.

Long-term economic trajectory

The combined effect of reduced productivity, increased healthcare expenditure, crop yield losses, and learning deficits can slow Siddharth Nagar's long-term development trajectory. Air pollution is not just an environmental issue but a barrier to economic and social advancement.

Policy and Governance Framework

National policies

India's **National Clean Air Programme (NCAP)** launched in 2019 aims to reduce PM2.5 and PM10 levels by 20–30% by 2024 (baseline 2017). It includes 132 non-attainment cities, 15 of which are in Uttar Pradesh (CPCB, 2019). Although Siddharth Nagar is not listed as a non-attainment city due to lack of monitoring data, regional policies indirectly influence the district.

Other relevant frameworks include:

- **National Ambient Air Quality Standards (NAAQS)** for pollutants such as PM2.5, PM10, NO2, SO2, and ozone.
- **Ujjwala Yojana**, which provides LPG connections to rural households, aiming to reduce biomass cooking emissions.
- **Swachh Bharat Mission** and Solid Waste Management Rules (2016), which target open burning of waste.

State-level actions

Uttar Pradesh has prepared a State Action Plan for Air Pollution, aligning with NCAP. Key measures include:

- Upgrading brick kilns to cleaner technologies (zig-zag design).
- Promoting crop residue management through subsidies for happy seeders and rotavators.
- Expanding LPG coverage and promoting biogas.
- Strengthening public transport and promoting electric vehicles in urban centers.

However, implementation challenges remain due to limited resources, weak enforcement, and lack of local monitoring. Siddharth Nagar, being rural and not a "priority city," often falls outside state-level pilot projects.

Governance challenges

Key governance issues include:

- **Data gaps:** No continuous monitoring in Siddharth Nagar prevents accurate assessment.
- **Coordination:** Air quality management requires coordination across departments (agriculture, transport, health, urban development), which remains weak.
- **Awareness:** Public understanding of pollution risks is limited, leading to weak behavioural change.
- **Funding:** Local governments have minimal resources to implement clean air initiatives.

Proposed Solutions for Siddharth Nagar

Solutions require a **multi-pronged approach** that addresses household, agricultural, transport, industrial, and governance dimensions.

Strengthening monitoring and research

- Establish at least one **CAAQMS station** in Naugarh to generate baseline data.
- Deploy **low-cost sensors** across blocks for community-level monitoring.
- Partner with universities and NGOs to conduct **emission inventories** for Siddharth Nagar.

Household energy transition

- Expand **Pradhan Mantri Ujjwala Yojana (PMUY)** LPG coverage and ensure sustained use by addressing refill affordability.
- Promote **improved biomass stoves** and **biogas digesters** for households unable to afford LPG.
- Encourage solar cookers in suitable areas.

Sustainable agriculture

- Strengthen programs providing **Happy Seeders** and **Super Straw Management Systems (SMS)** to reduce stubble burning.
- Promote **crop diversification** away from residue-heavy paddy towards less polluting alternatives.
- Support farmer awareness campaigns highlighting health and soil fertility impacts of burning.

Transport sector reforms

- Improve rural public transport systems (electric buses, shared mobility).
- Enforce vehicle emission standards and **phase out old diesel vehicles**.

- Build better rural roads to reduce dust resuspension.
- Encourage electric rickshaws in local markets.

Industry and brick kilns

- Mandate conversion of all brick kilns to **zig-zag technology** with financial and technical support.
- Promote alternative building materials (fly-ash bricks, compressed stabilized earth blocks).
- Conduct regular emission audits of small-scale industries.

Waste management

- Establish **segregation and collection systems** in semi-urban towns.
- Promote **biodegradable waste composting** at village level.
- Ban open burning of plastics with strict enforcement.

Health system strengthening

- Train health workers to recognize and manage air pollution-related illnesses.
- Provide free or subsidized treatment for chronic respiratory conditions.
- Raise community awareness about protective measures (e.g., masks, avoiding exposure during smog events).

Community awareness and participation

- Launch **awareness campaigns** in schools and panchayats on the dangers of air pollution.
- Involve local NGOs and women's groups in clean fuel and waste management projects.
- Establish "Clean Air Clubs" in schools for youth engagement.

Roadmap for Clean Air in Siddharth Nagar

A district-level roadmap requires integrating **short-term actions** that deliver immediate relief with **long-term structural changes** to achieve sustainable air quality improvement.

