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Temporal Analysis of No_2 in Atmosphere of Delhi and its Effect on Ambient Air Quality: A Review from 2020 to 2023

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Abstract

Nitrogen dioxide (NO_2) is one of the harmful pollutants in ambient air and predominantly occurs in urban areas. Vehicular emission is one of the major sources of NO_2 pollution in urban areas and can impact human health to a larger extent. This review examines the temporal variations in NO_2 concentrations in Delhi's atmosphere from 2020 to 2023 and its implications for ambient air quality. Over the past few years, NO_2 levels in Delhi have shown significant fluctuations due to numerous factors including seasonal changes, traffic patterns, industrial activities, and the impacts of lockdown during COVID -19 pandemic. The analysis of air quality data reveals a correlation between increased NO_2 concentrations and the deterioration of air quality, leading to increasing health risks. This review underscores the need for continuous monitoring and more stringent regulatory measures to manage NO_2 emissions, aiming to improve air quality and mitigate the associated health impacts in Delhi.

Keywords: Nitrogen dioxide; Ambient air quality; Temporal variation; NO_2 dynamics; Vehicular pollution.

Introduction

Different forms of nitrogen oxide exist in our surroundings, but NO_2 occurs in abundant ambient air and can affect human health to great extent. This gas has characteristics of reddish-brown color and distinct pungent smell, is formed when nitric oxide is exposed to air. Nitrogen dioxide is a potent oxidizer, reacting with water to create nitric acid and nitric oxide [1]. Its significance in the atmosphere extends beyond health impacts, as it absorbs visible solar radiation, reducing atmospheric visibility and potentially influencing global climate change.

Alongside nitric oxide, nitrogen dioxide is a primary regulator of the oxidizing capacity in the free troposphere, influencing the concentration and behavior of radical species such as hydroxyl radicals. It also plays a crucial role in deciding ozone levels in the troposphere, as the photolysis of nitrogen dioxide is the primary trigger for ozone formation in both polluted and non-polluted environments [2]. Furthermore, nitrogen dioxide undergoes numerous atmospheric transformations, leading to the creation of strong oxidants that convert it into nitric acid and sulfur dioxide into sulfuric acid, eventually forming ammonium salts [3]. This photochemical reaction process, driven by sunlight's interaction with nitrogen dioxide, contributes to the formation of organic, nitrate, and sulfate particles measured as PM_{10} or $PM_{2.5}$. Consequently, nitrogen dioxide is a significant precursor to various secondary pollutants that have well-documented effects on human health [4].

NO_2 primarily forms through the combustion of fossil fuels in vehicles, power plants, and industrial processes [5]. In Delhi, the major sources of NO_2 include vehicular emissions, thermal power plants, industrial activities, and biomass burning. The city's rapid urbanization, coupled with a significant increase in vehicular traffic, has worsened the emission of NO_2 over the years.

The formation of NO_2 in the atmosphere can be understood through the following reaction:

$$NO + \frac{1}{2}O_2 \rightarrow N0_2$$

Here, nitric oxide (NO), produced during combustion, reacts with atmospheric oxygen to form NO_2. This reaction is particularly prevalent in areas with high traffic density and industrial activities, contributing significantly to the ambient NO_2 levels in Delhi.

The temporal analysis of NO_2 levels in Delhi from 2020 to 2023 highlights the complex interplay between human activities, environmental factors, and policy interventions in shaping air quality. The abundance of NO_2 in the atmosphere of Delhi has far-reaching implications for ambient air quality and public health. NO_2 is a precursor to several harmful pollutants, including ozone (O_3) and particulate matter ($PM_{2.5}$), both of which are known to have severe health impacts. NO_2 plays a crucial role in the formation of ground-level ozone, a major part of smog [6]. During daylight hours, NO_2 undergoes photolysis to produce nitric oxide (NO) and an oxygen atom (O), which then reacts with molecular oxygen (O_2) to form ozone:

$$NO_2 + hv \rightarrow NO + O$$

$$O + O_2 \rightarrow O_3$$

Elevated levels of ozone in the lower atmosphere can lead to respiratory issues, aggravate asthma, and reduce lung function, particularly in vulnerable populations such as children and the elderly [7]. NO_2 also contributes to the formation of fine particulate matter ($PM_{2.5}$), a pollutant known for its ability to penetrate deep into the respiratory tract and enter the bloodstream [8]. NO_2 reacts with ammonia, moisture, and other compounds in the atmosphere to form nitrate aerosols, a part of $PM_{2.5}$. The high levels of $PM_{2.5}$ in Delhi, often exacerbated by NO_2, have been linked to a range of health problems, including cardiovascular diseases, respiratory infections, and premature death.

NO_2 can also lead to the formation of acid rain when it reacts with water vapor in the atmosphere to form nitric acid (HNO_3).

Acid rain can have detrimental effects on soil, water bodies, vegetation, and infrastructure [9]. While acid rain is not as prominent a concern in Delhi as in other regions, it still stands for a potential risk due to the elevated levels of NO_2 and other nitrogen oxides in the atmosphere.

Prolonged exposure to elevate NO_2 levels has been associated with a range of adverse health effects [10]. These include respiratory problems such as bronchitis, reduced lung function, and an increased susceptibility to respiratory infections. Children, the elderly, and individuals with pre-existing respiratory conditions are particularly vulnerable to the health impacts of NO_2. Moreover, there is growing evidence linking NO_2 exposure to cardiovascular diseases and adverse birth outcomes, further emphasizing the need for stringent measures to control NO_2 emissions in Delhi [11].

Air pollutants measured include $PM_{2.5}$ and PM_{10} (particles with an aerodynamic diameter of equal or less than 2.5, also called fine, and 10 micrometer respectively), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO) and sulfur dioxide (SO_2) [12]. The WHO Air quality guidelines recommend levels and interim targets for common air pollutants: PM, O_3, NO_2, and SO_2. The World Health Organization (WHO) updated its Air Quality Guidelines (AQGs) in 2021, including revised recommendations for nitrogen dioxide (NO_2), a key air pollutant linked to various health problems.

