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(RESEARCH ARTICLE)

Long term trend analysis and Spatio-temporal variation of air pollutants over Uttar Pradesh, India

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Abstract

Air pollution poses a significant challenge for developing countries like India, particularly in cities where industrial growth and urban development have led to increased levels of air pollutants. Due to limited monitoring resources and a focus on specific variables, there is a lack of comprehensive understanding regarding air quality in Indian urban areas. This study aims to explore the spatial and temporal variations in air pollutant concentrations and identify long-term trends over a seven-year period (2016-2022) in the state of Uttar Pradesh. Data for PM_{10}, SO_2, and NO_2 were collected from 78 ambient air quality monitoring stations. The study investigates how these pollutants behave in terms of their distribution on different temporal scales (seasonal, yearly) as well as across various locations. The findings reveal that the concentration of PM_{10} consistently exceeds national and international air quality standards. Using the Inverse Distance Weighting (IDW) technique, air pollutant distribution maps were created to identify specific hotspots. Additionally, the Mann-Kendall Test was applied to analyze trends within the available data. This research can serve as valuable information for local government authorities to formulate effective strategies for mitigating air pollution in the region.

Keywords: Particulate matter (PM_{10}); SO_2; NO_2; Inverse distance weight; Spatio-temporal

1. Introduction

Ensuring clean air is an essential prerequisite for human health and overall well-being. However, as nations undergo economic development, the issue of air pollution has emerged as a significant global health threat. It has raised various environmental concerns, poses severe risks to human health, and contributes A substantially elevated mortality rate that equally affects developed and impoverished countries [1,2,3,4,5,6]. Air pollution comprises pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NO and NO_2), Sulphur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3). In accordance with the organization known as the World Health Organization (WHO), pollution of the air is the tainting of indoor and/or outdoor settings by chemical, physical, or biological elements, leading to in alterations to the ambient air's normal attributes. Alarmingly, according to the WHO (WHO, 2023), air pollution contributes to millions of fatalities worldwide each year.

The World Health Organization (WHO) reports stated outdoor ambient air pollution poses a serious threat to human health [7]. The air quality standards (AQS) ought to be amended in order to address the related health concerns as it is liable for roughly 4.2 million annual fatalities (WHO, 2023). India, in particular, has faced substantial challenges related to air pollution in recent years [8,9]. In India, the number of fatalities exclusively owing to air pollution has increased from 1.24 million in 2017 [10] to roughly 1.67 million in 2019 [11], accounting for 17.8% of all fatalities that year. Among these, 0.98 million were connected to ambient air pollution (AAP), 0.61 million to indoors or household air pollution,

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and 0.17 million to exposure to outdoor O3 pollution [11]. This information demonstrates how AAP has developed into a severe public health issue in Indian urban regions.

According to the most recent IQ Air report, India holds the unenviable fifth position on the list of the world's most polluted countries (IQ Air, World Air Quality Report 2021). Notably, neither in 2019 [12] nor in 2021 (IQ Air, World Air Quality Report 2021) did any Indian city achieve the air quality requirements advised by the World Health Organization (WHO). India had a staggering count of over 35 cities among the top 50 most polluted globally, with 14 of those cities situated in the state of Uttar Pradesh (UP), including its capital, Lucknow (IQ Air, World Air Quality Report 2021). The Unfavourable distinction of having the highest documented death rate among Indian states belongs to Uttar Pradesh. A total of 0.35 million deaths in 2019 were reported by UP as being related to air pollution, with 0.22 million of those deaths being due to ambient air pollution (AAP) and 0.11 million related to domestic air pollution [11]. According to several studies [13,14,15,16,17,18] household cooking, industrial operations, combustion of waste and the biomass, and congestion in traffic are the main causes of air pollution in UP.

A vital requirement for a thorough analysis of the precise levels and related health hazards caused by pollutants like PM_{10}, SO_2, and NO_2 in the area arises from the recognition of the serious health effects of poor air quality on people of UP. The central objective of our proposed study is to conduct a thorough analysis of the spatial and temporal fluctuations in the concentrations of these pollutants within Uttar Pradesh.