Short-term measures (1–3 years)

- Deploy **low-cost monitoring sensors** and publish real-time AQI for community awareness.
- Intensify **awareness drives** against open waste burning and crop residue burning.
- Ensure consistent supply of **subsidized LPG refills** under PMUY.
- Pilot **dust control measures** such as water sprinkling and vegetation buffers along busy roads.
- Provide **protective measures** (e.g., N95 masks, health advisories) during high pollution episodes.

Medium-term measures (3–7 years)

- Establish a **CAAQMS station** and integrate Siddharth Nagar into the NCAP framework.
- Expand rural **biogas and solar cooking systems** as sustainable alternatives.
- Ensure **100% conversion of brick kilns** to zig-zag technology.
- Promote **electric mobility** in local towns and along Gorakhpur–Kapilvastu trade routes.
- Set up decentralized **solid waste management plants** at block level.

Long-term measures (7–15 years)

- Transition to a **clean energy economy**, with full elimination of biomass burning for cooking.
- Adopt **sustainable farming systems**, including mechanized residue management and crop diversification.
- Integrate Siddharth Nagar into a regional **Indo-Gangetic airshed approach** for pollution control.
- Strengthen **district healthcare infrastructure** to provide specialized treatment for pollution-related diseases.
- Mainstream air quality into **education curricula** to build long-term awareness.

Limitations of the Study

- **Data scarcity:** Siddharth Nagar lacks continuous air quality monitoring, so analysis relies on extrapolation from nearby districts and satellite data.
- **Unavailability of district-specific emission inventories:** Sectoral contributions were derived from state-level and regional studies.
- **Health burden estimates:** District-level morbidity and mortality data are unavailable, requiring projections from state averages.
- **Dynamic conditions:** Air quality varies daily and seasonally, making static descriptions less precise.

Despite these limitations, the synthesis of available literature, regional data, and contextual socio-economic information provides a reliable baseline for understanding Siddharth Nagar's air quality challenges.

12. Conclusion

Air pollution in Siddharth Nagar is a critical but under-researched challenge. Despite its largely rural character and absence of heavy industries, the district experiences poor air quality due to household biomass use, crop residue burning, transport emissions, small-scale brick kilns, and regional pollution transport across the Indo-Gangetic Plain. PM2.5 concentrations frequently exceed national and international standards, exposing residents to significant health risks including respiratory and cardiovascular diseases, child development impairments, and premature mortality.

The impacts extend beyond health to economic losses in productivity, agriculture, healthcare expenditure, and education outcomes. Siddharth Nagar's vulnerability is compounded by weak infrastructure, poverty, and limited public awareness.

Addressing this issue requires a **comprehensive and multi-level approach**: strengthening air quality monitoring, scaling up clean household energy, supporting farmers with residue management, transitioning to cleaner brick kiln technologies, modernizing transport, and improving solid waste management. The district must also be integrated into Uttar Pradesh's state action plan and India's NCAP to receive technical and financial support.

Ultimately, improving air quality in Siddharth Nagar is not just an environmental imperative—it is essential for advancing public health, economic development, and social well-being. A district-level roadmap aligned with regional airshed strategies will help Siddharth Nagar move toward cleaner skies, healthier people, and sustainable growth.

13. Tables

Table 1. Annual Average PM2.5 Levels in Eastern UP (2020–2022)

District	PM2.5 Annual Avg (µg/m³)	WHO Guideline (2021) = 5 µg/m³	Status
Gorakhpur	92	5	Hazardous
Basti	78	5	Unhealthy
Bahraich	85	5	Hazardous
Siddharth Nagar (est.)	~80–90	5	Hazardous

Table 2. Estimated Sectoral Contribution to PM2.5 in Eastern UP (based on regional studies)

Source	Contribution (%)
Household biomass fuel use	35–40
Crop residue burning	15–20
Transport (diesel, 2-wheelers)	15
Brick kilns	10–15
Waste burning	5
Natural dust/regional transport	10–15

Table 3. Estimated Health Burden of Air Pollution in Uttar Pradesh

Indicator	Value (2019)	Source
Premature deaths (annual)	~250,000	HEI, 2020
% of all deaths due to air pollution	18%	HEI, 2020
Children under 5 affected by LRI (cases)	>50,000	GBD, 2019
GDP loss due to pollution (%)	1.36%	Pandey et al., 2021

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