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Change in the Concentration of Pollutants in the Air over the City of Lucknow, Together with HYSPLIT4.0's Trajectory and Dispersion Analysis

Vipin Kumar^a, and Prabhat Kumar Patel^{*b}

^{a,b}Civil Engineering Department, Institute of Engineering and Technology Lucknow, Lucknow- 226021, Uttar Pradesh, India

^{*}Corresponding author: Dr. Prabhat Kumar Patel; Email: p Prabhat1991@gmail.com

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Abstract: This study examines the mean daily concentrations of oxides of carbon (CO), sulphur dioxide (SO₂), nitrogen dioxide (NO₂), and respirable suspended particles (RSPM-PM₁₀) at seven monitoring stations in Lucknow city: Hazratganj, Gomti Nagar, Talkatora, Aliganj, Sarai Mali Khan, Mahanagar, and Ansal TC. The data is collected between 2016 and 2022. Based on the analysis, it can be observed that at all locations, the yearly average concentration of RSPM varies between 148.74 and 323.05 $\mu\text{g m}^{-3}$, SO₂ between 7.11 and 8.94 $\mu\text{g m}^{-3}$, NO₂ between 23.52 and 31.86 $\mu\text{g m}^{-3}$, and CO between 27.38 and 33.89 $\mu\text{g m}^{-3}$. The study of seasonal variation reveals that the lowest recorded concentration of RSPM was 81.59 $\mu\text{g m}^{-3}$ during the monsoon, while the highest recorded concentration was 447.47 $\mu\text{g m}^{-3}$ during the post-monsoon. On the other hand, seasonal variations in SO₂ and NO₂ were found to be below the recommended requirements, ranging from 5.55 to 10.94 $\mu\text{g m}^{-3}$ and 20.23 to 38.40 $\mu\text{g m}^{-3}$, respectively. The COVID-19 lockout in 2020 caused the pollution level to somewhat decline, but it did not fall below the recommended limit for CO and RSPM. The Indian government has banned factories and implemented various measures within the city, but the levels of CO and PM₁₀ in Lucknow are not decreasing. The Trajectory and Dispersion study of the HYSPLIT4.0 model indicates that the wind, which blows from the northwest, carries pollutants from close by areas to maintain daily pollution levels above the Central Pollution Control Board's guidelines (i.e., 100 $\mu\text{g m}^{-3}$). This suggests that there is insufficient local pollution control. The results suggest that controlling particulate matter and carbon monoxide pollution in the city is a serious challenge and has an alarming situation as compared to SO₂ and NO₂ pollutants.

Keywords: HYSPLIT4.0; Vehicular emission; PM_{2.5}; SO₂; NO₂; CO; Lucknow

I. INTRODUCTION

One of the primary challenges is air pollution, especially in nations like India where environmental issues constantly coexist with fast development. Just consider for a moment that the daily activities we perform are threatening the air we breathe, which is essential for every life on earth. The air quality has been degraded by the rapid growth in population, industrial activity, vehicular emissions, and unsustainable agricultural practices (Patel et al. 2023). Pollutant emissions from this degradation include PM_{2.5} and PM₁₀, SO₂, NO₂, and CO. Directly generated from sources like industrial facilities and vehicles, these air pollutants severely threaten the health of those who are exposed to them either any individuals or the environment, and worsen the quality of the air (Patel et al.

2024). Particulate matter and gaseous pollutants are the two most important airborne contaminants (Gupta et al. 2023).

Air pollution is a severe problem with the environment that has an impact on people's quality of life, the state of the environment, and overall wellness. One of the primary causes of air pollution is vehicle emissions, particularly in cities where traffic congestion is a daily occurrence. When fossil fuels are used in automobiles, a complex cocktail of pollutants is released, such as particulates (PM), nitrogen oxides (NO_x), sulfur oxides (SO_x), the gas carbon monoxide (CO), and other hazardous pollutants. These substances cause major threats to both human health and the environment (Singh et al.).

A fast-growing nation like India in present time confronted with the problems of outdoor as well as indoor air pollution. The research conducted by highlighted that in India like country addressing air pollution is more important and also a big challenge to the government and other stakeholders. In the study conducted by, the increase in pollutant concentration in the atmosphere is influenced by various meteorological variables which consist of precipitation, humidity, wind speed, and temperature. Global urbanization and industrialization without a doubt have accelerated to an extreme level which continuously leads to the increase in pollutant concentration in the atmosphere. (Ilarri et al. 2022).

In Indian cities indicate several major sources of air pollution in urban area including road and soil dust, open burning, construction and industrial activities. As of March 31, 2020, there were 34,24,478 car orders registered with the Regional Transport Office (RTO) in Lucknow, which represents a 13.35 gain over the previous period. On some of Lucknow City's roads, the Uttar Pradesh State Road Transport Corporation (UPSRTC) launched machine services under the name "Lucknow Mahanagar Parivahan Sewa." (Biramo and Mekonnen 2022; Kovács et al. 2021). There is a major route close to Hazarat Ganj, Mahanagar, Talkatora, Aliganj, Sarai Malikhan, ATC, and Gomti Nagar that sees a lot more traffic than other roads do year-round. A regulatory framework is required for the management of traffic, air quality, and emissions at the local, regional, and national levels due to the negative consequences of increasing pollution and traffic on public health and urban air quality (Rodriguez-Rey et al. 2021). Constant exposure to vehicle exhaust fumes can cause lower respiratory tract symptoms such as coughing, dyspnea, and inspiratory pain (Vipin Kumar et al. 2024).

Furthermore, real-time data or information on certain vehicle types and emission parameters could not be available using these approaches. One area of concern is the composition of the air quality due to changes in technology and the usage of different fuels. There has long been research on the relationship between death rate and particle air pollution, although many studies may be constrained by the absence of controls for confounding factors (Saini et al.) Numerous scientific investigations are underway in India as well as other regions of the world. Nearly all major cities, including Lucknow, are polluted, according to studies. Certain criterion pollutants, particularly PM_{10} , exceed the allowed level as outlined in the regulations. There may be a link between vehicle emissions and a rise in respiratory ailments, according to recent research (Singh et al. 2016a).

The complex blend of chemical agents with varying sizes and forms that make up tiny particulate matter. Research shows that, in addition to PM's quantity and mass concentration, the impact of tiny particulate matter on human health will also rely on its chemical makeup. Both groups have the potential to raise population mortality and morbidity at high levels. It is well known that SO_2 has an impact on both ecosystems and human health. At high concentrations, SO_2 can exacerbate pre-existing heart and lung conditions and cause respiratory illnesses, especially in children and the elderly. Understanding the levels

of air quality both today and in the future is crucial for assessment studies. The aforementioned restriction is circumvented by statistical distributional models that are "non-causal" and rely on historical data. and calculate the 'extreme' concentrations with logical precision (Chen et al. 2022).

Consequently, air pollution causes several issues for health, some of which may be caused by a combination of various pollutants rather than a single pollutant. Particulate matter is one of these pollutants; it is generated by a variety of indoor and outdoor activities and contributes to diseases such as neoplastic, cardiovascular, respiratory, autoimmune, etc. Other pollutants that are harmful to both the environment and human health include NO_2 , which is produced when fuels like diesel and petrol used in cars burn. When these fuels burn, minute particles smaller than 10 micrometers go out into the air, which may significantly affect people (Wang et al. 2017). The atmosphere's quality is affected by meteorological factors such as temperature, humidity, wind speed, and sun radiation (Fabregat et al. 2022).