2. Materials and methods

2.1. Site description

The study area entails 27 main cities in the province of Uttar Pradesh, which is also known as UP. embedded in the Indo-Gangetic plain, UP ranks as the India's 4th largest state in terms of industrialization and boasts approximately 15,000 industrial units, primarily concentrated in the manufacturing and agricultural sectors. Covering a vast expanse of 240,928 square kilometers, UP is renowned for its substantial population, which stands at 199.81 million, resulting in a population density of 829 individuals per square kilometer. As it turns out, UP is among the states in India with the highest population density. Furthermore, the population continues to grow, with a projected estimate of 227.65 million for the year 2021, according to IBEF Uttar Pradesh 2021.

Over the past decade, there has been a notable surge in the total number of vehicles within the state. Specifically, vehicle numbers have escalated from 1.73 million in 2011–2012 to 3.53 million in 2019–2020, in accordance with Uttar Pradesh's Statistical Dairy 2020.

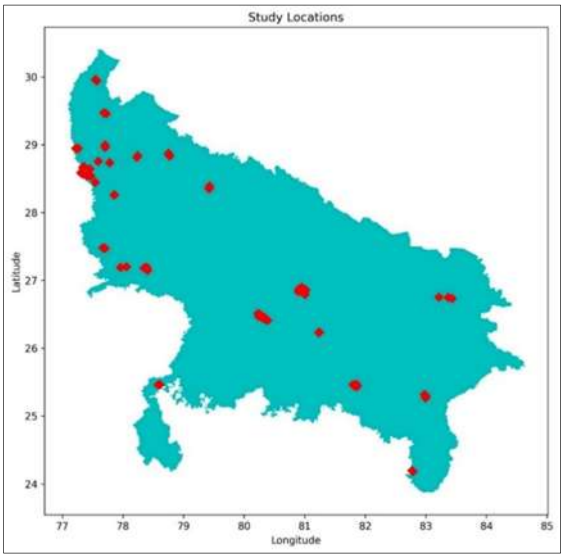

Figure 1 Map of study area, Uttar Pradesh state, India

The study focuses on a selection of 27 districts within UP. These areas were chosen based on the availability of air quality data on the UPPCB portal. The list includes prominent cities such as Agra, Firozabad, Ghaziabad, Gorakhpur, Kanpur, Lucknow, Meerut, Moradabad, Noida, Prayagraj, and Varanasi, along with others like Sonbhadra, Gajraula, Jhansi, Khurja, Ayodhya, Bareilly, Mathura, Rae Bareli, Saharanpur, Unnao, Hapur, Greater Noida, Muzaffarnagar, Aligarh Hathras and Bagpat.

2.2. Data collection and analysis

Continuous data from Uttar Pradesh's air quality monitoring network are rarely accessible for long-term research purposes. Given the limited availability of continuous data from monitoring stations, this study focused on a specific timeframe and specific pollutants. The Uttar Pradesh Pollution Control Board (UPPCB) monitored concentrations of PM_{10}, SO_2, and NO_2 at 78 sampling stations strategically located across the study area. These sites were carefully selected to facilitate an analysis of the spatial distribution of pollutant concentrations. Table1 provides details such as latitude, longitude, and land use type for each monitoring station. This study utilized data on particulate matter, sulfur dioxide, and nitrogen dioxide concentrations collected from January 2016 to November 2022.

To assess the spatial distribution of PM_{10}, SO_2, and NO_2 levels in Uttar Pradesh, a Geographic Information System (GIS) tool was employed. The study utilized the Inverse Distance Weighting (IDW) interpolation method to predict pollutant concentrations at unknown locations within the research area. The IDW interpolator operates on the premise that each input point exerts a localized influence that diminishes as the distance from the point increases. Points closer to the target location are accorded greater weight than those farther away. The IDW interpolation method calculates the value for an unknown location using the following equation:

(Equation 1) presents the fundamental IDW interpolation formula. In this equation, (x*) represents the value we wish to determine at a specific location, (w) corresponds to the weight assigned to this calculation, and (x) represents the known value at a specific point. The weight (w) is determined based on the inverse distance from each known point to the location in question, and this calculation can be straightforwardly achieved using (Equation 2).

