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Research Article

Spatio-Temporal Assessment of Ambient Air Pollution in Firozabad City Using Exceedance Factor Analysis

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Abstract

Firozabad, a prominent industrial city in Uttar Pradesh, India, renowned for its extensive glass manufacturing industry, has been grappling with escalating air pollution levels, posing significant environmental and public health challenges. This study undertakes a comprehensive spatio-temporal assessment of ambient air pollution in Firozabad over twelve years (2013–2024), focusing on key pollutants: particulate matter (PM_{10}), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). Utilizing data from three strategically located monitoring stations representing industrial (CDGI area), residential (Tilak Nagar), and commercial (Raja Ka Taal) zones, the research employs the Exceedance Factor (EF) methodology as prescribed by the Central Pollution Control Board (CPCB) to evaluate pollution levels against the National Ambient Air Quality Standards (NAAQS). The findings reveal persistently critical levels of PM_{10} across all sites, with concentrations significantly surpassing the NAAQS limit of 60 µg/m³, particularly in residential areas where values peaked at 1100 µg/m³ in 2024. SO_2 levels remained within permissible limits throughout the study period, indicating effective control measures. However, NO_2 concentrations exhibited a concerning upward trend post-2020, approaching the NAAQS threshold, especially in residential zones, likely due to increased vehicular emissions and industrial activities. The study underscores the urgent need for targeted air quality management strategies, including adopting cleaner technologies, stringent emission controls, and enhanced public awareness to mitigate pollution levels and safeguard public health in Firozabad.

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1. INTRODUCTION

Air pollution remains a major global environmental and public health issue, especially in developing countries like India, where rapid urbanisation and industrialisation have exacerbated existing challenges. (Gurjar et al., 2016; Guttikunda et al., 2019). Among various pollutants, fine particulate matter ($PM_{2.5}$ and PM_{10}) has been identified as particularly hazardous, contributing significantly to the incidence of respiratory and cardiovascular disorders (HEI, 2020; Manisalidis et al., 2020). Globally, an estimated 1.1 billion individuals endure adverse health impacts from poor air quality over their lifetimes (UNEP, 2002). Firozabad, located in Uttar Pradesh, is distinguished by its glass manufacturing industry, a critical sector supporting the regional economy (Srivastava et al., 2018). Multiple mechanisms contribute to atmospheric pollution in the city, including industrial production, vehicular emissions, combustion of fossil fuels, thermoelectric power generation, and waste incineration (Williams and Matt, 2016; Popescu and Ionel, 2010). The resulting pollutants—carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_2), volatile organic compounds (VOCS), ozone (O_3), and fine particulate matter—pose serious threats to environmental and public health (Agrawal and Singh, 2000). Glass manufacturing has been recognized as a significant contributor to the formation of photochemical smog and the emission of suspended particulates in both urban and rural areas. (Pathak and Rana, 2011). The expansion of glass production facilities has further exacerbated air pollution levels, with studies showing that concentrations of PM_{10} and $PM_{2.5}$ in Firozabad often surpass the National Ambient Air Quality Standards (NAAQS), posing significant health risks to the local population (CPCB, 2021; Yadav et al., 2022).

1.1 Firozabad's Population Growth and Vehicular Trends

Firozabad has experienced significant demographic changes over the past decade. According to the 2011 Census, the city's population was 604,214, and projections estimate that by 2025, it will reach approximately 881,000, reflecting a substantial growth of around 45.8% over 14 years (Census of India, 2011; World Population Review, 2025). This rapid urbanisation has led to an increased demand for transportation, resulting in a notable rise in the number of registered vehicles. Data indicates that the number of registered motor vehicles in Firozabad has increased from an average of 2,296 units in 2006 to over 3,700 units by 2025 (CEIC Data, 2025). The population and vehicular density surge have impacted the city's air quality. Vehicular emissions significantly contribute to elevated concentrations of fine particulate matter, particularly $PM_{2.5}$ and PM_{10}. Recent studies reveal that the levels of these pollutants in Firozabad consistently exceed the permissible limits set by the National Ambient Air Quality Standards (NAAQS), posing serious public health concerns (CPCB, 2021; Yadav et al., 2022). The correlation between growing vehicle numbers, urban expansion, and the rise in PM concentrations underscores the urgent need for targeted air pollution mitigation strategies in Firozabad.

1.2 Impacts of Air Pollution

Regarding specific pollutants, sulfur dioxide (SO_2) is particularly detrimental, causing lung dysfunction, respiratory tract inflammation, eye irritation, and aggravation of cardiovascular diseases (Darryl, 2017). Similarly, nitrogen oxides (NO_x), primarily emitted from vehicular exhausts, contribute to respiratory illnesses and are significant factors in sudden mortality events (Dales et al., 2004). Particulate matter (PM) includes both primary particles—direct emissions such as diesel soot— and secondary particles formed through the physicochemical transformation of gases like sulphates and nitrates. (Limaye and Salvi, 2010). PM is typically categorised into $PM_{2.5}$ (diameter <2.5 µm), coarse particles ($PM_{2.5-10}$), and PM_{10} (diameter <10 µm) (Kim et al., 2015). Primary particles originate from vehicular emissions, stone crushing, and biomass burning, while natural sources include volcanic activity, oceanic sprays, and soil dust (Limaye and Salvi, 2010). Urban areas of developing countries are particularly vulnerable, as rapid population growth and industrialisation have led to a sharp rise in vehicular numbers and energy consumption (Nagdeve, 2004). According to the World Health Organization (WHO), over 25% of global deaths are directly linked to environmental pollution. (Amal et al., 2018). In Firozabad, the health implications of deteriorating air quality are profound, with residents near industrial zones exhibiting higher rates of respiratory diseases, including asthma and bronchitis (Kumar et al., 2017; Singh et al., 2022). Indoor air pollution, aggravated by using traditional fuels and inadequate ventilation, further amplifies these health risks (Rehman et al., 2019; WHO, 2018).