As particle matter is absorbed by drops of rain, rainfall contributes to a lower pollution level. According to various reports, $PM_{2.5}$ pollution is accountable for 6.4 million lives lost and 0.8 million premature deaths worldwide each year. Additionally, magnetic minerals may be present in a sample of particulate matter. About 5 and 15 % of urban air PM is composed of iron oxides and hydroxides, which make up the remaining 10 to seventy percent of the bulk iron content. Magnetite was the most common mineral in the particle components (Saini et al. n.d.).

The objective of this study is to assess Air Quality, Identification of Pollutants, Quantification of Emissions, and seasonal variation of air pollutants, HYSPLIT4.0 is used to analyse the trajectory frequencies of air mass particles over four seasons.

In eastern India, changes in the particulate matter concentration have been found by air trajectories. Rising levels may occur via transportation from origins, as evidenced by findings in Africa, Australia, Asia, the Middle East, North America, South America, and Europe. Table 1 presents the research that is taken to be considered about the Indian environment (Saini et al. n.d.).

II. MATERIALS AND METHODS

Study Area

Uttar Pradesh's capital and largest megacity is Lucknow, which comes in third behind Delhi and Kolkata. Among the megacities in North, East, and Central India, it comes in third place. Situated around 123 meters above sea level, the area spans 2,528 square km. The humid tropical weather of Lucknow has four distinct seasons: summer, post-monsoon, thunderstorms, and idle time. Major cities including Raebareli, Unnao, Barabanki, Kanpur, Sitapur, and Farrukhabad are located in the vicinity of Lucknow. Seven monitoring stations are located in the megacity by the UPPCB:

TABLE 1
Studies from many research about the concentration of pollutants

Study area	Pollutants type	Technique used	Key observation	References
5 Indian rural sites	PM _{2.5} aerosol optical depth	Temporal fluctuation and association	Increment of AOD due to urbanization and transportation	Gautam et al; 2022
Delhi, Lucknow, Nagpur, Kanpur, Chennai (East India)	PM ₁₀ , Black carbon PM _{2.5}	Back paths with daily fluctuations	Black carbon increases with the increases in PM _{2.5} concentration	Chelani et al; 2022
Karunya Nagar (Tamil Nadu)	PM ₁₀ , CO ₂ PM _{2.5} formaldehyde	CHAID decision tree 3D visualization statistical technique	Indian cities have higher concentrations than those in other nations because location and metrology have a greater impact on concentration than height above the surface.	Gautam et al;2021
Nagpur	PM ₁₀ , SO ₂ , NO ₂	Annual variation	Due to COVID-19, the concentration of the contaminant was reduced.	Saini et al;2021
Lucknow	CO ₂ , CO, PM NO ₂ ,	Variation and correlation throughout a year	Emission permissible limits	Ambade et al;2021

Hazratganj, Mahanagar, Aliganj, Sarai Mali Khan, Ansal TC, Gomti Nagar, and Talkatora. The largest populated location and main source of pollution is Hazratganj; the Talkatora industrial sector also contributes to air pollution. The study area is shown in the Fig.1.

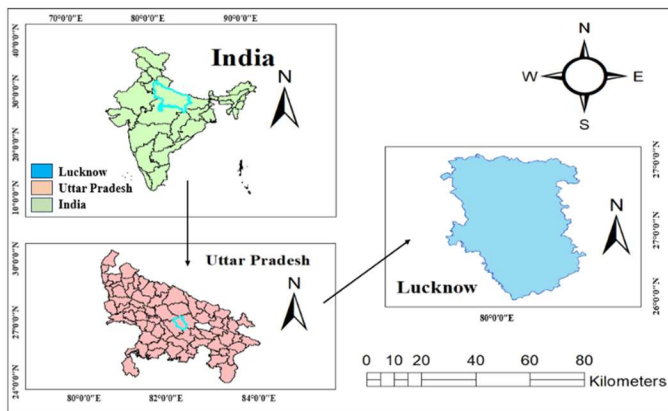


Fig.1 Lucknow city study area map with all seven monitoring locations.

The UPPCB website provided the RSPM, SO₂, NO₂, and CO data utilized in this study, while the Indian Meteorological Department provided the meteorological parameters.

Monitoring Scheme: The CPCB has ordered that the daily average of PM₁₀, SO₂, NO₂, and CO at all seven monitoring sites be based on the SAMP for monitoring. Control Panel. Gravimetric analysis is used to estimate the particle issue RSPM. For a full day, eight hours a day, at a flow rate of 0.8 to 1.3 m³/min, experienced air was run through a fiberglass filter. With its protective enclosure, blower, voltage regulator, time collector, Rota meter, and filter holder, the High-Volume Sampler (HVS) is equipped to remove dust from a 20.3 x 25.4 cm fiberglass filter, which is a cyclone separator that uses centrifugal force (An et al. 2022).

HYSPLIT4.0

The National Oceanic and Atmospheric Administration created Hybrid Single Particle Lagrangian Integrated Orbits. It

is frequently used to mimic the flow of contaminants like exhaust from moving cars. Researchers may analyze vehicle emissions breakdown patterns using HYSPLIT to learn more about how emissions from vehicles affect the environment, human health, and air quality. Researchers may predict the dispersion of vehicle-emitted pollutants across time and space by gaining access to data on emission rates, vehicle types, weather, and topographical features. Urban planning, public health initiatives, and policymaking that try to lower air pollution all benefit from this knowledge. In this investigation, discrete runs were also conducted using GDAS 1 data (Sánchez et al. 2021b). With a top swing, this model permits sawing speed. of 0.1 cm/s. at 50 m AGL and bottom swing at 0 m AGL. It assumes a 1-hour unit size oscillation at 12 UTC of the day and an estimated 24-hour back diffusion with a mean period of 6 hours and an average layer above 100 m AGL. In this study, the online version HYSPLIT4.0 was used for trajectory and diffusion studies(Singh et al. 2016).

Orbit : Numerous orbital models have been created to study atmospheric motion. They can examine the oscillations of air. This work made use of the NOAA Hybrid Single Particle Lagrangian Integrated Trajectories (HYSPLIT4.0) model. Online at (http://www.arl.noaa.gov/HYSPLIT_info.php.) the model is accessible (Goel and Guttikunda 2015). The model is used to calculate the initial position of the air returned from the receiving site at the start of the sampling period. Using the HYSPLIT4.0 model, a four-season continuous survey of Lucknow city was conducted to examine aerosol routes from different places up to 500 meters above ground level (Kovács et al. 2021b). Long-range transmission of aerosols from various sources over 6 hours was studied. 48-hour mass isentropic back trajectories in Lucknow were computed in the investigation of long-term transport of aerosols from various places, at 6-hour intervals (Sadiq et al. 2016). The RSPM allowable value recommended by the Central Pollution Control Board is 100 (µg-m⁻³).

Table 2 shows annual averages concentration of air pollutants in different areas, such as commercial, residential, industrial over a study period. An air pollution's annual average

concentration is the mean concentration of different dangerous compounds in the atmosphere over a specific period of time, usually a year. Particulate matter, carbon monoxide, nitrogen dioxide, and sulphur dioxide represent a few types of these contaminants. Monitoring air quality and any potential risks to people depends on the monitoring and reporting of these concentrations. In order to safeguard the environment and public health, regulatory authorities and environmental agencies frequently develop standards or guidelines for acceptable concentrations of particular contaminants. The actual average concentrations may vary significantly based on a number of variables, including geographic features, traffic density, industrial activity, location (rural vs. urban), and weather patterns. For the purpose of to track these concentrations and give information to the public, academics, and policymakers, monitoring stations and air quality indices are helpful (Kumar et al. 2020b).