For NO_2, the 2021 WHO guidelines recommend the following:

- Annual Mean Concentration: The annual mean concentration of NO_2 should not exceed 10 $\mu g/m^3$ (micrograms per cubic meter of air)

- 24-hour Mean Concentration: The 24-hour mean concentration of NO_2 should not exceed 25 $\mu g/m^3$

These guidelines are more stringent than the earlier 2005 WHO guidelines, which recommended an annual mean concentration of 40 $\mu g/m^3$ and did not set a specific 24-hour mean concentration.

The tightening of these guidelines reflects the growing body of scientific evidence linking long-term exposure to lower levels of NO_2 with adverse health effects, including respiratory and cardiovascular diseases [13]. The WHO's updated recommendations are aimed at reducing these health risks by encouraging stricter regulation and monitoring of NO_2 levels in the air.

While the COVID-19 pandemic temporarily reduced NO_2 levels, the later rebound underscores the challenges of achieving sustained improvements in air quality. The review also shows the significant impact of NO_2 on ambient air quality, contributing to the formation of other harmful pollutants and posing serious risks to public health.

To address the issue of NO_2 emissions, a multi prolonged approach is needed that includes technical, policy and behavioral actions. NO_2 is primarily emitted from combustion processes that take place in vehicles [14]. The technologies such as selective catalytic reduction (SCR) can reduce NO_2 emissions from internal combustion engines by converting the nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbons (HC), into gases such as nitrogen (N_2), carbon dioxide (CO_2), and water vapor (H_2O). SCR is widely implemented and effective in reducing NO_2 emissions from vehicles, however the limitation is that the performance of the technology can degrade over time [15].

In addition to SCR, transition to cleaner fuels is a promising strategy for reducing NO_2 emissions. The tail pipe emissions account for more than 60% of vehicle emissions which are primarily due to fuel type. The use of alternate fuels, natural gas, and renewable energy can help achieve a cleaner and sustainable transportation system [16]. Electric vehicles are one such substitute for diesel and petrol vehicles that offer advantages such as zero exhaust emissions, reduced noise pollution, and better air quality [17]. Though the adoption of these vehicles is still limited, the governments can incentivize electric vehicles by providing financial incentives, tax breaks, or rebates for purchasing EVs.

Moreover, there is a need to enforce stricter emission standards for vehicles. Due to the high density of vehicles in a traffic area, NOx emissions are quite high. By enforcing strategies such as restricted entries for heavy vehicles in traffic areas and managing traffic flow are useful strategies for reducing vehicular pollution [18]. Odd-Even rule is one such example of traffic management implemented by Delhi government earlier.

Along with all this, there is certainly needed to raise public awareness campaigns to educate the public about the health impacts of NO_2 emissions and the benefits of reducing vehicle emissions [19]. Public behavior should be changed to adopt less energy intensive options and minimize per capita gaseous emissions by using public transport, carpooling, ridesharing to reduce the number of vehicles on the road.

Literature Review

In metropolitan cities like Delhi, the effects of increasing NO_2 concentration can be significant primarily due to increasing urbanization and associated changes. It is seen during the COVID period when all industrial and transportation related activities are at their minimum, the air pollution is also at minimum in the said regions. Since then, in general, people are much more sensitive towards air pollution. Recent studies are also focused on industrial and vehicular gaseous emissions that lead to air pollution. Researchers also studied temporal analysis of NOx gases in the atmosphere of Delhi-NCR region.

Vadrevu [15] studied air pollution for 41 cities of India for the COVID period. The data was studied using NO_2 and Aerosol Optical Depth (AOD) from TROPOMI and MODIS satellite datasets. The results indicate NO_2 reduction of about 13 percent during the lockdown period of March 2020 to May 2020 in comparison to pre-lockdown period, from January 2020 to 24 March 2020. The top cities where NO_2 reduction occurred were New Delhi (61.74%), Delhi (60.37%), Bangalore (48.25%), Ahmedabad (46.20%), Nagpur (46.13%), Gandhinagar (45.64) and Mumbai (43.08%) with less reduction in coastal cities. The temporal analysis revealed a progressive decrease in NO_2 for all seven cities during the 2020 lockdown period. Shankar and Gadi [14] also evaluated the variation in air quality for the period of 2019 and 2020 for Delhi Region. The study focused on spatio-temporal variations of atmospheric pollutants over eight regions in National Capital Territory (NCT) Delhi during the four phases of lockdown and unlock with varying restrictions. As compared to 2019, the results show decrease in relative percent by for fine particulate matters (~ 11.6%), oxides of nitrogen (~ 7%), oxides of Sulphur (~ 3.7%), ozone (~ 7.7%), carbon monoxide (~ 20.7%), benzene (~ 11%) and toluene (~ 14%). The reduced concentration of the pollutants is primarily due to strict lockdown conditions. In the later phases, when lockdown conditions were somewhat changed, the variations are seen but not prominent. Post that, anthropogenic activities were restarted and change in meteorological factors resulted in a rise in pollutant concentration. Kaushik and Das [3] also done statistical analysis of long-term data (2016–2021) to examine seasonal, weekly, and daily variations in NOx and other pollutants at the Anand Vihar interstate bus terminal in Delhi. Researchers also investigated the influence of meteorological parameters on NOx concentrations, particularly NO_2. The study revealed the significant impact of temperature and relative humidity on NO_2 levels. NO_2 concentration was found lower during the monsoon season and higher in winter and post-monsoon periods, except for ozone. Vehicular activities directly influence pollution, evident through reduced NO_2 and benzene levels during the COVID-19 lockdown. Study also highlighted higher NO_2 concentrations in areas with heavy vehicular traffic in comparison to less transportation-impacted site. Another study by Soni [16] also examined the intertwined influences of agricultural burning, industrialization, and meteorological conditions in reference to expanding air pollution in the northern regions of India. The key pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, O_3) across ten monitoring stations in Uttar Pradesh, Haryana, Delhi, and Punjab were analyzed. Strong positive correlations between $PM_{2.5}$ and NO_2 (0.71 to 0.93) suggested similar source of emissions for many cities. Regional distribution of pollutants was also addressed. As per the study, Delhi predominantly faces air masses from southeast and northeast directions. Nirwan [4] also worked on air pollution in Delhi airshed and its association with stubble burning. Transboundary movement of pollutants considered as one of the major contributors in deteriorating Delhi's air quality. The highest standard deviations exceeding days in winter for NO_2

(7.14–9.63%) and SO_2 (4.04–7.42%) in 2019–2022 underscore the role of meteorological conditions in Delhi's pollution. The existing literature presents the analysis of air pollution of major cities of India at a broader level and discusses about severity of pollution in Delhi. However, the in-depth analysis of NO_2 across all the districts of Delhi is missing. In a current study the severity of NO_2 pollution in Delhi across all the districts was analyzed in detail by reviewing data from 40 Central Control room (C-CR) stations of Delhi spread across all the 11 districts.