Urban air pollution stems from multiple sources: human and animal respiration, decomposition of organic matter, combustion of coal, oil, and gas, and industrial emissions of dust, fumes, vapours, and gases (Barman et al., 2010). Given the large urban population exposed, urban air pollution presents a significant concern for human and environmental health. Spatial and temporal analyses have become essential for understanding pollution patterns and informing mitigation strategies (Jat et al., 2009; Sahu et al., 2011). Geospatial technologies, such as Geographic Information Systems (GIS) and remote sensing, are increasingly used to map pollutant dispersion and identify hotspots (Pathak et al., 2020; Kumar & Singh, 2021). Notably, between 1998 and 2010, the proportion of Indian districts exceeding the annual $PM_{2.5}$ standard (40 µg/m³) increased from 27% to 45% (Guttikunda et al., 2019). Currently, nine out of the ten most polluted cities in the world are located in India.(Yuda, 2019). In Firozabad, industrial activities are deeply intertwined with residential settlements, exacerbating human exposure to harmful pollutants (Yadav et al., 2022). Meteorological factors such as temperature inversions, wind speed, and humidity significantly influence the dispersion and concentration of pollutants, with winter months often witnessing elevated pollution levels due to stagnant atmospheric conditions.

Rapid economic growth, increasing incomes, and the surge in vehicle ownership are further aggravating air quality in Indian cities (Wang and Tang, 2019). While major cities like

Allahabad, Agra, Lucknow, Kanpur, and Amritsar have been studied extensively, smaller industrial cities like Firozabad remain critically under-monitored (Ghosh and Parida, 2015). In Uttar Pradesh, where approximately 72.2% of the population resides in rural areas, urban centres face intense environmental pressures. Policy interventions are crucial in addressing these challenges. The National Green Tribunal (NGT) and the Uttar Pradesh Pollution Control Board (UPPCB) have implemented regulatory measures to monitor and reduce emissions from industrial units. However, enforcement remains inconsistent, necessitating stronger community engagement and the adoption of cleaner technologies for sustainable improvements in air quality. This study aims to conduct a comprehensive spatiotemporal analysis of ambient air pollution in Firozabad, focusing on the following objectives:

1. To evaluate the spatial variation of key air pollutants ($PM_{2.5}$, SO_2, NO_2) across industrial, commercial, and residential zones of Firozabad city.
2. To analyse the temporal trends and determine periods of elevated pollution levels over 2013–2024 using the Exceedance Factor (EF) method.

2. Rationale of the Study

Rapid urbanisation, industrial expansion, and increasing vehicular emissions have led to significant air quality deterioration in many medium-sized cities in India, including Firozabad, known for its dense cluster of glass industries. Despite its economic importance, Firozabad has received limited scholarly attention regarding ambient air quality trends and pollution impacts at a localised level. The city exhibits a unique industrial-residential-commercial mix, making it an important case study for evaluating spatial and temporal air pollution patterns. To address this research gap, the present study conducts a twelve-year (2013–2024) spatio-temporal analysis of ambient air pollution using three key pollutants—$PM_{2.5}$, SO_2, and NO_2—across three distinct activity-based monitoring sites in Firozabad: industrial (CDGI area), residential (Tilak Nagar), and commercial (Raja Ka Taal). This study employs the Exceedance Factor (EF) methodology outlined by the Central Pollution Control Board. (CPCB, 2016) To systematically assess the pollution levels according to National Ambient Air Quality Standards (NAAQS). The rationale behind Exceedance Factor (EF) lies in its simplicity and effectiveness in classifying pollution severity into distinct categories—low, moderate, high, and critical—allowing for consistent interpretation across time and space. The findings offer critical insights into pollutant-specific and area-specific pollution behaviour, supporting better environmental planning, policy formulation, and emission control strategies at the municipal and regional levels. This evidence-based, spatially explicit analysis contributes to the broader discourse on urban environmental health and sustainable city planning, particularly in second-tier industrial cities.

3. MATERIALS AND METHODS

This study used data from three Ambient Air Quality Monitoring Stations established by the Central Pollution Control Board (CPCB) within the municipal area of Firozabad city, Uttar Pradesh. The selected stations represent three major land-use types: residential, commercial, and industrial zones, as detailed in Table 1. These sites were strategically chosen to capture the spatial variability of air pollution across different city functional areas. The study period spans twelve years, from 2013 to 2024. Ambient air quality data for three key pollutants—particulate matter (PM10), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2)—were collected on an annual basis.

3.1 Exceedance Factor Method

The Exceedance Factor (EF) method was applied to assess pollution levels systematically following CPCB guidelines (CPCB, 2016). The EF for each pollutant was calculated as:

$$EF = \frac{Pollutant\ Annual\ Mean\ Concentration}{\text{Annual Standard for pollutant}}$$

Where the "Annual Standard" refers to the prescribed limits under the National Ambient Air Quality Standards (NAAQS). Based on the calculated EF values, the pollution level at each site was classified into four categories:

Low pollution (L): EF < 0.5
Moderate pollution (M): 0.5 ≤ EF < 1.0
High pollution (H): 1.0 ≤ EF ≤ 1.5
Critical pollution (C): EF > 1.5

3.2 Spatial and Temporal Analysis

The spatial distribution of pollution was assessed by comparing EF values across the three different zones (industrial, commercial, and residential) for each year. Temporal trends were analysed by evaluating changes in EF values over the twelve years to identify periods of heightened pollution. All statistical analyses were conducted using descriptive statistics, and spatiotemporal trends were visualised using trend plots and comparative charts to highlight variations over time and space.