III. RESULTS AND DISCUSSION

In the following sections, average concentration variations with PM₁₀, SO₂, NO₂, and CO has been evaluated and discussed:

Annual average concentration: Fig.2(a) displays the yearly average PM₁₀ concentration over Lucknow City. At every monitoring site between 2016 and 2022, there is a significant amount of fluctuation. Hazratganj (323.05 $\mu\text{g}\cdot\text{m}^{-3}$) station had the highest yearly average concentration of any station in 2017 because of its high population density and substantial traffic problems. Hazratganj is a business neighborhood. Conversely, Ansal TC displayed varying attention during the study period, presumably as a result of the institution's annual holidays on certain days. Due to the Covid lockdown, several anthropogenic activities were shut down in 2020. As a result, Sarai Mali Khan and Gomti Nagar showed a gradual increase until 2017, with a peak concentration of 243.25 and 233.55 $\mu\text{g}\cdot\text{m}^{-3}$ in 2017, respectively, and a variation of 163.56 and 158.96 $\mu\text{g}\cdot\text{m}^{-3}$ respectively till 2022.

In 2020, the residential areas of Aliganj and Mahanagar exhibited a minimum concentration of 118.34 and 153.52 $\mu\text{g}\cdot\text{m}^{-3}$, respectively. Due to the COVID-19 pandemic-related lockdown, there were also fewer anthropogenic activities and vehicle movements in the region, which contributed to the fall in concentrations. Throughout the investigation, it was found that the Talkatora and Sarai Mali Khan stations had the highest yearly average concentration of SO₂ [Fig.2(b)]. It may be the result of the area's heavy usage of fossil fuels, such as coal and oil. The industrial Talkatora station has the highest concentration in 2022 8.88 $\mu\text{g}\cdot\text{m}^{-3}$, while the commercial Ansal TC station displays the lowest concentration 8.40 $\mu\text{g}\cdot\text{m}^{-3}$ in 2019 due to the closure of the institutional sector during the Covid shutdown. Because they have the highest population density relative to other commercial areas, residential neighbourhoods like Mahanagar and Aliganj also exhibit a notable concentration of SO₂. [Fig.2(c)] illustrates the annual fluctuation of NO₂, which abruptly decreased in 2019 as a result of the COVID-19 lockdown and continued to rise until 2022. The stations in Talkatora (an industrial region) and Hazratganj (a commercial district) have the highest concentrations due to the highest levels of traffic congestion, whereas Aliganj displays the lowest concentration surge (2022). The commercial areas of Ansal TC, Gomti Nagar, and Sarai Mali Khan exhibit an average increase in NO₂ concentration. Annual variation of CO shows [Fig.2(d)] Talkatora (industrial), Hazratganj (commercial) and Ansal TC, (commercial) stations account for maximum concentrations of 33.67,30.69,31.87 $\mu\text{g}\cdot\text{m}^{-3}$ respectively. While Aliganj and Mahanagar, which are mainly residential areas, see only a small leap in concentration, those regions have the highest levels of traffic congestion(Huangfu and Atkinson 2020). The commercial zones, Sarai Mali Khan, and Gomti Nagar show an average increase in CO concentration.

Seasonal variation: At each of the seven monitoring stations, the seasonal fluctuation in the pollutants' concentrations has been examined. Winter (December to February) and Summer are the seasons taken into consideration (March to June), post-monsoon (October to November), and Monsoon (June to September).

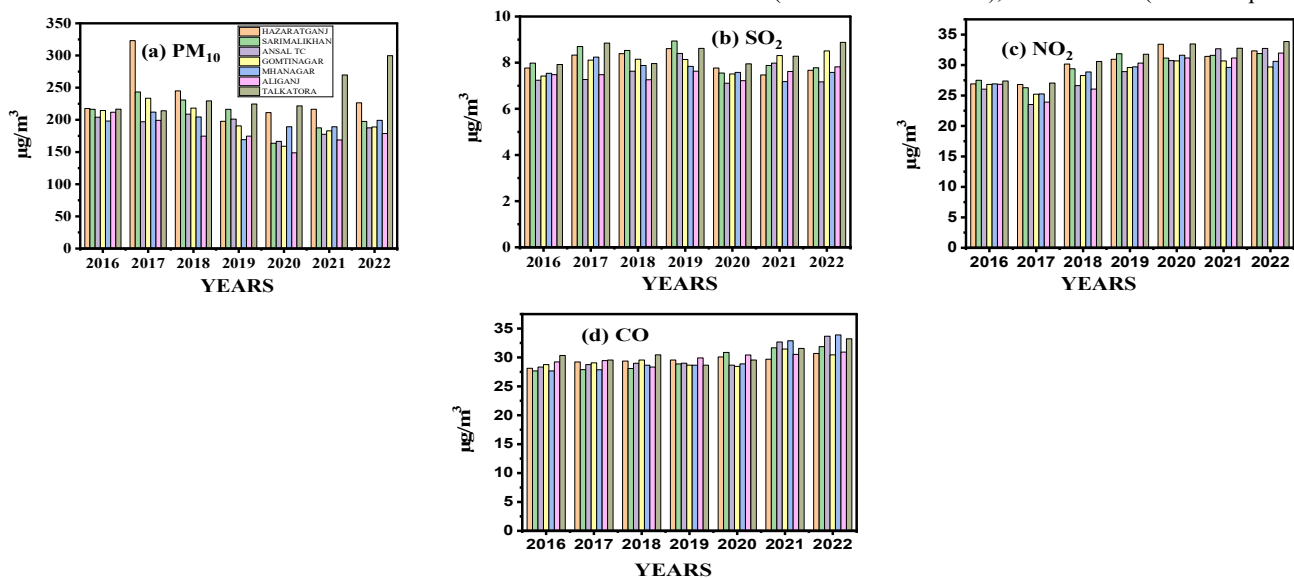


Fig.2 Pollutant yearly Mean Concentration (in $\mu\text{g}\cdot\text{m}^{-3}$) (a) PM₁₀, (b) SO₂ (c) NO₂, and (d) CO Over the research period of 2016–2022 at all monitoring stations.