$$\frac{x^*=w_1x_1+w_2x_2+\cdots+w_nx_n}{w_1+w_2+\cdots+w_n}\text{..........}\ \text{(eq.1)}$$

$$w_1=\frac{1}{d_{ix^*}^{P}}\qquad\text{.....................(eq.2)}$$

Table 1 Air quality monitoring sites

		Area Type				
S. No	**Cities**	**Commercial**	**Residential**	**Industrial**	**Sensitive**	**Total No. of Stations**
1	Lucknow	4	2	1		7
2	Kanpur	2	5	1		8
3	Agra				2	2
4	Sonbhadra		2			2
5	Gazraula	1		1		2
6	Ghaziabad	1	1	2		4
7	Varanasi	1	3	1		5
8	Noida	1	2	1		4
9	Firozabad				3	3
10	Jhansi	1	1			2
11	Khurja		1	1		2
12	Allahabad	4	1			5
13	Merrut	1	1			2
14	Moradabad	1	1			2

15	Bareilly	1	1			2
16	Rae Bareli	1	1	1		3
17	Mathura				2	2
18	Saharnpur	1	1			2
19	Gorakhpur	1	1	1		3
20	Unnao		2			2
21	Hapur		1	1		2
22	Greater Noida			2		2
23	Muzaffarnagar	2				2
24	Bagpat		1	1		2
25	Ayodhya	1	1			2
26	Aligarh	1	1			2
27	Hathras	2				2
						Total Station=78

2.3. Seasonal variation

The data was organized into the four distinct tropical seasons, following the classification established by the India Meteorological Department (IMD): winter (December to February), summer (March to June), monsoon (July to September), and post-monsoon (October to November). This classification was employed to assess the variations in air pollution across these different seasons. The study involved the examination of air pollutant levels, encompassing PM_{10}, SO_2, and NO_2, at 78 air quality monitoring stations situated throughout Uttar Pradesh, covering each of these four seasons from January 2016 to November 2022.

2.4. Mann- kendall (mk) trend test

We employed a non-parametric statistical analysis, specifically the Mann-Kendall (MK) test, to investigate the monthly trends in PM_{10} concentrations at the top three stations representing Commercial, Industrial, Residential, and Sensitive areas. Recognizing the issue of serial correlation that can affect the original Mann-Kendall test, we opted for the Modified Mann-Kendall (MMK) test, which was introduced by Yue and Wang in 2004. This modified approach addresses the problem of serial correlation through a technique known as variance correction. To obtain the statistic (S) for the MK test, we utilized Equation (1).

$$\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(Y_j - Y_i\ )$$

The total number of observations in the given case is n, and the ranks of the ith (i = 1, 2, 3...n -1) and jth (j = i + 1, 2, 3...n) observations are Yi and Yj, respectively (for a more detailed explanation, see Mann, 1945; Kendall, 1957). Yue and Wang (2004) suggested the modified variance of S statistics V*(S), which is as follows:

$$v^*(s) = v(s)\frac{n}{n^*}$$

Where V(S) is calculated using the original MK test calculations, and n/n* is referred to as a correction factor (for more information, see Mann, 1945; Bayley and Hammersley, 1946; Yue and Wang, 2014). The percentage (%) variance in PM features is calculated using Eq (3).

$$x\% = \left(a * \frac{N}{\bar{x}}\right) * 100$$

Where x is the variable, $\bar{x}$ denotes the average value, N denotes the total number of days, months, or years during the study period (with data), and a denotes the slope value obtained by Theil-Sen estimator/slope for analysis.