Table 1: Monitoring Locations for Ambient Air Quality in Firozabad City

Sampling Site	Activities	Latitudes and longitudes	General Features
Site 1	CDGI	27° 8'54.93"N & 78°24'22.54"E	Industrial Area
Site 2	Tilak Nagar	27°10'59.12"N & 78°21'2.88"E	Residential Area
Site 3	Raja Ka Taal	27°11'45.15"N & 78°23'24.82"E	Commercial Area

Source: UPPCB, Firozabad

3.3 Study Area Description

Firozabad, renowned for its numerous small-scale glass industries, is situated in the western part of Uttar Pradesh (latitude: 27°12′ to 27°18′ N; longitude: 78°35′ to 78°42′ E) in north-central India (District Census Handbook, Firozabad, 2011The city is bounded to the north by the Etah district, to the east by the Mainpuri and Etawah districts, and to the south by the Yamuna River. (District Census Handbook, Firozabad, 2011). It has a sub-humid climate with an average annual rainfall of 715.2

mm, primarily falling during the summer monsoon season from June to September. (IMD, 2020). A significant portion of the local population is engaged in the centuries-old tradition of glass manufacturing. Every day, over five crore bangles are produced and sold across IndiaFirozabad serves as the main hub, which has earned it the nickname 'Suhag Nagri.'(Chandra, 2016). Despite its economic importance, the glass industry relies on outdated processing and waste management technologies. While glass is often recycled and reused, the process requires a significant amount of water for moulding, cooling, washing, and glazing. This untreated wastewater is frequently released directly into the environment, contaminating soil and groundwater. (Singh, Tiwari, & Sharma, 2014).

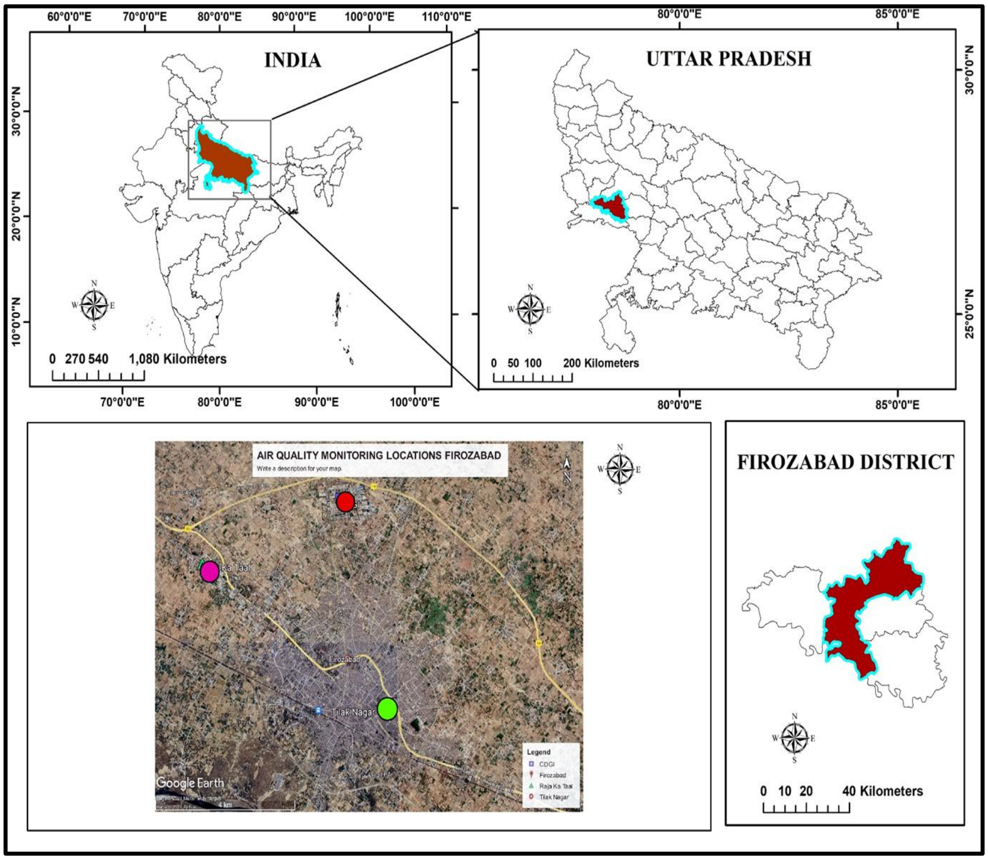

Figure 1: Geographical location of the Study area and sampling sites

Furthermore, emissions from the glass factories contribute significantly to air pollution, adversely affecting the health of residents and exacerbating environmental degradation (CPCB, 2018; Tiwari & Singh, 2020). The city's population has steadily increased, with the urban population estimated at around 941,758 in 2025, up from 603,797 recorded in 2011 (World Population Review, 2025). This demographic growth has been accompanied by a rise in vehicular numbers, contributing to elevated levels of air pollutants. Recent air quality assessments indicate that PM2.5 concentrations in Firozabad have reached levels as high as 60 µg/m³, significantly exceeding the World Health Organisation's recommended limits (AQI India, 2025). The increasing trend in PM2.5 levels highlights the urgent need for implementing effective pollution control measures to safeguard public health and the urban environment.

4. RESULTS AND DISCUSSION

4.1 PM_{10} Concentration

Particulate Matter with a diameter of less than 10 micrometres (PM_{10}) is a critical air pollutant due to its ability to penetrate the respiratory system and contribute to various health disorders, including bronchitis, asthma, and cardiovascular diseases (HEI, 2020; Manisalidis et al., 2020). In urban and industrial regions, PM_{10} primarily originates from vehicular emissions, industrial activities, construction dust, and combustion of fossil fuels (Guttikunda et al., 2019). Table 2 presents the average annual concentrations of PM_{10} recorded across three monitoring sites—representing industrial (Site 1), commercial (Site 2), and residential (Site 3) areas—in Firozabad city between 2013 and 2024. The National Ambient Air Quality Standard (NAAQS) for PM_{10} in India is prescribed at 60 µg/m³ (CPCB, 2009).