TABLE 2
Pollutant yearly Mean Concentration (in $\mu\text{g m}^{-3}$) PM_{10} , SO_2 , NO_2 , and CO at all seven monitoring Stations
(i.e. Industrial, Residential, Commercial, area)

STATION	CONCENTRATION ($\mu\text{g m}^{-3}$) (ANNUAL AVERAGE)							
	YEARS	2016	2017	2018	2019	2020	2021	2022
HAZRATGANJ (COMMERCIAL)	PM_{10}	217.68	323.05	244.95	197.76	211.21	216.45	226.45
	SO_2	7.77	8.33	8.39	8.61	7.77	7.47	7.67
	NO_2	26.91	26.81	30.16	30.95	33.42	31.32	32.32
	CO	28.12	29.22	29.38	29.56	30.09	29.69	30.69
SARAI MALI KHAN (COMMERCIAL)	PM_{10}	216.33	243.25	230.86	216.38	163.56	187.56	197.56
	SO_2	7.98	8.70	8.53	8.94	7.55	7.88	7.78
	NO_2	27.50	26.28	29.30	31.86	31.15	31.59	31.89
	CO	27.67	27.89	28.09	28.88	30.87	31.67	31.87
ANSAL T.C. (COMMERCIAL)	PM_{10}	204.13	197.09	208.84	201.09	166.61	177.61	187.61
	SO_2	7.24	7.27	7.63	8.40	7.11	7.98	7.17
	NO_2	26.05	23.52	26.62	28.92	30.73	32.53	32.73
	CO	28.34	28.76	28.99	29	28.67	32.67	33.67
GOMTI NAGAR (COMMERCIAL)	PM_{10}	214.50	233.55	218.22	190.02	158.96	182.96	188.96
	SO_2	7.42	8.11	8.15	8.14	7.51	8.31	8.51
	NO_2	26.82	25.22	28.27	29.59	30.68	30.68	29.68
	CO	28.76	29.07	29.56	28.67	28.45	31.45	30.45
MAHANAGAR (RESIDENTIAL)	PM_{10}	198.13	212.06	204.50	169.28	189.26	189.26	199.26
	SO_2	7.54	8.24	7.88	7.84	7.58	7.18	7.58
	NO_2	26.91	25.26	28.87	29.70	31.61	29.61	30.61
	CO	27.67	27.87	28.65	28.66	28.89	32.89	33.89
ALIGANJ (RESIDENTIAL)	PM_{10}	211.87	199.28	174.73	174.75	148.74	168.74	178.74
	SO_2	7.48	7.48	7.26	7.63	7.22	7.62	7.82
	NO_2	26.84	23.92	26.06	30.32	31.16	31.36	31.96
	CO	29.23	29.45	28.34	29.92	30.43	30.53	30.93
TALKATORA (INDUSTRIAL)	PM_{10}	216.59	214.07	229.43	224.60	221.73	269.73	299.73
	SO_2	7.92	8.85	7.96	8.62	7.95	8.28	8.88
	NO_2	27.38	27.04	30.59	31.77	33.46	32.76	33.86
	CO	30.34	29.56	30.45	28.67	29.56	31.56	33.23

Variation in PM₁₀ : Fig.3 shows the seasonal variation of PM₁₀ concentration ($\mu\text{g m}^{-3}$) and shows discernible changes during the research period. The post-monsoon season at Hazratganj station Fig.3(a) has the greatest PM₁₀ concentration, with winter, summer, and monsoon following suit. The CPCB threshold of $100 \mu\text{g m}^{-3}$ was exceeded by the maximum concentration of $447.46 \mu\text{g m}^{-3}$ for the post-monsoon of 2017 and the minimum concentration of $114.30 \mu\text{g m}^{-3}$ for the monsoon of 2016 (Chaurasia et al. 2018). Similar to this, the post-monsoon and winter values at Sarai Mali Khan, Gomti Nagar, and Talkatora [Fig.3(b), Fig.3(d), and Fig.3(g)] are

nearly higher than those of the other two seasons. Elevated measurements during the post-monsoon and winter seasons may be attributed to the existence of locally generated and transported contaminants, in addition to the maintenance of stable conditions throughout the area during that period. Furthermore, a region-wide temperature inversion may occur, intensifying the pollutants and increasing their concentration over the research area. During the monsoon season, rainfall lowers the concentration, allowing pollutants to disperse throughout the region.

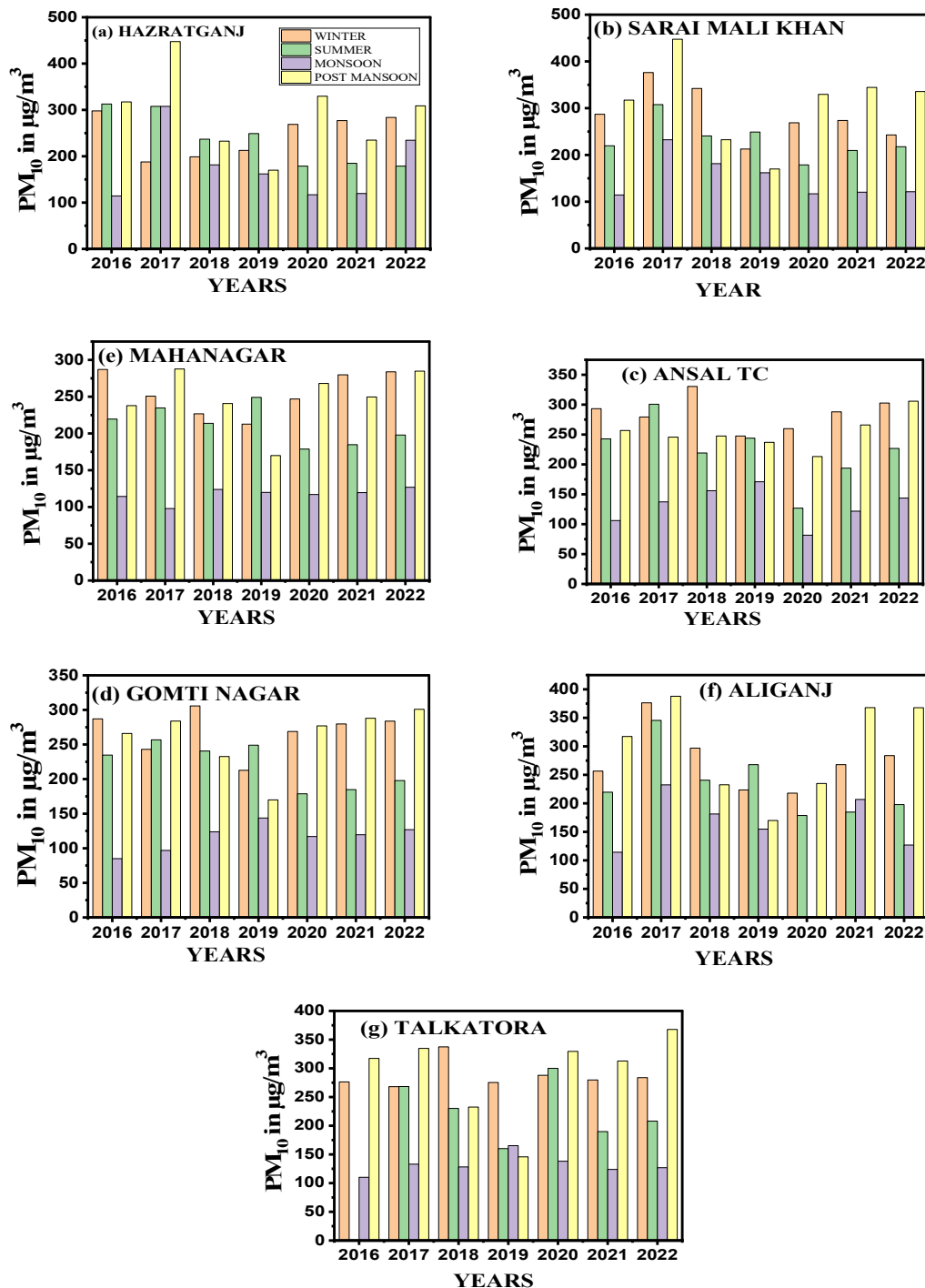


Fig.3 PM₁₀ seasonal variation graphs (, monsoon, and post-monsoon, winter, summer) for the study period of 2016–2022 at all monitoring stations.