Study Area

The study area includes and lies within the administrative boundary of the National Capitol Territory (NCT) of Delhi and comprises of eleven districts (Figure 1.0). The selection of study areas was done based on the CCR stations located across all the district in – NCT of Delhi who monitor the air quality at periodic intervals. There are 40 CCR stations in Delhi where ambient air quality data is being monitored at different intervals.

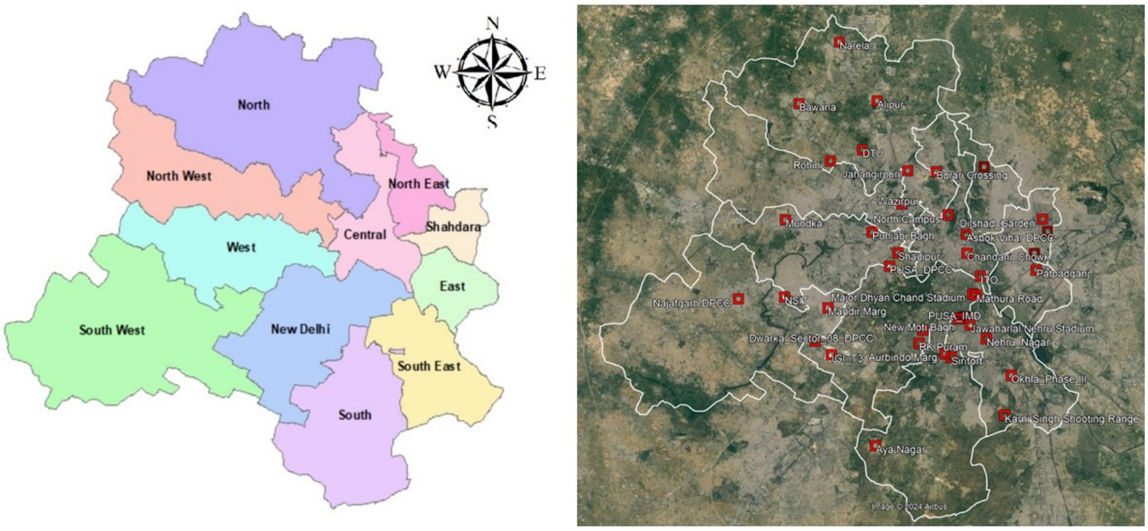


Figure 1.0: Delhi District boundary (Left) and location of CCR station (Right)

Material and Method (Data Collection and analysis)

The air quality data for all 40 monitoring stations in Delhi over the past four years (2020-2023) is available for download on the Central Pollution Control Board (CPCB) website. This study relies heavily on the raw data obtained from the CPCB's online portal, which serves as the primary source for analyzing pollution trends during this period. The CCR station was identified based on its district wise location in Delhi (Table 1.0). The raw data was statistically analyzed for monthly average across the different CCR stations for interpretation of results. To understand the variation in data, the outlier values were not removed during the statistical analysis. The list of CCR station where ambient air quality is being monitored in Delhi by CPCB is provided in Table 1.0

Acknowledgment of Data Limitations

While the CPCB data is a critical resource for this analysis, it is essential to acknowledge several limitations inherent in the data that could potentially affect the study's findings:

Potential Gaps in Monitoring: The data set may contain gaps due to equipment malfunctions, maintenance periods, or other disruptions in monitoring. These gaps can result in incomplete data, potentially leading to biased interpretations, particularly for stations with intermittent data coverage.

Measurement Errors: Air quality monitoring equipment, despite being calibrated regularly, may still experience inaccuracies due to environmental factors, sensor degradation, or calibration issues. These measurement errors can introduce noise into the data, affecting the precision of trend analysis and the reliability of the conclusions drawn.

Outlier Inclusion: The decision to include outliers in the statistical analysis allows for capturing extreme pollution events that may be significant for understanding the full impact of air quality fluctuations. However, this approach can also skew averages, particularly if the outliers are due to anomalous conditions rather than consistent trends, thereby complicating the interpretation of results.

Spatial Coverage: Although the CPCB network covers 40 stations across Delhi, the spatial distribution may not be uniform, potentially leading to over-representation of certain areas while under-representing others. This uneven coverage can affect the generalizability of findings across the entire city.

Temporal Consistency: Over the four years, there may have been changes in monitoring protocols, technology upgrades, or shifts in station locations that could introduce inconsistencies in the data, making direct comparisons across time challenging.

Impact on Findings

These limitations could influence the study's conclusions by introducing uncertainties in the trend analysis. Gaps in monitoring and measurement errors could lead to either underestimation or overestimation of pollution levels, particularly during critical periods such as seasonal changes or high pollution events. The inclusion of outliers, while capturing extreme events, might exaggerate certain trends, necessitating cautious interpretation. Despite these challenges, the data remains a valuable resource for understanding general trends in air quality across Delhi, provided that these limitations are kept in mind when interpreting the results.