Table 2: PM_{10} pollutant levels for three locations from 2013 to 2024

Year	Average Annual concentration of PM_{10} (µg/m³)			
	NAAQS PM_{10} Limit (µg/m³)	**Site 1**	**Site 2**	**Site 3**
2013	60	250	600	800
2014	60	200	450	600
2015	60	220	470	650
2016	60	230	500	780
2017	60	210	510	750
2018	60	180	480	700
2019	60	160	450	680
2020	60	150	420	650
2021	60	250	600	800
2022	60	300	700	950
2023	60	350	800	1050
2024	60	380	850	1100

Source: UPPCB, 2024

Across all years and sites, PM_{10} concentrations substantially exceeded the NAAQS limit. Site 3, representing the residential area, consistently recorded the highest PM_{10} levels, reaching up to 1100 µg/m³ in 2024. Similarly, Site 2 (commercial area) and Site 1 (industrial area) also exhibited persistently elevated PM_{10} levels, although comparatively lower than Site 3. From 2013 to 2020, there is a slight declining trend in PM_{10} concentrations across all sites, possibly reflecting minor improvements due to regulatory interventions or temporary changes in industrial activity. However, a sharp escalation in PM_{10} concentrations is observed from 2021 onwards, culminating in peak values in 2024. Notably, between 2021 and 2024, PM_{10} levels at all sites approximately doubled, indicating a significant deterioration in air quality. The extreme exceedances observed, particularly after 2021, may be attributed to rapid industrial expansion, increased vehicular density, and resumption of economic activities post-pandemic disruptions. Such elevated levels of PM_{10} pose severe health risks to the population, particularly vulnerable groups such as children, the elderly, and individuals with pre-existing respiratory conditions. These findings underscore the urgent need for enhanced pollution control measures, stricter industrial emissions regulations, and citywide interventions targeting vehicular emissions and dust control in Firozabad.

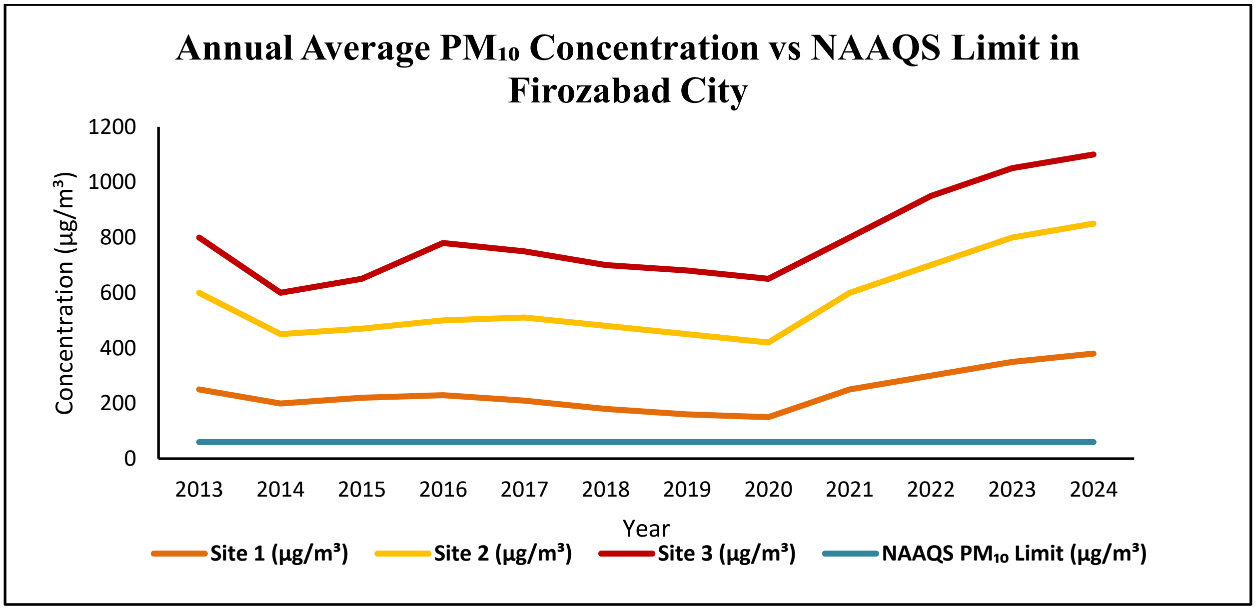

Figure 2: Annual Average PM_{10} Concentration vs NAAQS Limit in Firozabad City

4.1.1 Trend of Exceedance Factor Analysis of PM_{10}

An analysis of the EF values reveals consistently critical pollution levels (EF > 1.5) across all sites throughout the study period. Notably, Site 3 (residential area) exhibits the highest EF values, escalating from 13.33 in 2013 to 18.33 in 2024. Similarly, Site 2 (commercial area) and Site 1 (industrial area) show significant increases, with EF values rising from 10.00 to 14.17 and 4.17 to 6.33, respectively.