SO₂ variation : The concentration is below the 80 $\mu\text{g m}^{-3}$ recommended limits set by the Central Pollution Control Board, as indicated by the horizontal lines in Fig.4 and the seasonal variation of SO₂ depicted. The concentrations at Stations Hazratganj [Fig.4(a)] and Sarai Mali Khan [Fig.4(b)] during the post-monsoon season in 2017 peaked at 10.92 $\mu\text{g m}^{-3}$ and 10.97 $\mu\text{g m}^{-3}$, respectively. On the other hand, Gomti Nagar [Fig.4(d)] displays the highest concentration during the winter of 2016 of 10.09 $\mu\text{g m}^{-3}$, whereas Ansal TC [Fig.4(c)] has a highest concentration of 11.40 $\mu\text{g m}^{-3}$ during the post-monsoon of 2019. In the winter of 2016, the maximum SO₂ concentrations at

Mahanagar [Fig.4(e)] and Aliganj [Fig.4(f)] were 10.09 $\mu\text{g m}^{-3}$ and 10.84 $\mu\text{g m}^{-3}$, respectively, however they were lower. focus on other stations. In the post-monsoon season of 2017, Talkatora [Fig.4(g)] had a maximum of 11.06 $\mu\text{g m}^{-3}$. The usage of biomass as a residential fuel in cities may be the source of the elevated SO₂ concentrations observed in the winter and post-monsoon seasons. Significantly more SO₂ is produced at night as a result of the city burning biomass to fight the bitter cold. Similar to the commercial sector, the SO₂ content is higher there, most likely as a result of excessive biomass burning.

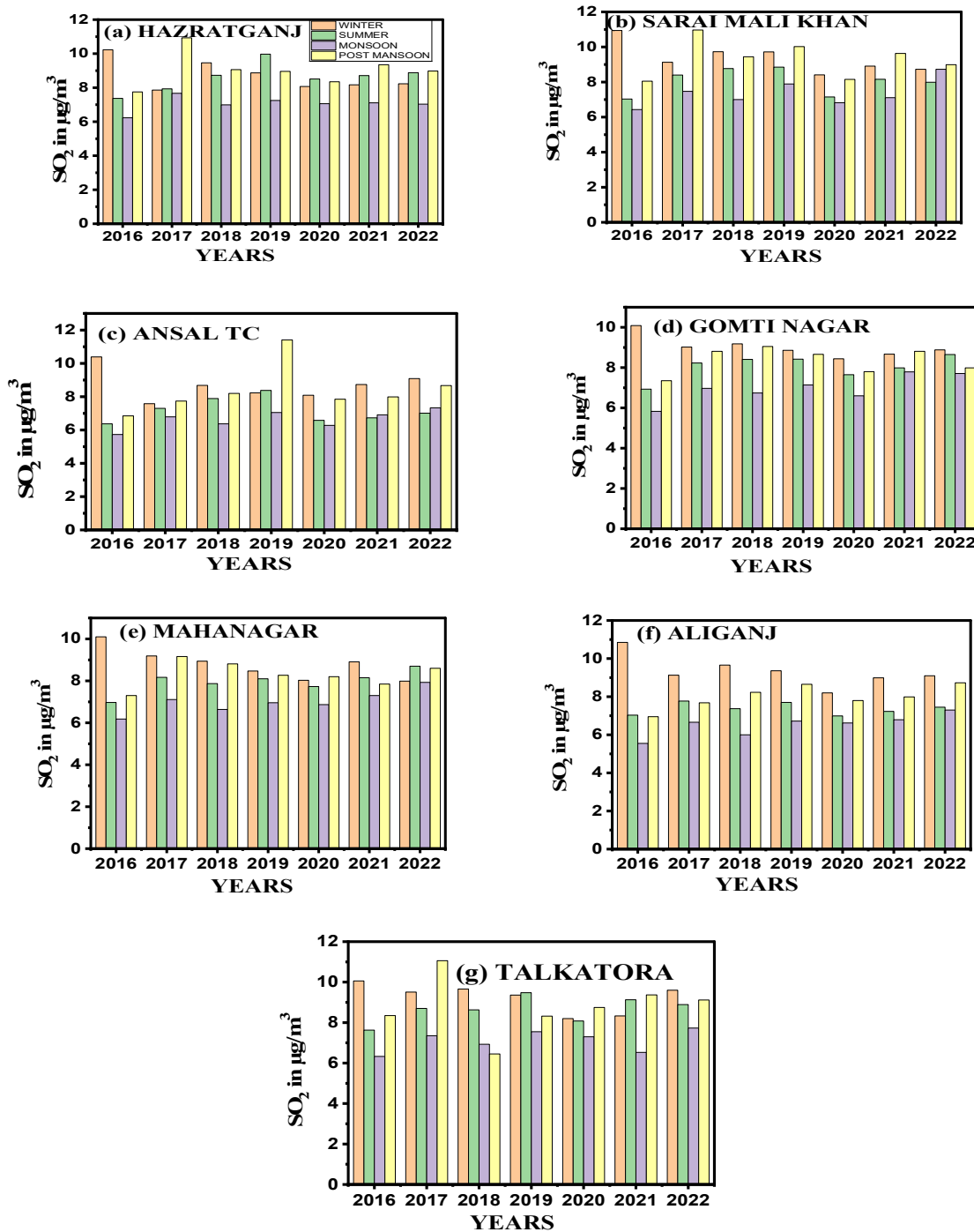


Fig.4 SO₂ seasonal variation graphs (monsoon, and post-monsoon, winter, summer,) for the study period of 2016–2022 at all monitoring stations.

NO₂ variation : The seasonal change in NO₂ concentration is seen in Fig.5. The NO₂ concentrations at Talkatora and Hazratganj and [Fig.5(g), Fig.6(a)] show a progressive increase during almost every season, peaking at 38.40 and 37.20 $\mu\text{g m}^{-3}$ in the post-monsoon of 2022. Sarai Mali Khan and Ansal TC [Fig.5(b), Fig.5(c)] show almost the same variation throughout the study; their highest concentrations were 35.00 $\mu\text{g m}^{-3}$ during the winter of 2019 and 34.40 $\mu\text{g m}^{-3}$ during the post-monsoon

of 2020, respectively. The summer of 2019 is when Gomti Nagar [Fig.5(d)] reaches its highest concentration of 33.33 $\mu\text{g m}^{-3}$. Peak concentrations were recorded in Mahanagar and Aliganj [Fig.5(e), Fig.5(f)] during the post-monsoon of 2020 and the winter of 2019, respectively, at 34.90 and 35.40 $\mu\text{g m}^{-3}$. In comparison to other commercial and residential monitoring locations, there might be less vehicle traffic on this industrial site.