Table 1.0: List of CCR Stations across Delhi

S.NO	District	CCR Station	S.NO	District	CCR Station
1	Southwest	Mandir Marg	**21**	Southeast	Nehru Nagar
2	Southwest	Najafgarh DPCC	**22**	Southeast	PUSA_IMD
3	West	Punjabi Bagh	**23**	Southeast	Lodhi Road ITM
4	West	Mundaka	**24**	Southeast	Jawaharlal Nehru Stadium
5	West	Shadipur	**25**	Southeast	Lodhi Road IMD
6	West	NSIT	**26**	South	Aurobindo Marg
7	Northwest	Wazirpur	**27**	South	Siri fort
8	North	Narela	**28**	South	Aya Nagar
9	North	Bawana	**29**	New Delhi	RK Puram
10	North	Alipur	**30**	New Delhi	Dwarka_Sector_08_DPCC
11	North	Rohini	**31**	New Delhi	IGI_T3
12	North	Jahangir Puri	**32**	New Delhi	Major Dhyan Chand Stadium
13	North	DTU	**33**	New Delhi	Mathura Road
14	Northeast	Sonia Vihar	**34**	New Delhi	PUSA_DPCC
15	Shahdara	Vivek Vihar	**35**	New Delhi	New Moti Bagh

16	Shahdara	Anand Vihar	**36**	Central	ITO
17	Shahdara	Dilshad Garden	**37**	Central	North Campus
18	East	Patparganj	**38**	Central	Chandani Chowk
19	Southeast	Karni Singh Shooting Range	**39**	Central	Burari Crossing
20	Southeast	Okhla Phase II	**40**	Central	Ashok Vihar DPCC

District wise Data Analysis of NO_2 and its interpretation

Raw data on NO_2 levels was analyzed for all eleven districts of Delhi. The raw data was averaged and both monthly and annual values were analyzed to understand the pre and post COVID trends. Fig.2.0 presents year wise NO_2 concentration in air quality - for all districts of Delhi. The data is shown in descending order, i.e., district with highest NO_2 concentration to district with lowest NO_2 concentration The cumulative annual average NO_2 concentration for the year 2020 – 2023 for all districts of Delhi is represented in Fig.3.0

On comparing the -NO_2 levels from 2020 to 2023 across various districts in Delhi, significant variations appears that highlights the changing landscape of air pollution in the capital. Figure 4.0 shows the comparative data for 4 years for each district. NO_2 is a key indicator of air quality and is primarily emitted by vehicles, industrial activities, and combustion processes. Understanding the trends across these four years provides insights into the effectiveness of pollution control measures and the challenges that persist.

2020: The Year of Lockdowns

In 2020, NO_2 levels were moderate across most districts. The Shahdara district recorded the highest annual average NO_2 level at 48 μg/m^3, followed closely by Northwest, West, and New Delhi, all of which reported levels of 43 μg/m^3. The lowest NO_2 concentration was observed in the East district, with an annual average of 20 μg/m^3. The lower levels of NO_2 in 2020 can be attributed to the nationwide lockdowns imposed in response to the COVID-19 pandemic, which significantly reduced vehicular traffic and industrial activities. This temporary reduction in emissions provided a brief respite from high pollution levels, although the overall air quality remained a concern.

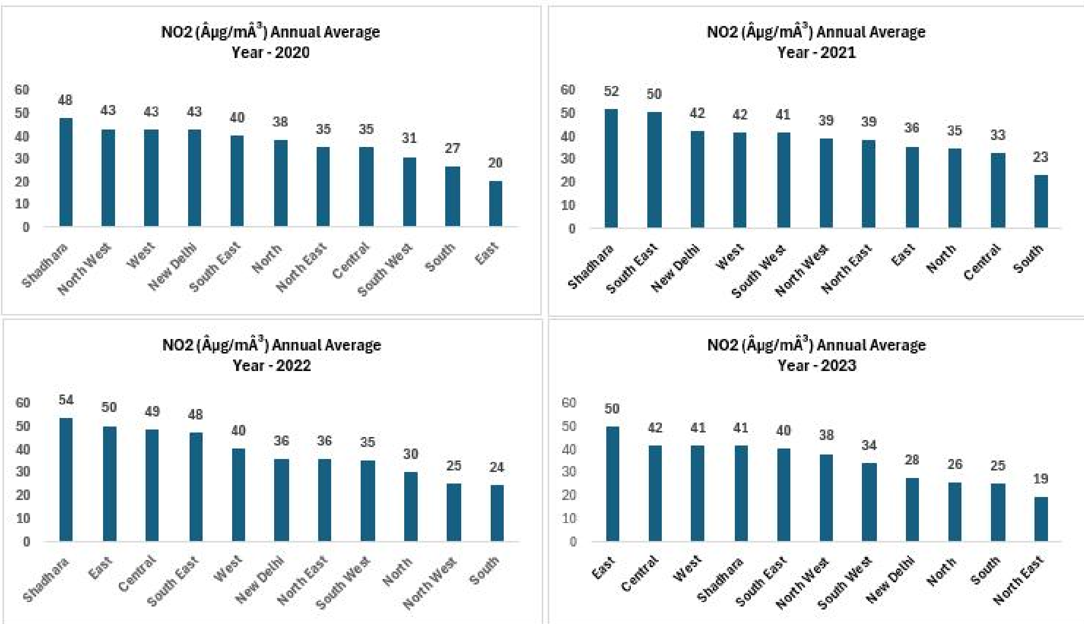


Figure 2.0: District wise Annual average of NO_2 in descending order for the year 2020 – 2023