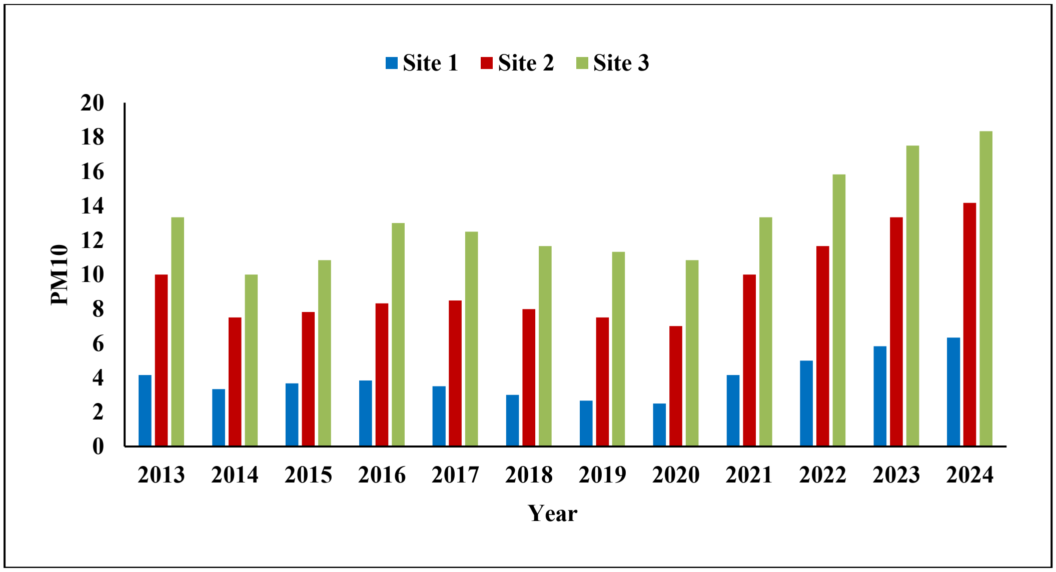

Figure 3: Exceedance factor graph for PM10 pollutants in 2013–2024

A slight decline in EF values is observed between 2013 and 2020, potentially attributable to temporary regulatory measures or reduced industrial activity. However, a sharp increase is noted from 2021 onwards, indicating a resurgence in pollution levels, possibly due to the resumption of industrial operations and increased vehicular traffic post-pandemic. Spatial analysis indicates that the residential area (Site 3) consistently experiences the highest EF values, suggesting significant exposure of the local population to PM_{10} pollution. The commercial area (Site 2) follows closely, while the industrial area (Site 1) records comparatively lower EF values. This pattern may be due to the proximity of residential and commercial zones to pollution sources and higher population density, leading to increased emissions from domestic activities and vehicular traffic. The consistently high EF values at all sites highlight a serious public health issue. Long-term exposure to elevated PM_{10} levels is linked to respiratory and cardiovascular diseases, especially impacting vulnerable groups like children and the elderly. This data calls for immediate and ongoing actions to reduce pollution levels and safeguard public health.

Table 3: Exceedance factor (EF) and the pollution level for PM10, SO_2, and NO_2 pollutants in 2013–2024. L—low pollution; M—moderate pollution; C—critical pollution

Year	Exceedance Factor of PM_{10}				Exceedance Factor of SO_2				Exceedance Factor of NO_2			
	Site 1	Site 2	Site 3	Pollution Level	Site 1	Site 2	Site 3	Pollution Level	Site 1	Site 2	Site 3	Pollution Level
2013	4.17	10.00	13.33	C	0.18	0.18	0.18	L	0.83	0.85	0.83	M
2014	3.33	7.50	10.00	C	0.16	0.16	0.16	L	0.73	0.75	0.78	M
2015	3.67	7.83	10.83	C	0.16	0.18	0.16	L	0.78	0.80	0.83	M
2016	3.83	8.33	13.00	C	0.16	0.16	0.16	L	0.78	0.80	0.75	M
2017	3.50	8.50	12.50	C	0.16	0.16	0.18	L	0.80	0.83	0.85	M
2018	3.00	8.00	11.67	C	0.16	0.16	0.14	L	0.75	0.80	0.75	M
2019	2.67	7.50	11.33	C	0.14	0.12	0.12	L	0.68	0.70	0.70	M
2020	2.50	7.00	10.83	C	0.10	0.12	0.12	L	0.55	0.60	0.63	M
2021	4.17	10.00	13.33	C	0.14	0.12	0.12	L	0.68	0.63	0.65	M
2022	5.00	11.67	15.83	C	0.14	0.14	0.16	L	0.75	0.73	0.80	M
2023	5.83	13.33	17.50	C	0.20	0.22	0.20	L	0.93	0.93	0.90	M
2024	6.33	14.17	18.33	C	0.22	0.22	0.20	L	0.93	0.95	0.88	M
Standard = 60 µg/m3					**Standard = 50 µg/m3**				**Standard = 40 µg/m3**			

4.2 SO_2 Concentration

Sulfur dioxide (SO_2) is a significant atmospheric pollutant primarily emitted from the combustion of sulfur-containing fossil fuels, industrial processes, and vehicular emissions. Prolonged exposure to elevated SO_2 levels can lead to respiratory ailments, particularly among vulnerable populations such as children, the elderly, and individuals with pre-existing respiratory conditions.

Table 2: SO_2 pollutant levels for three locations from 2013 to 2024

Year	NAAQS SO_2 Limit (µg/m³)	Average Annual Concentration of SO2 (µg/m³)		
		Site 1	Site 2	Site 3
2013	50	9	9	9
2014	50	8	8	8
2015	50	8	9	8
2016	50	8	8	8
2017	50	8	8	9
2018	50	8	8	7
2019	50	7	6	6
2020	50	5	6	6
2021	50	7	6	6
2022	50	7	7	8
2023	50	10	11	10
2024	50	11	11	10

Source: UPPCB, 2024

4.2.1 Temporal Trends of Average Annual Concentration of SO_2: An analysis of the annual average SO_2 concentrations across three monitoring sites in Firozabad—designated as Site 1 (industrial area), Site 2 (commercial area), and Site 3 (residential area)—from 2013 to 2024 reveals that SO_2 levels remained consistently below the National Ambient Air Quality Standards (NAAQS) annual limit of 50 µg/m³ throughout the study period. The concentrations fluctuated within a narrow range, with values spanning from 5 µg/m³ to 11 µg/m³. From 2013 to 2020, a gradual decline in SO_2 levels is observed across all sites, with the lowest concentrations recorded in 2020—5 µg/m³ at Site 1 and 6 µg/m³ at Sites 2 and 3. This downward trend may be attributed to stricter emission controls, the adoption of cleaner technologies, and a temporary reduction in industrial activities during this period. However, a slight uptick in SO_2 concentrations is noted from 2021 onwards, culminating in the highest recorded levels in 2024—11 µg/m³ at Sites 1 and 2, and 10 µg/m³ at Site 3. Despite this increase, the concentrations remained well within the permissible limits set by the NAAQS, indicating effective management of SO_2 emissions in the region.