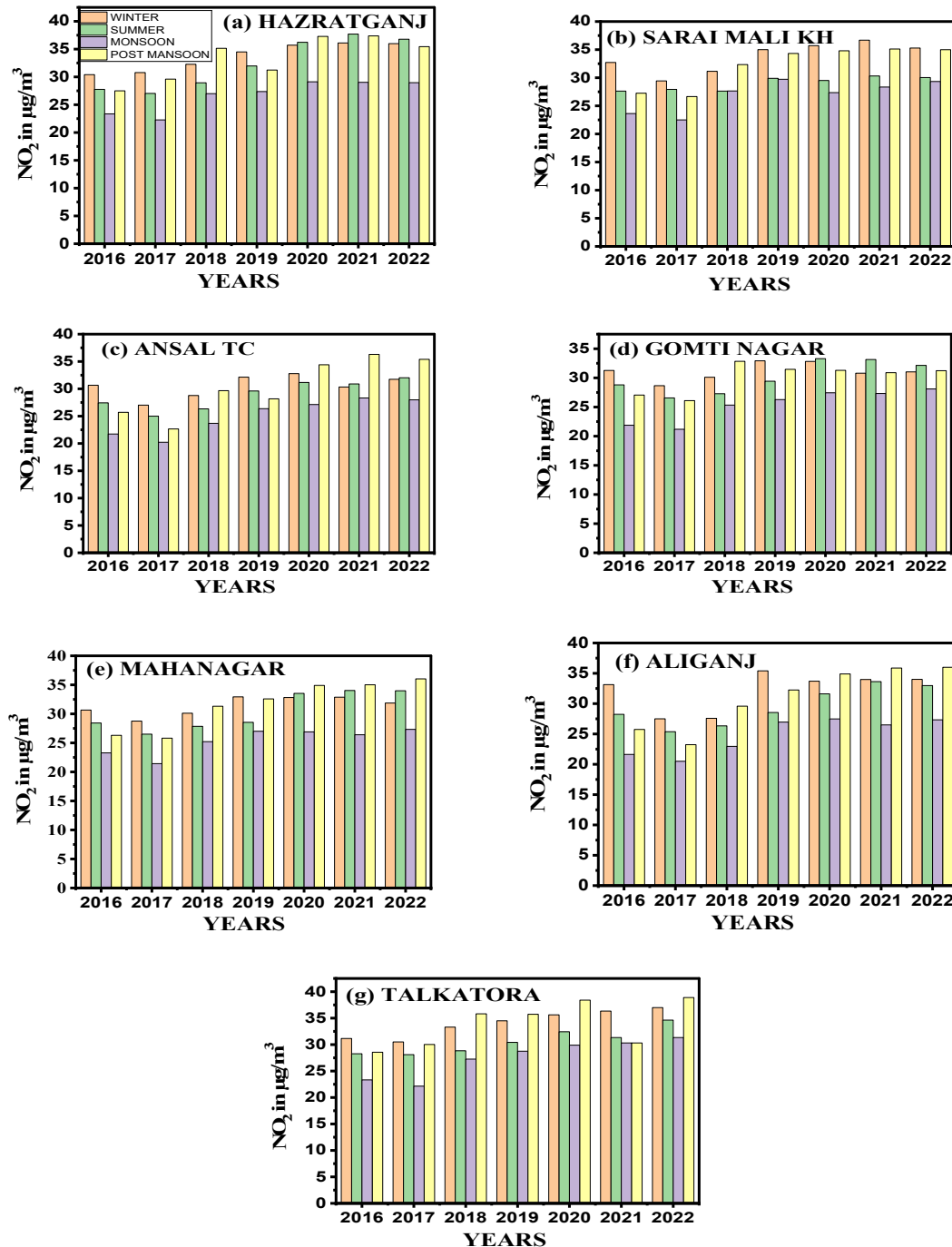


Fig.5 NO₂ seasonal variation graphs (monsoon, and post-monsoon, winter, summer) for the study period of 2016–2022 at all monitoring stations.

CO variation

shows how the concentration of CO varies with the season. The CO concentrations in Hazratganj and Talkatora [Fig. 6(a), Fig.6(g)] show a progressive increase across almost every season, peaking at 37.71 and 37.0 $\mu\text{g m}^{-3}$ during the post-monsoon in 2022. Ansal TC and Sarai Mali Khan [Fig.6(c), Fig.6(b)] show almost the same variation throughout the study; their peak concentrations were 37.67 during the winter of 2022

and 36.30 $\mu\text{g m}^{-3}$ during the post-monsoon of 2022, respectively. Gomti Nagar [Fig.6(d)] gets its peak concentration of 34.45 $\mu\text{g m}^{-3}$ in the summer of 2017. Peak concentrations were measured at 36.03 and 36.00 $\mu\text{g m}^{-3}$ in Mahanagar and Aliganj [Fig.6(e), Fig.6(f)] in the winter of 2022 and the post-monsoon of 2022, respectively. In comparison to other commercial and residential monitoring locations, there might be higher vehicle traffic on this industrial site.

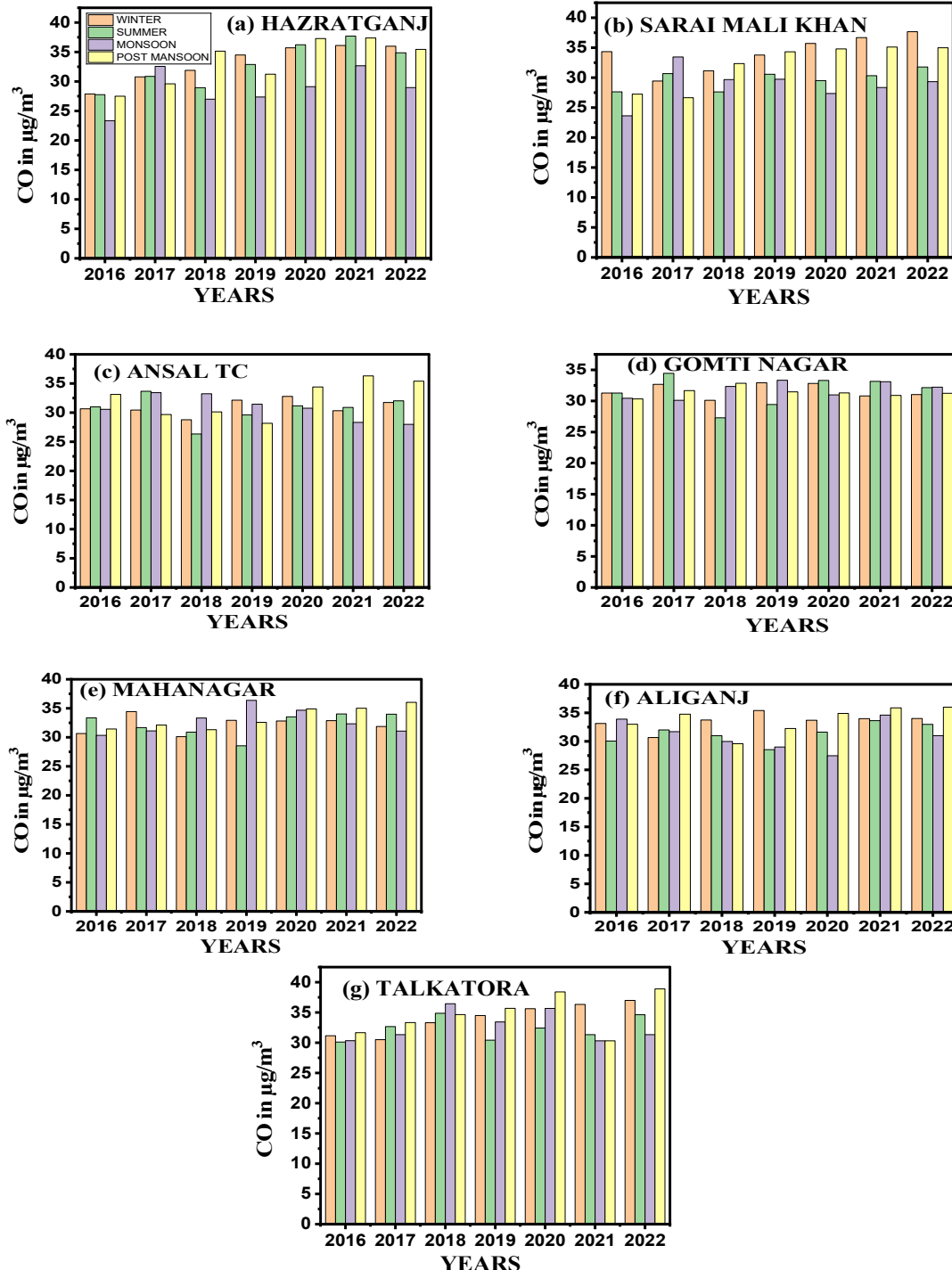


Fig.6 CO seasonal variation graphs (monsoon, and post-monsoon, winter, summer,) for the study period of 2016–2022 at all monitoring stations.