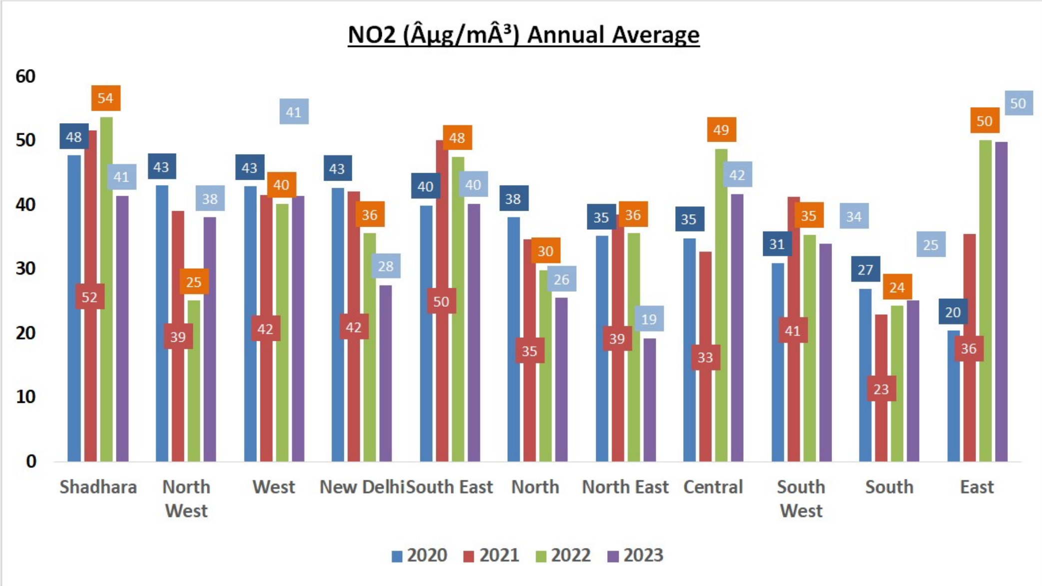


Figure 3.0: District wise Annual average of NO_2 for the year 2020 – 2023

2021: A Rebound in Emissions

As restrictions eased in 2021, there was a noticeable rebound in NO_2 levels across several districts. Shahdara recorded the highest increase, with NO_2 levels rising to 52 μg/m³, indicating a 4 μg/m³ increase from the previous year. The Southeast district also saw a significant rise, with NO_2 levels reaching 50 μg/m³, up from 40 μg/m³ in 2020. However, some districts like Northwest and Central recorded slight decreases, suggesting localized variations in pollution sources or the effectiveness of emission control measures. The overall increase in NO_2 levels in 2021 reflects the resumption of economic activities and the return of vehicular traffic to pre-pandemic levels.

2022: Divergent Trends

In 2022, the data presents a mixed picture, with some districts experiencing reductions in NO_2 levels, while others saw increases. Shahdara remained the district with the highest NO_2 concentration, recording 54 μg/m³, continuing its upward trend. The East district also saw a substantial increase, with NO_2 levels jumping to 50 μg/m³ from 36 μg/m³ in 2021. In contrast, Northwest and New Delhi districts experienced significant reductions, with NO_2 levels dropping to 25 μg/m³ and 36 μg/m³, respectively. The South and Northeast districts recorded moderate NO_2 levels, suggesting that pollution control measures may have had a localized impact. However, the continued elevated levels in certain districts indicate that more stringent measures are needed to achieve uniform reductions across the city.

2023: Mixed Results and Persistent Challenges

By 2023, the data reveals both successes and ongoing challenges in managing NO_2 pollution in Delhi. The East district's NO_2 levels remained at 50 μg/m³, indicating no improvement from the previous year. However, other districts like Shahdara and Northwest showed notable reductions, with NO_2 levels falling to 41 μg/m³ and 38 μg/m³, respectively. The Central district, which had seen a spike in 2022, also recorded a decrease to 42 μg/m³ in 2023. Despite these improvements, some districts like Northeast continued to struggle, with NO_2 levels dropping significantly to 19 μg/m³, the lowest in the city. The varying levels across districts highlight the complexity of air pollution in Delhi, where localized factors such as traffic density, industrial activities, and topography play a significant role in determining air quality.

The analysis of NO_2 data from 2020 to 2023 across Delhi's districts shows a dynamic and complex air quality scenario. The initial reduction in NO_2 levels in 2020 due to lockdowns was followed by a rebound in 2021 as economic activities resumed. In 2022 and 2023, while some districts showed improvements, others continued to experience high NO_2 levels, underscoring the need for more targeted and sustained pollution control measures.

The variations in NO_2 levels across districts suggest that while city-wide initiatives like the promotion of electric vehicles and stricter emission norms have had an impact, localized efforts are equally important. Measures such as better traffic management, stricter industrial regulations, and public awareness campaigns need to be tailored to the specific needs of each district to achieve more uniform air quality improvements across Delhi. The persistent elevated levels of NO_2 in certain districts indicate that ongoing efforts must be intensified to protect public health and ensure a cleaner environment for all residents of Delhi.

Data Analysis and Interpretation for Delhi from 2020 to 2023

The monthly average of NO_2 level was calculated for all the raw data across 40 CCRs of Delhi from the year 2020 to 2023 as shown in table 2.0 and its interpretation is presented in below section.

2020: A Year Marked by Lockdowns

The year 2020 was characterized by unprecedented events due to the global COVID-19 pandemic, which led to nationwide lockdowns, significantly impacting air quality. In Delhi, the NO_2 levels varied throughout the year, with noticeable dips in certain months:

- **January to March:** The NO_2 levels were relatively high at the beginning of the year, with January recording 47 μg/m³, February 49 μg/m³, and March dropping to 34 μg/m³.
- **April to June:** As the strict lockdowns were implemented in April, a sharp decline in NO_2 levels was observed, with the lowest in April at 21 μg/m³. May and June saw slight increases to 25 μg/m³ and 23 μg/m³, respectively, as restrictions began to ease.
- **July to December:** The latter half of 2020 saw fluctuations, with NO_2 levels rising gradually from July (22 μg/m³) to a peak in November (66 μg/m³), before slightly dropping in December to 57 μg/m³. The rise towards the end of the year is due to the resumption of economic activities and the onset of winter, which typically worsens air pollution in Delhi.

Table 2.0: Monthly average of NO_2 (μg/m³) level in Delhi from Year 2020 – 2023

S.NO	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	2020	47	49	34	21	25	23	22	22	31	58	66	57
2	2021	47	56	44	43	32	29	25	24	23	38	64	58
3	2022	40	45	46	50	34	32	23	22	25	42	54	48
4	2023	41	43	34	38	35	27	21	19	22	36	47	46

2021: Gradual Recovery and Pollution Rebound

In 2021, as economic activities resumed and lockdowns were lifted, NO_2 levels began to increase compared to 2020:

- **January to March:** The year started with similar NO_2 levels as the previous year, with January recording 47 μg/m³. However, there was a noticeable increase in February (56 μg/m³) and March (44 μg/m³), indicating a return to pre-pandemic pollution levels.

- **April to June:** The NO_2 levels remained stable during these months, with slight variations—April (43 μg/m³), May (32 μg/m³), and June (29 μg/m³).

- **July to December:** The latter half of 2021 showed a steady decline in NO_2 levels during the monsoon months of July (25 μg/m³) and August (24 μg/m³). However, post-monsoon months saw an increase, particularly in November (64 μg/m³) and December (58 μg/m³), reflecting the impact of winter pollution and Diwali celebrations.