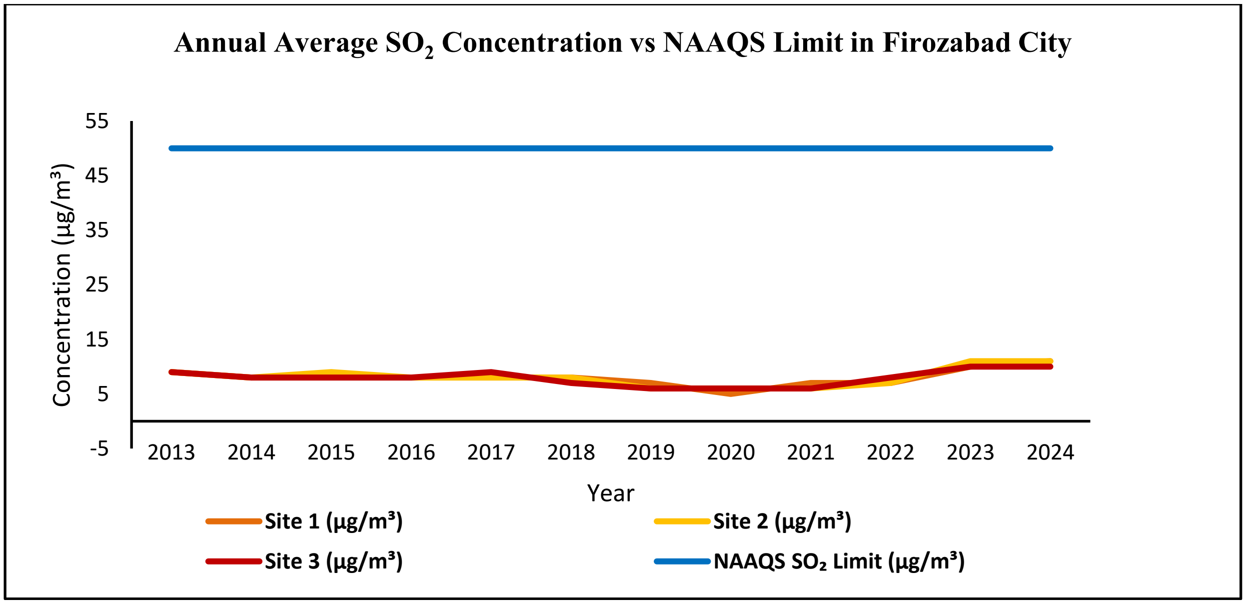

Figure 4: Annual Average SO2 Concentration vs NAAQS Limit in Firozabad City

4.2.2 Spatial Variations

Spatial analysis indicates minimal variation in SO_2 concentrations among the three sites. The industrial area (Site 1) consistently recorded marginally higher SO_2 levels compared to the commercial and residential areas, likely due to the proximity to emission sources such as manufacturing units and heavy vehicular traffic. Nevertheless, the differences are not substantial, suggesting a uniform distribution of SO_2 across the city. The sustained low levels of SO_2 in Firozabad indicate effective air quality management strategies and adherence to environmental regulations. Maintaining SO_2 concentrations within safe limits is crucial for safeguarding public health, as elevated SO_2 levels can exacerbate respiratory conditions and contribute to the formation of secondary pollutants like particulate matter and acid rain. Continued monitoring and proactive measures are essential to ensure that SO_2 levels remain within acceptable thresholds, especially in the face of potential industrial expansion and increasing vehicular emissions.

4.2.3 Trends of Exceedance Factor Analysis of SO_2

The analysis of the Exceedance Factor (EF) for SO_2 from 2013 to 2024 across the three monitoring sites — Site 1 (CDGI Industrial Area), Site 2 (Tilak Nagar Residential Area), and Site 3 (Raja Ka Taal Commercial Area) — reveals that sulfur dioxide pollution remained consistently low throughout the study period. Across all sites, the EF values remained well below the critical threshold of 0.5, indicating a "low pollution" category per CPCB (2016) guidelines. At Site 1, the industrial area, EF values hovered around 0.16–0.18 between 2013 and 2018, suggesting controlled emissions despite industrial activities. A slight dip was observed from 2019 to 2021, likely due to reduced industrial operations during the COVID-19 pandemic, followed by a moderate rise reaching 0.22 in 2024, possibly reflecting post-pandemic industrial recovery. Site 2, representing a residential area, showed a similar trend, with EF values around 0.16 initially, dropping to 0.12 during the pandemic years, and increasing to 0.22 by 2024, potentially due to higher vehicular usage and localized emissions. Site 3, the commercial area, maintained slightly lower EF values around 0.14–0.18 until 2018, dropped to 0.12 during 2019–2021, and rose to 0.20 by 2024, aligning with the revival of commercial activities. Overall, while sulfur dioxide levels across all three sites remained well within safe limits during the entire period, the slight upward trend after 2021 highlights the need for continued monitoring and proactive environmental management to sustain air quality amid ongoing urban and industrial development.