3. Results and discussion

3.1. Spatial and temporal aspects of the air quality

The annual mean concentrations and ranges of various pollutants across Uttar Pradesh are depicted in Table2. This section discusses the data collected from 2016 to 2022 unless specified otherwise. The annual mean concentrations of SO_2, NO_2, and PM_{10} for the entire study area showed a range of (10.05 to 11.88) μg/m^3, (28.84 to 33.09) μg/m^3, and (176.34 to 204.88) μg/m^3, respectively. In the context of the air quality in the cities examined within this study, Ayodhya displayed the lowest annual mean SO_2 concentration at 1.57μg/m^3, while Gorakhpur exhibited the highest at 40.61 μg/m^3. Similarly, when considering NO_2 levels, Gorakhpur recorded the lowest concentration at 5.45 μg/m^3, whereas Meerut registered the highest at 77.58 μg/m^3. Furthermore, the city of Gorakhpur had the highest annual mean PM_{10} concentration measuring 355.06 μg/m^3, while Jhansi showcased the lowest at 85.56 μg/m^3. Regarding the mean annual concentrations of the pollutants, which were determined by averaging the data from all stations, the highest SO_2 concentration of (11.88±6.88) μg/m^3 was observed in 2018. The highest concentration of NO_2, another anthropogenic pollutant, was observed in 2019, with a value of (33.09±11.82) μg/m^3. Regarding the PM, the highest concentration of PM_{10} was observed in 2018, with a value of (204.88±44.30) μg/m^3.

Table 2 Descriptive statistics for PM_{10}, SO_2, NO_2

		Pollutants		
Years		**PM_{10} (μg/m^3)**	**SO_2(μg/m^3)**	**NO_2(μg/m^3)**
2016	Max	292.11	25.98	62.12
	Min	95.65	2	8.75
	Mean	193.28±43.05	10.68±5.23	30.96±10.15
2017	Max	323.05	26.54	62.17
	Min	97.3	2	13.14
	Mean	198.21±53.01	11.02±5.67	31.61±11.35
2018	Max	314.64	40.61	73.35
	Min	88.66	2	14.47
	Mean	204.88±44.30	11.88±6.88	32.94±12.76
2019	Max	340.84	34.75	77.55
	Min	88.95	2	13.8
	Mean	199.38±41.60	11.71±6.74	33.09±11.82
2020	Max	307.95	25.67	70.76
	Min	85.56	1.57	8.05
	Mean	177.00±42.02	10.05±5.21	30.59±13
2021	Max	348.3	27.88	63.89
	Min	95.12	1.7	5.75
	Mean	183.74±45.33	10.05±5.52	29.38±11.80
2022	Max	355.06	33.44	58.4
	Min	95.65	1.7	5.45
	Mean	176.34±47.33	10.75±5.99	28.84±10.71

3.2. Seasonal variations of pollutant

Seasonal variations in air pollutant concentrations across the study area are depicted in Table3 &Figures (2, 3, 4 and 5). Notably, for all pollutants, the highest concentrations were consistently spotted during the winter season. This pattern can likely be relating to specific meteorological conditions, including stagnant atmospheric conditions, lower temperatures, and shallower boundary layer heights. Additionally, higher usage of coal and biomass fuels for heating during winter compared to other seasons contributes to this increase. Specifically, the highest and lowest concentrations of PM_{10} occurred during the winter and monsoon seasons, with values of (228.45 ± 53.29 $\mu g/m^3$) and (127.906 ± 33.303 $\mu g/m^3$), respectively. Likewise, largest and smallest concentrations of SO_2 were observed during the winter and monsoon seasons, registering values of (12.18 ± 6.35 $\mu g/m^3$) and (8.93 ± 4.12 $\mu g/m^3$), respectively. Similarly, largest and smallest concentrations of NO_2 were identified during the winter and monsoon seasons, with values of (34.62 ± 12.26 $\mu g/m^3$) and (24.63 ± 9.54 $\mu g/m^3$), respectively.

Table 3 Descriptive statistics of air parameters concentration in the seasons.

		Pollutants		
Seasons		**PM_{10} ($\mu g/m^3$)**	**SO_2 ($\mu g/m^3$)**	**NO_2 ($\mu g/m^3$)**
Winter	Max	370.97	33.76	66.87
	Min	103.3	2	13.96
	Mean	228.45±53.29	12.18±6.35	34.62±12.26
Summer	Max	294.79	30.72	61.77
	Min	97.59	2.32	13.34
	Mean	191.81±38.34	11.32±5.24	30.48±10.12
Monsoon	Max	233.57	22.62	51.8
	Min	39.1	2.08	10.78
	Mean	127.90±33.30	8.93±4.12	24.63±9.54
Postmonsoon	Max	369.37	29.12	66.4
	Min	106.64	2	12.65
	Mean	219.23±54.50	12±5.96	33.09±11.57