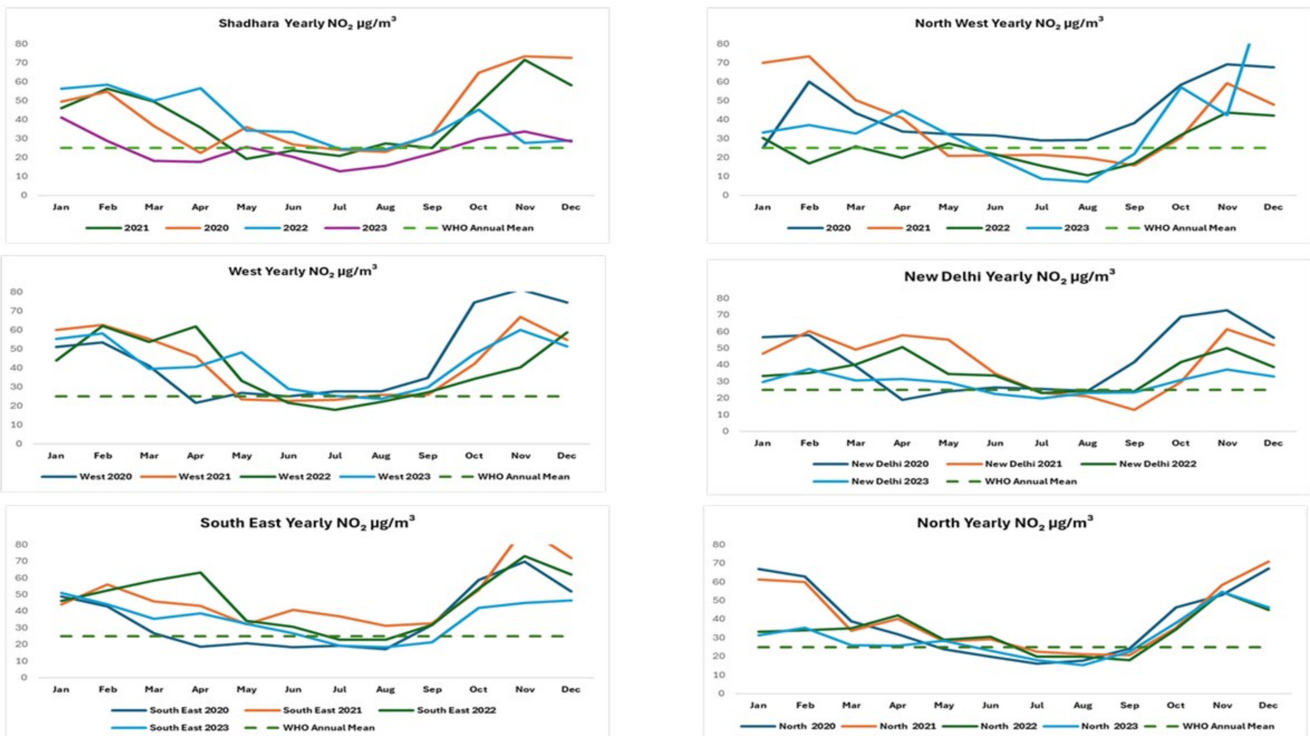
2022: Continued High Levels with Seasonal Variations

The year 2022 continued the trend of high NO_2 levels, with significant seasonal variations:

- **January to March:** The year started with moderate NO_2 levels, with January at 40 μg/m³, February at 45 μg/m³, and March at 46 μg/m³, showing a slight increase as winter ended.

- **April to June:** The levels peaked in April at 50 μg/m³, due to increased vehicular activity and industrial emissions, followed by a decrease in May (34 μg/m³) and June (32 μg/m³).

- **July to December:** The monsoon months saw a reduction in NO_2 levels, with July at 23 μg/m³ and August at 22 μg/m³. However, as in previous years, the levels increased post-monsoon, reaching 54 μg/m³ in November and slightly dropping to 48 μg/m³ in December.