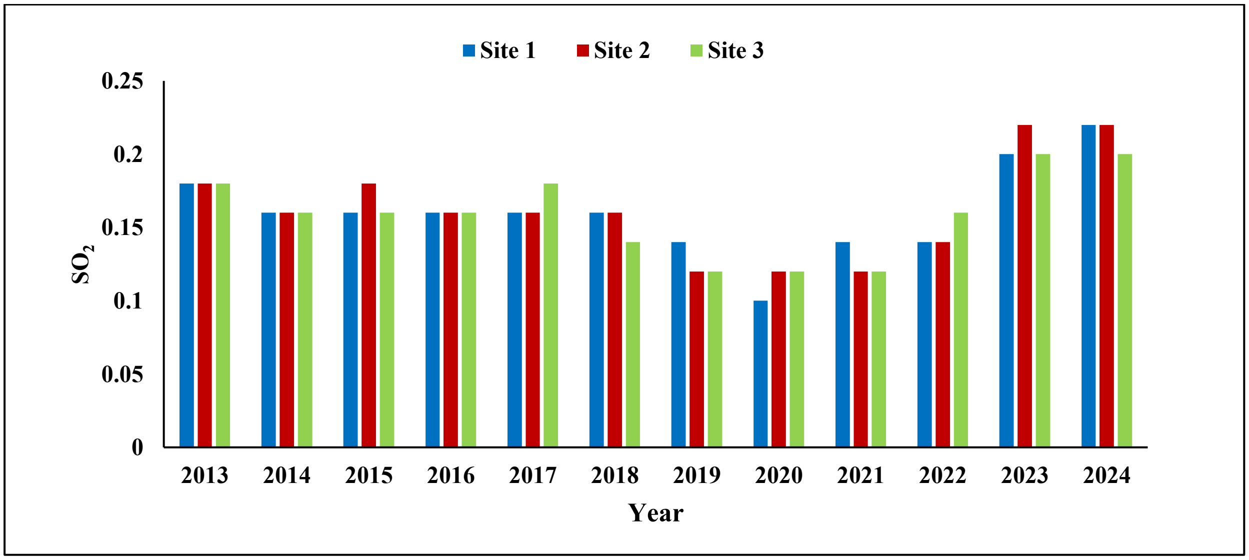

Figure 5: Exceedance factor graph for SO_2 pollutants in 2013–2024

4.3 Analysis of NO_2

Nitrogen dioxide (NO_2) is a significant atmospheric pollutant primarily produced through high-temperature combustion processes, including those from motor vehicles, industrial facilities, and power plants. It plays a crucial role in forming ground-level ozone and secondary particulate matter, substantially affecting air quality and public health. Exposure to elevated NO_2 levels can lead to respiratory issues, particularly in vulnerable populations such as children and the elderly.

In Firozabad city, known for its extensive glass industry and dense vehicular traffic, monitoring NO_2 levels is essential to assess air quality and implement appropriate mitigation strategies. According to data from 2013 to 2024, the annual average concentrations of NO_2 across three monitoring sites—industrial (Site 1), commercial (Site 2), and residential (Site 3)—have remained below the National Ambient Air Quality Standards (NAAQS) limit of 40 μg/m³. The concentrations fluctuated within a narrow range, with values spanning from 22 μg/m³ to 38 μg/m³.

Table 2: NO_2 pollutant levels for three locations from 2013 to 2024

Year	NAAQS NO_2 Limit (µg/m³)	Average Annual Concentration of NO2 (µg/m³)		
		Site 1	Site 2	Site 3
2013	40	33	34	33
2014	40	29	30	31
2015	40	31	32	33
2016	40	31	32	30
2017	40	32	33	34
2018	40	30	32	30
2019	40	27	28	28
2020	40	22	24	25
2021	40	27	25	26
2022	40	30	29	32
2023	40	37	37	36
2024	40	37	38	35

Source: UPPCB, 2024

A notable decline in NO_2 levels was observed in 2020, coinciding with reduced industrial activities and vehicular movements during the COVID-19 lockdowns. However, a gradual increase in concentrations has been recorded post-2020, likely due to the resumption of economic activities and increased traffic. Despite these fluctuations, the NO_2 levels have consistently remained within the permissible limits of the NAAQS. Continuous monitoring and implementation of emission control measures are imperative to maintain air quality and protect public health in Firozabad. Strategies may include promoting cleaner technologies in industries, enhancing public transportation, and enforcing stringent vehicular emission standards.

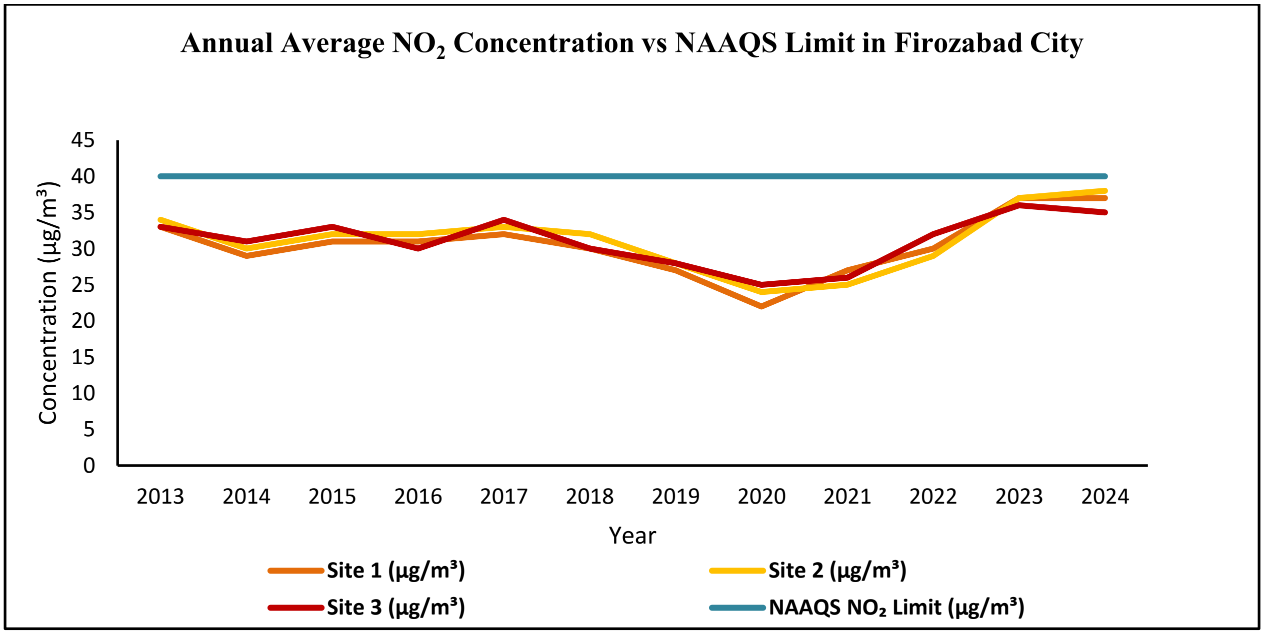

Figure 6: Annual Average NO_2 Concentration vs NAAQS Limit in Firozabad City

4.3.1 Trends of Exceedance Factor Analysis of NO_2

From 2013 to 2024, the Exceedance Factors (EF) for nitrogen dioxide (NO_2) in Firozabad City reveal distinct pollution trends across three different types of urban settings: the CDGI Industrial Area (Site 1), Tilak Nagar Residential Area (Site 2), and Raja ka Taal Commercial Area (Site 3). Each site reflects varying sources and scales of NO_2 emissions shaped by the area's dominant activities. At Site 1, located in the industrial zone of CDGI, NO_2 levels fluctuated moderately over the years, starting at 33 µg/m³ in 2013 (EF 0.825), dropping significantly to 22 µg/m³ in 2020 (EF 0.550) during the nationwide COVID-19 lockdowns when industrial activity was sharply curtailed. However, post-pandemic recovery saw NO_2 levels surge back to 37 µg/m³ by 2023 and remain at that level in 2024 (EF 0.925), approaching the regulatory threshold. This rebound points to the restoration of full-scale industrial production, suggesting that industrial air pollution could soon exceed safe limits unless emission control technologies are implemented.