3.3. Evaluation of trend analysis

To comprehend the trends in the PM_{10} parameter, a trend analysis was conducted at nine monitoring stations over the study period. The statistical trend analysis results for the PM_{10} parameter at each of these nine stations are summarized in Table 4. The slope values from the Theil-Sen estimator, which represent the monthly variations, are presented in this table together with the percentage difference and related statistical significance, as shown by P-values. a P-value was used to determine each case's statistical significance of the slope, with values less than 0.05 indicating statistical significance at the 95% confidence level (*).

Throughout the study period, positive trends were identified at Ramadevi Kanpur (0.322 $Month^{-1}$), Gorakhpur GIDA (2.1941 $Month^{-1}$), and Kanpur Dadanagar (0.765 $Month^{-1}$). Conversely, negative trends were observed at Aliganj Lucknow (-0.4215 $Month^{-1}$) and Agra Nunhai (-0.4148 $Month^{-1}$).

Table 4 Result of Mann–Kendal trend test and Sen's slope estimator of PM_{10} over 12 Stations of Uttar Pradesh state from 2016 January to November 2022

CITIES	TYPE	STATION	MEAN ($\bar{x}$)	TREND / MONTH	(%)	P
Moradabad	Commercial Area	Buddh Bazar	230 ± 50.44	-0.423	-15.32	0.075
Prayagraj		Crossing Mahalaxmi Talkies	233 ± 59.14	-0.102	-3.66	0.4
Kanpur		Ramadevi	285± 128.18	0.322	9.38	0.039*
Varanasi	Industrial area	Chandpur	246 ± 73.91	-1.171	-39.51	4.733
Gorakhpur		Gida	278 ± 88.33	2.1941	65.57	0.0*
Hapur		Zindal Pipes Limited	273 ± 115.01	0.034	1.04	0.873
Lucknow	Residential Area	Aliganj	217 ± 84.09	-0.4215	-16.1	0.0177*
Kanpur		Dadanagar	252 ± 120.50	0.765	25.2	0.00045*
Noida		Regional Office	213 ± 89.94	0.173	6.75	0.4355
Firozabad	Sensitive Area	Cdgisn Marg	205.7 ± 80.42	-0.5694	-22.98	3.296
Agra		Nunhai	212 ± 93.95	-0.4148	-16.26	0.0098*
Firozabad		Tilak Nagar	207 ± 81.84	-0.4074	-16.31	6.0197