Area-wise variation

Fig.7 shows the area-wise fluctuation of PM₁₀, SO₂, NO₂, and CO concentrations for all monitoring stations. When it comes to PM₁₀ concentration at commercial stations [Fig. 7(a)], Hazratganj is in the lead among other stations, having peaked in 2017 at 323.05 μg m⁻³. Other stations that follow include Gomti Nagar, Ansal TC, and Sarai Mali Khan. After 2017, Talkatora, an industrial station, had the highest concentration of PM₁₀ of any place. This could be attributed to an increase in industrial activity in Lucknow city's surrounding districts. In 2018, Talkatora recorded a maximum concentration of 229.43 μg m⁻³, whereas Aliganj and Mahanagar had minimal concentrations of 174.72 and 174.75 μg m⁻³, respectively, in 2019 and 2018. Sarai Mali Khan has the highest SO₂

concentration [Fig.7(b)], at 8.94 μg m⁻³, followed by Hazratganj, Gomti Nagar, and Ansal TC, which is for commercial zones. Nonetheless, compared to the other locations, the industrial zones had a higher concentration. The industrial region of Talkatora has the highest concentration 9.13 μg m⁻³, followed by the residential areas of Mahanagar and Aliganj. Hazratganj and Sarai Mali Khan exhibit competition for variance in NO₂ concentration [Fig.7(c)], with the former having the highest concentration of 33.01 μg m⁻³ in 2022 and the latter having the highest concentration of 31.86 μg m⁻³ in 2019. Hazratganj and Talkatora indicate competition for variation in CO concentration [Fig.7(d)], with the former having a highest concentration of 31.00 μg m⁻³ in 2021 and the latter having a maximum concentration of 32 μg m⁻³ in 2022.

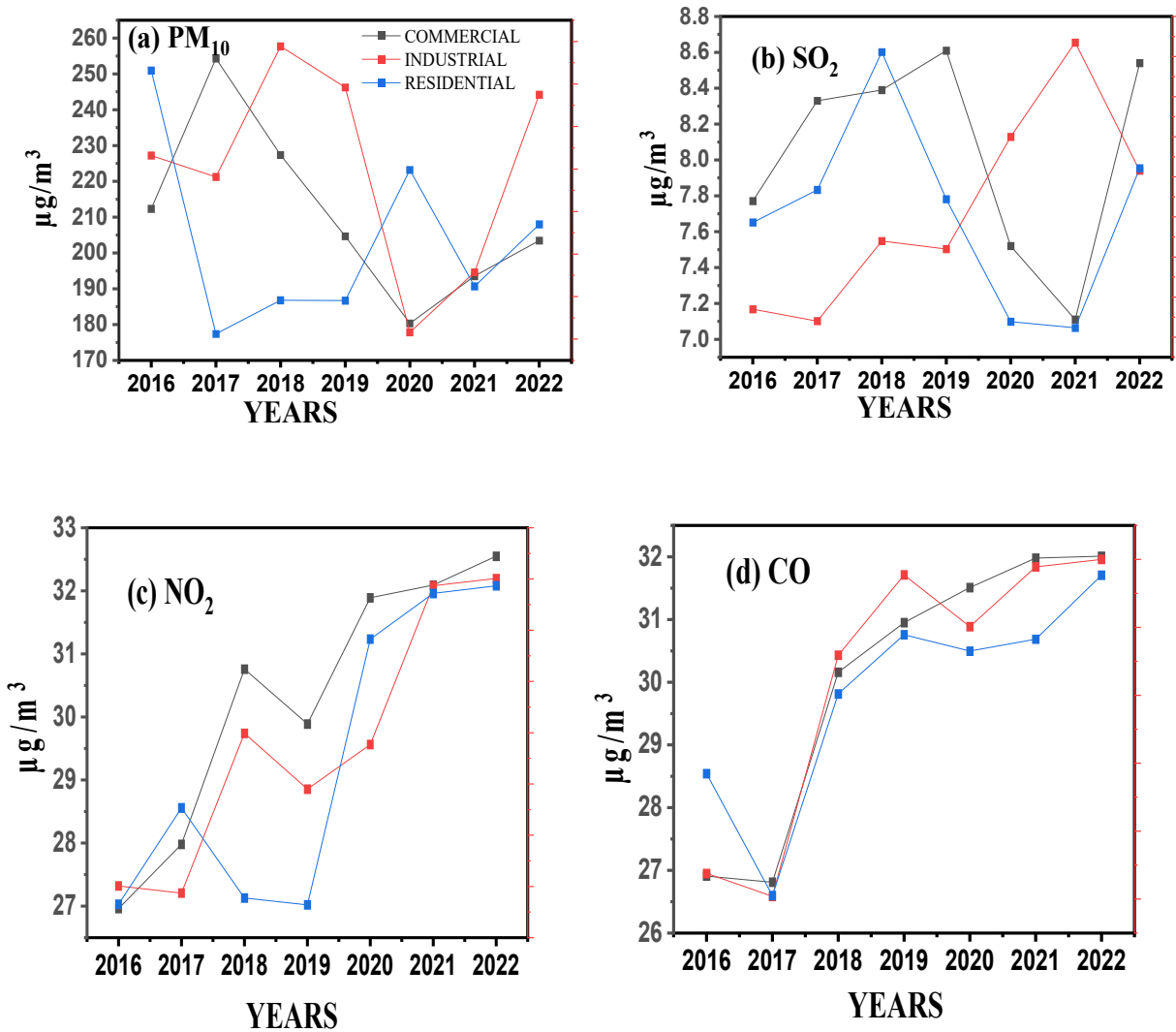


Fig.7 During the study period of 2016–2022, an area-wise annual average comparison was conducted between commercial stations, industrial stations, and residential stations for (a) PM₁₀, (b) SO₂, (c) NO₂, and (d) CO

Dispersion Model

The dispersion of pollutants in Lucknow city has been studied using the HYSPLIT4.0 dispersion modelling. Pollution dispersion is used in HYSPLIT4.0 dispersion modelling for the

winter, summer, monsoon, and post-monsoon seasons. The online version of HYSPLIT4.0 employs Backward dispersion for 24 hours, with average intervals of 6 hours each, to disperse pollutants. The findings show Fig.8 that the backward trajectories for PM₁₀, SO₂, NO₂ and CO from the northwest, to east-south.