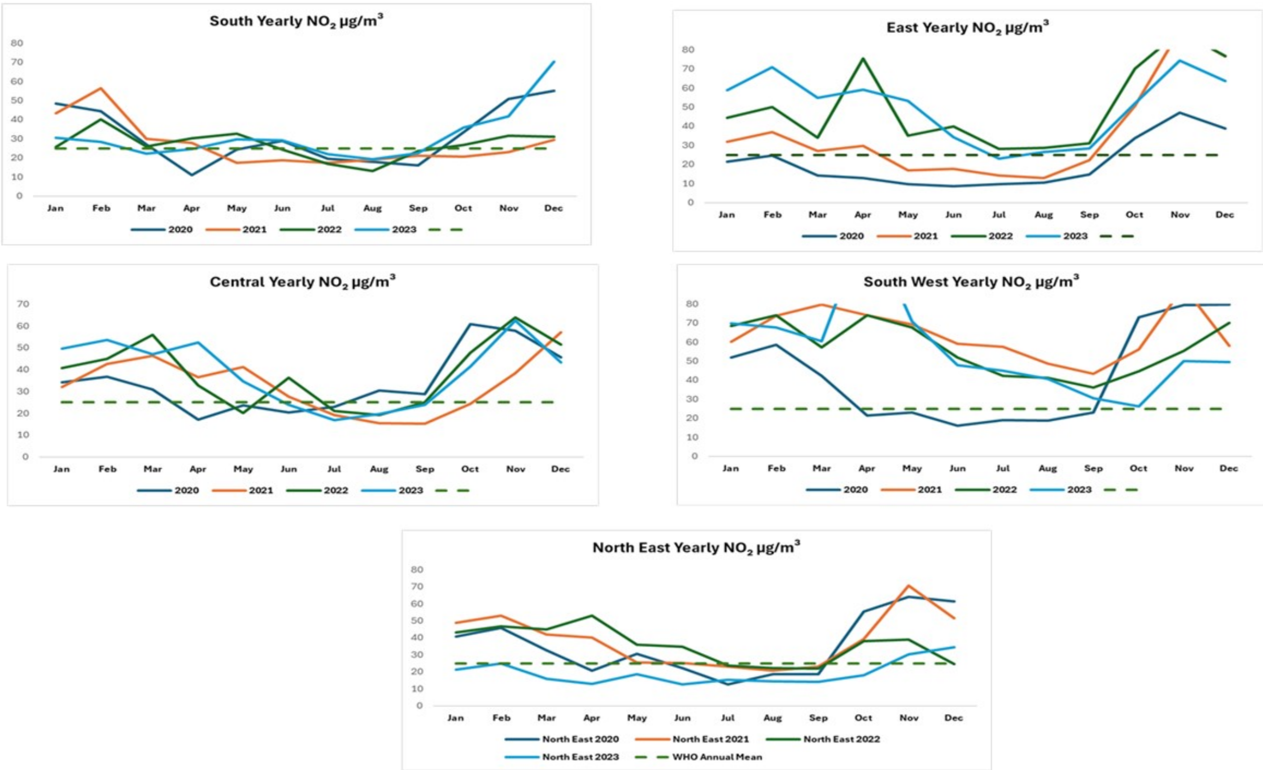


Figure 4.0: Comparative analysis of month-wise, year-wise average NO_2 concentration

2023: A Return to Pre-Pandemic Levels

By 2023, the NO_2 levels in Delhi appeared to have stabilized, resembling pre-pandemic levels:

- **January to March:** The year began with relatively low NO_2 levels, with January at 41 µg/m³, February at 43 µg/m³, and March dropping to 34 µg/m³.

- **April to June:** There was an increase in NO_2 concentrations in April (38 µg/m³) and May (35 µg/m³), followed by a decline in June (27 µg/m³).

July to December: The NO_2 levels continued to decrease during the monsoon, with the lowest in August (19 µg/m³). However, post-monsoon months saw an increase, with November recording 47 µg/m³ and December at 46 µg/m³. The interesting facts about the monthly average NO_2 levels for 4 years at each of the 11 sites are presented, it is evident that annual average of NO_2 concentrations is above WHO air quality guidelines (25 µg/m³) for all 11 districts. It is also illustrated that the NO_2 concentrations vary significantly during the year, perhaps due to the seasonal impact on air quality. During the months of April to September, the average NO_2 levels are nearly around the guideline's values, post September NO_2 concentrations start increasing in the ambient air and remain high during the winter season. Post January, the NO_2 levels again take downward trend and its impacts lower down in the ambient air.

Public awareness and community engagement in air quality management

Public awareness and community engagement are pivotal in driving behavioral changes that can significantly impact air quality. Awareness campaigns play a critical role in educating citizens about the sources of pollution, its health impacts, and actionable steps to reduce their personal contributions [20]. During the COVID-19 lockdowns, for instance, many people witnessed a marked improvement in air quality, primarily due to reduced traffic and industrial activity. This experience highlighted the direct link between human activity and environmental health, reinforcing the importance of individual and collective responsibility in combating air pollution [21].

Community engagement initiatives, such as carpooling programs, cycling clubs, and community-led air quality monitoring, further empower citizens to take ownership of their environment [22]. These initiatives not only foster a sense of responsibility but also encourage sustainable practices that can lead to significant reductions in pollutants like NO_2. For example, in Delhi, the Odd-Even scheme, which restricted vehicle usage based on license plate numbers, showcased how temporary, community--driven actions could complement broader policy measures to reduce pollution levels.

Behavioral changes inspired by public awareness and community engagement are essential in creating a sustained impact on air quality [23]. Reducing car usage, opting for public transport, and supporting car-free days are just a few ways individuals can contribute to lowering NO_2 emissions [24]. When citizens are well-informed and actively participate in air quality management, they become partners in the effort to create a cleaner, healthier environment [25]. These combined efforts not only amplify the effectiveness of governmental policies but also pave the way for a more sustainable future, where community-driven actions and informed public behavior are integral to maintaining air quality.

Policy Interventions for improvement of air quality in Delhi-NCR

To address the alarming air pollution problem in Delhi and NCR region, the commission for Air Quality Management in NCR and adjoining areas (CAQM) has been constituted in 2021. The Commission has the goal of addressing air pollution abatement and control in Delhi/ NCR. CAQM devised a comprehensive policy for air pollution in July 2022 that entails sector wise interventions, qualified targets and timelines for various sectors contributing to air pollution (PIB, December 2023).

Ministry of Environment, Forest, and Climate Change (MoEFCC) is implementing a nation-wide clean air program with an aim to improve air quality in more than 100 cities in 24 States/UTs of India. Under the program, Government of India (GoI) has taken several initiatives to improve air quality by reducing the sources of air pollution including vehicular emission, industrial emission, air pollution due to waste and biomass - dumping and burning, and road dust and construction & demolition (PIB, March 2023). Some important initiatives are:

- Leapfrogging from BS-IV to BS-VI norms for fuel and vehicles
- Introduction of cleaner/alternate fuels like CNG, LPG, ethanol blending in petrol
- Faster Adoption and Manufacturing of Electric Vehicles (FAME) -2 schemes has been rolled out.
- Ban on use of pet coke and furnace oil in NCR, use of pet coke in processes in cement plants, lime kilns and calcium carbide manufacturing units.
- Stringent emission norms for Coal based Thermal Power Plants (TPPs)
- Shifting of industrial units to PNG/cleaner fuel in Delhi
- Shifting of brick kilns in Delhi- NCR to zig-zag technology for reduction of pollution
- Notification of 8 waste management rules covering solid waste, plastic waste, e-waste, bio-medical waste, C&D waste, hazardous waste, battery waste and ash generated from thermal power plants.
- Extended Producer Responsibility (EPR) framework for plastic packaging, battery waste, tyre waste and e-waste have

been implemented.

In addition, Delhi government has also taken steps to address the alarming rise in air pollution. These efforts have been driven by the need to improve the capital's air quality, which has consistently ranked among the worst in the world.

Delhi government has rolled out an ambitious Electric Vehicle Policy in August 2020, aiming to make 25% of all new vehicle registrations electric by 2024. This policy has incentivized the adoption of EVs through subsidies, tax exemptions, and the development of charging infrastructure across the city. The move towards electrification is seen as a critical step in reducing NO_2 emissions, given that vehicles are among the largest contributors to urban air pollution.