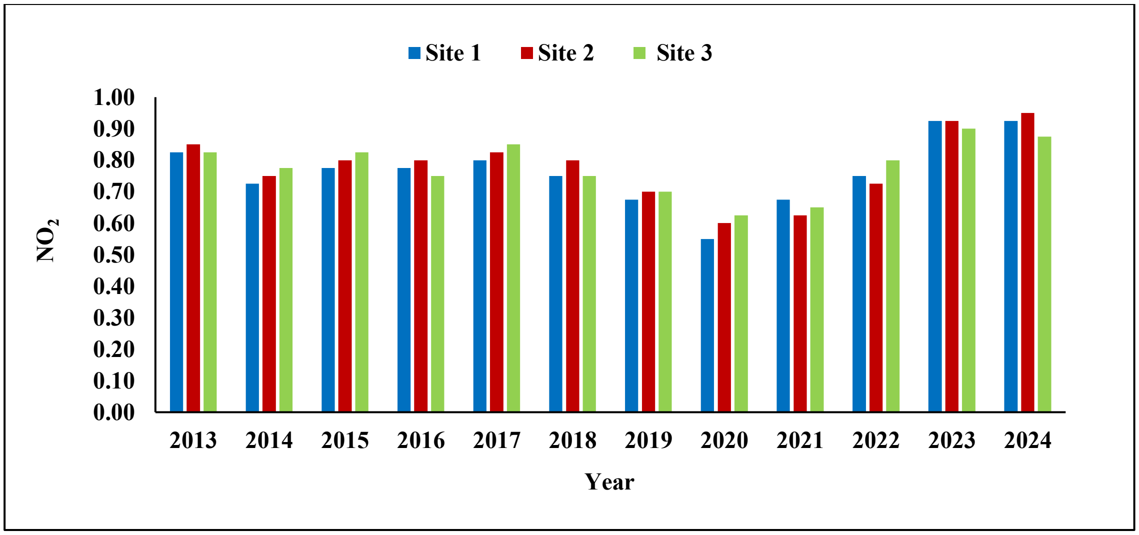

Figure 7: Exceedance factor graph for NO_2 pollutants in 2013–2024

In contrast, Site 2 in Tilak Nagar, a densely inhabited residential area, followed a similar but more concerning pattern. NO_2 concentrations fell from 34 µg/m³ in 2013 (EF 0.850) to 24 µg/m³ in 2020 (EF 0.600), reflecting reduced vehicular movement during lockdowns. However, by 2024, concentrations peaked at 38 µg/m³ (EF 0.950), the highest among all three sites. This increase is indicative of rising vehicle use, localized emissions from diesel generators, and potentially insufficient enforcement of clean energy policies in residential settings. The rise of the EF to nearly 1.0 in a residential area where vulnerable populations like children and the elderly live is particularly troubling and highlights the urgency for low-emission mobility options and household energy reforms.

Site 3, the commercial area of Raja ka Taal, displayed a more stable yet steadily rising pattern of NO_2 levels. Starting at 33 µg/m³ in 2013 (EF 0.825), the concentration decreased to 25 µg/m³ (EF 0.625) during the 2020 lockdown, with commercial activity at a standstill. However, NO_2 levels quickly rebounded as businesses reopened, reaching 36 µg/m³ in 2023 and slightly decreasing to 35 µg/m³ in 2024 (EF 0.875). The moderate rise here reflects continuous exposure from heavy commercial traffic, delivery vehicles, and fuel combustion in shops and eateries. While this site hasn't reached EF levels as high as Site 2, the persistently high values suggest that chronic exposure remains a risk without interventions like greener public transport and logistics solutions.

Collectively, all three sites illustrate a temporary dip in NO_2 levels during the 2020 lockdown, followed by a sharp and sustained rise in pollution from 2021 onwards. This pattern clearly shows that despite short-term improvements, NO_2 pollution in Firozabad is nearing critical levels again, especially in residential and industrial areas. It is important to note that Firozabad was ranked first in India's Clean Air Survey 2024 among cities with populations between 3 and 10 lakhs, as part of the National Clean Air Programme (NCAP), recognising efforts like mechanised road sweeping, traffic decongestion, and public awareness drives (Bhaskar, 2024). Still, the EF data indicate that despite these achievements, more comprehensive, site-specific interventions are essential. The local municipal body has now set a target to bring the average AQI down to 80 (Times of India, 2024), and achieving this will require sustained regulatory enforcement, adoption of cleaner technologies, and greater community involvement, especially in managing vehicular and industrial emissions.

CONCLUSION

This longitudinal study provides a detailed spatio-temporal analysis of ambient air pollution in Firozabad city, highlighting the critical levels of PM_{10} and the emerging concerns related to NO_2 concentrations. The persistent exceedance of PM_{10} levels across all monitoring sites, especially in residential areas, underscores the severe impact of industrial emissions, vehicular traffic, and inadequate urban planning on air quality. The relatively stable SO_2 levels suggest that existing control measures have been somewhat effective for this pollutant. However, the post-2020 surge in NO_2 concentrations, nearing the NAAQS limit, indicates a need for renewed focus on controlling vehicular and industrial emissions. The Exceedance Factor methodology has proven effective in categorising pollution severity and identifying critical hotspots, facilitating targeted interventions. The study's findings emphasize the necessity for integrated air quality management strategies encompassing technological upgrades in industries, promoting sustainable transportation, and community engagement to improve air quality significantly. Furthermore, the research highlights the importance of continuous monitoring and data-driven policymaking to address the dynamic nature of urban air pollution.

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