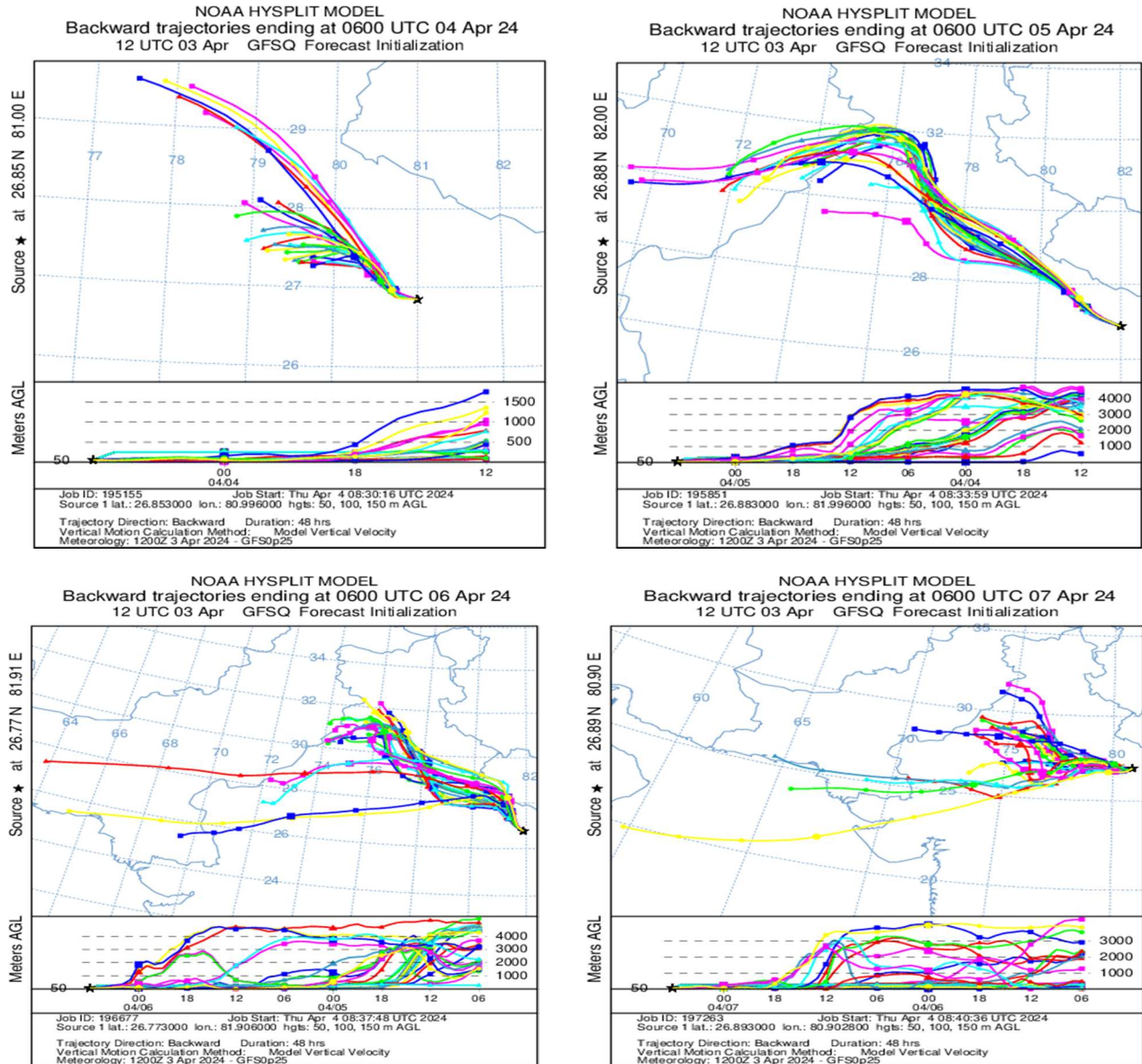


Fig.8 Dispersion map using HYSPLIT4.0 to forecast the concentration of air pollutants such as PM₁₀, SO₂, NO₂, and CO in all monitoring stations.

IV. CONCLUSION

The analysis of changes in the RSPM, SO₂, NO₂, and CO yearly average concentrations in Lucknow city between 2016 and 2022 was presented in this work. For this study, Hazratganj, Aliganj, Talkatora, Sarai Mali Khan, Gomti Nagar, Mahanagar, and Ansal TC were taken into consideration. It has been investigated how the concentrations of all four pollutants—

RSPM, SO₂, NO₂, and CO vary annually, seasonally, and area-wise. At each of the seven monitoring stations, the annual average concentration of RSPM ranges from 148.74 to 323.05 $\mu\text{g}\cdot\text{m}^{-3}$, SO₂ from 7.11 to 8.94 $\mu\text{g}\cdot\text{m}^{-3}$, NO₂ from 23.52 to 31.86 $\mu\text{g}\cdot\text{m}^{-3}$, and CO from 27.38 $\mu\text{g}\cdot\text{m}^{-3}$ to 33.89 $\mu\text{g}/\text{m}^3$. It was found that the RSPM and CO concentrations were above the CPCB-recommended limit. Conversely, it was found that the SO₂ and NO₂ concentrations were below the recommended levels. Based on a comparison of seasonal variations, the highest

recorded RSPM concentration during the post-monsoon season falls between 160.15 and 447.47 $\mu\text{g}\cdot\text{m}^{-3}$. Due to the rain at every monitoring site, the concentration is lower during the monsoon season than it is during the other seasons. For every season, the range of SO_2 , NO_2 , and CO concentrations was recorded to be 5.55 -10.94 $\mu\text{g}\cdot\text{m}^{-3}$, 20.23-38.40 $\mu\text{g}\cdot\text{m}^{-3}$, and 27.38-33.89 $\mu\text{g}\cdot\text{m}^{-3}$, respectively.

According to area-wise concentration, industrial locations have higher levels of pollution than commercial and residential areas. According to the statistics gathered, Lucknow city's pollution level for 2022 will significantly fall as a result of the lockdown brought on by the COVID-19 epidemic. Even during the COVID-19 Lockdown, the study period's annual average concentration of RSPM was found to be high at all stations and over the recommended level of 100 $\mu\text{g}\cdot\text{m}^{-3}$. Based on trajectory analysis, winds that blow from a north-westerly direction all year round are mostly responsible for the migration of aerosols from developed areas and cities. The present study shows that Lucknow's air quality is negatively impacted by pollution, which is not only generated locally but also mostly transported from nearby industrial and urbanized regions. This might be the reason for the declining air quality in the city despite measures taken by the Indian government or the local municipal authority. The dispersion analysis carried out with HYSPLIT4.0 for examples chosen based on the highest concentration for various seasons in the city across the research period has likewise supported this result. The RSPM time-series data indicates the presence of both yearly and semi-annual periodicity throughout the research period. However, in addition to theoretical and experimental understanding of source allocation studies and pollutant discharge across the region, more data collection and analysis in the Lucknow metropolitan area is required. When compared to SO_2 and NO_2 pollutants, the results show that lowering particulate matter and carbon monoxide pollution in the city is a serious problem and is at a critical stage.

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Authors Contributions

Vipin Kumar: Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing, Validation, Software investigation. **Prabhat Kumar Patel:** Supervision, Validation, Visualization, Writing – review & editing, Conceptualization.

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