In addition to promoting electric vehicles, both central and state governments have taken measures for control of emissions. Leapfrogging from Bharat Stage (BS) IV to BS VI fuel standards in April 2020 marked a significant advancement in reducing vehicle-related pollution. BS VI norms, which are equivalent to Euro 6 standards, mandate lower NO_2 emissions and particulate matter from vehicles. The introduction of BS VI fuel, which has significantly lower sulfur content than BS IV, also contributed to reducing NO_2 emissions from the existing vehicle fleet. Ban on all diesel vehicles older than 10 years and all petrol vehicles older than 15 years, in Delhi and NCR was also a significant step in reducing vehicular emissions in the region.

The Graded Response Action Plan (GRAP) has been another critical component to manage air pollution in Delhi. GRAP, introduced in 2017, is a set of emergency measures that are triggered when air quality deteriorates beyond certain thresholds. During periods of severe pollution, such as during the winter months, GRAP mandates actions like the banning of construction activities, halting the operation of diesel generator sets, and restricting the entry of heavy vehicles into the city. These measures, while temporary, aim to curb NO_2 emissions during the most critical periods of pollution.

There is focus on -reducing industrial emissions, which contribute significantly to NO_2 levels. This has involved the introduction of cleaner technologies in industries and a transition to cleaner fuels [26]. For instance, the switch from coal to natural gas in several industrial units has been a key factor in reducing NO_2 emissions. Moreover, the enforcement of stringent emission norms for industries and the closure of non-compliant units have further helped in this regard [27].

Despite these efforts, the improvement in NO_2 levels has been modest. While there was a slight reduction in NO_2 concentrations in 2022 and 2023, these gains were often undermined by episodic spikes in pollution. Such spikes typically occurred during the winter months and festival seasons, particularly around Diwali, when the burning of firecrackers leads to a sudden surge in air pollutants, including NO_2. Additionally, the phenomenon of temperature inversion during winter, which traps pollutants close to the ground, worsens the situation.

These observations as presented in Table 2.0- highlight the complexity of managing air quality in a megacity like Delhi. While government interventions have had a positive impact, the persistence of episodic pollution spikes indicates the need for more comprehensive and sustained efforts. This includes not only stricter enforcement of existing measures but also public participation in reducing pollution through lifestyle changes, such as reducing vehicle usage and avoiding the burning of firecrackers during festivals.

The data on NO_2 levels and the effectiveness of these measures can be correlated by reports and studies published by the CPCB and other environmental agencies. For instance, the CPCB regularly monitors and publishes air quality data for Delhi and other cities, which is available on its official website. These reports provide valuable insights into the trends and patterns of air pollution in Delhi, helping to assess the impact of various governmental policies and interventions.

While Delhi's efforts to curb NO_2 emissions have led to some improvements in air quality, ongoing challenges remain. The slight reduction in NO_2 levels observed in 2022 and 2023 demonstrates that while the strategies implemented have been effective to some extent, they need to be continuously adapted and reinforced to achieve long-term improvements in air quality.

Conclusion

The NO_2 levels in Delhi from 2020 to 2023 show a clear pattern influenced by both anthropogenic activities and seasonal factors. The air quality data of Delhi indicates following trends with respect to NO_2 levels:

- **Impact of Lockdowns:** The most significant reduction in NO_2 levels was observed in 2020, during the strict lockdown periods. This highlights the role of vehicular and industrial emissions as major contributors to NO_2 pollution in Delhi.

- **Seasonal Variations:** Across all four years, NO_2 levels consistently peaked during the winter months (October to December), due to temperature inversion, increased heating, and the burning of biomass. The monsoon months (July to September) saw a reduction in NO2 levels, attributed to increased precipitation and reduced industrial activity.

- **Gradual Return to Higher Levels:** Post-2020, as restrictions were lifted and economic activities resumed, NO_2 levels gradually returned to higher concentrations, particularly during the winter months, indicating a rebound in pollution levels.

While the lockdowns of 2020 provided a temporary respite from high pollution levels, the subsequent years saw a return to pre--pandemic levels. This underscores the need for sustained and effective pollution control measures, particularly in managing vehicular emissions and industrial activities, to improve air quality in Delhi and protect public health. Addressing these challenges will require a multi-faceted approach, while government interventions have had a positive impact, the persistence of episodic pollution spikes indicates the need for more comprehensive and sustained efforts. This includes not only stricter enforcement of existing measures but also public participation in reducing pollution through lifestyle changes, such as reducing vehicle usage and avoiding the burning of firecrackers during festivals.

While Delhi's efforts to curb NO_2 emissions have led to some improvements in air quality, ongoing challenges remain. The slight reduction in NO_2 levels observed in 2022 and 2023 demonstrates that while the strategies implemented have been effective to some extent, they need to be continuously adapted and reinforced to achieve long-term improvements in air quality. Reducing NO_2 emissions in Delhi is crucial and can be achieved by accelerated adoption of cleaner transportation. The government should offer encouraging incentives, expand charging infrastructure, and mandate EV usage in public and commercial transport fleets. In Delhi, the public transportation system is no doubt mostly streamlined, but there is need to improve the other local transport systems such as buses. There is also a need for identifying the hotspots of NO_2 emissions, for that real time monitoring of NOx is important and that can be done using advanced sensor-based technologies. For cities like Delhi, public participation also has a key role to play in pollution reduction. There is need to conduct awareness campaigns to educate the public on the sources of NOx pollution and associated health impacts and promote behavior changes, like encouraging use of public transport, use of bicycles for short distance, stopping in car engine on red lights, regular maintenance of vehicles, adoption of cleaner fuel and vehicle, etc. It is expected that by implementing a combination of these strategies in Delhi or any other place, can significantly reduce NOx emissions and contribute to cleaner air.

Data Availability Statement

The data that support the findings of this study are openly available on website of Central Pollution control board - https://airquality.cpcb.gov.in/ccr/#/caaqm-dashboard-all/caaqm-landing/caaqm-data-repository

Authors Contributions

Manas Kumar Jha: Was responsible for the conceptualization, drafting, and writing of the complete paper, including data collection and analysis.

Dr. Dilip Kumar Markandey: Provided critical review, proof correction, and valuable guidance throughout the writing process.

Dr. Ruchi Gupta: Contributed to the review, proof correction, and provided essential guidance and feedback.

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Competing Interests

The authors declare no competing interests.

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