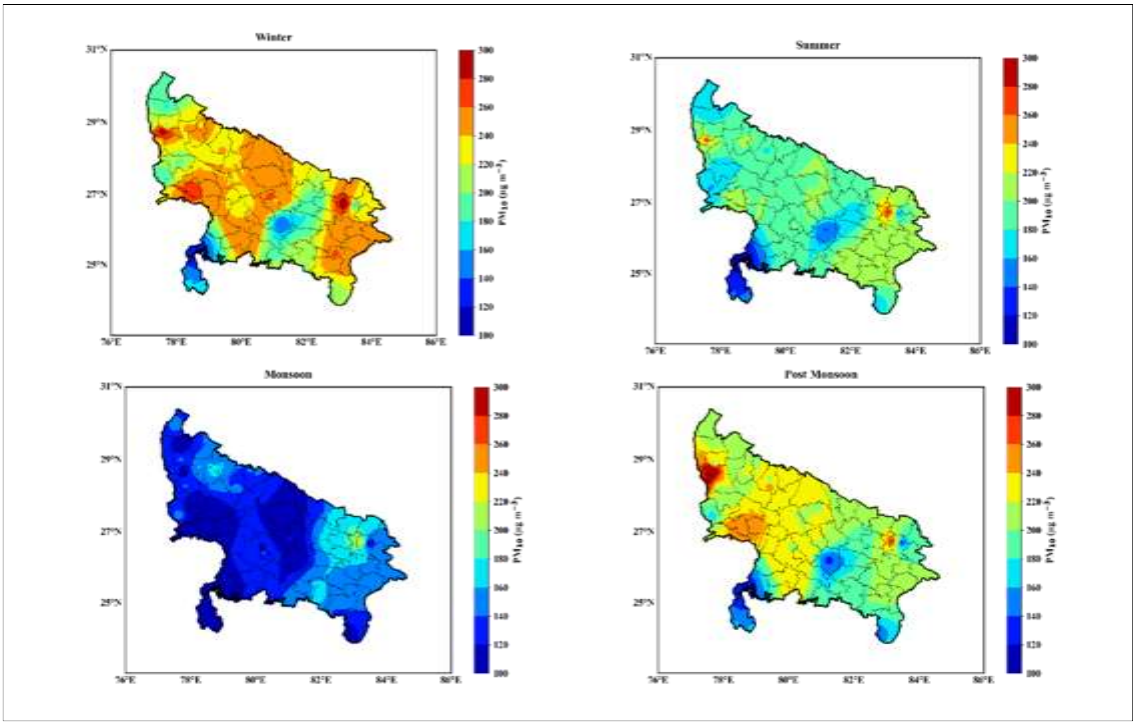

Figure 2 Inverse distance weighted (IDW) technique-based PM_{10} seasonal variation plot

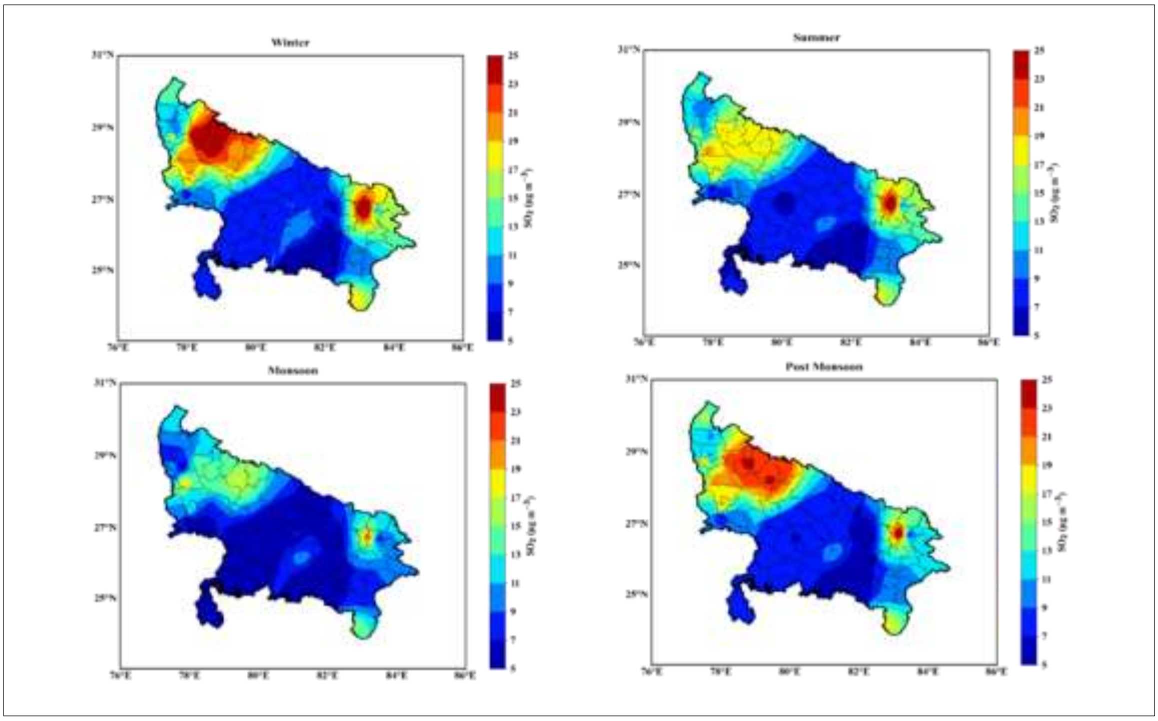

Figure 3 Inverse distance weighted (IDW) technique-based SO2 seasonal variation plot

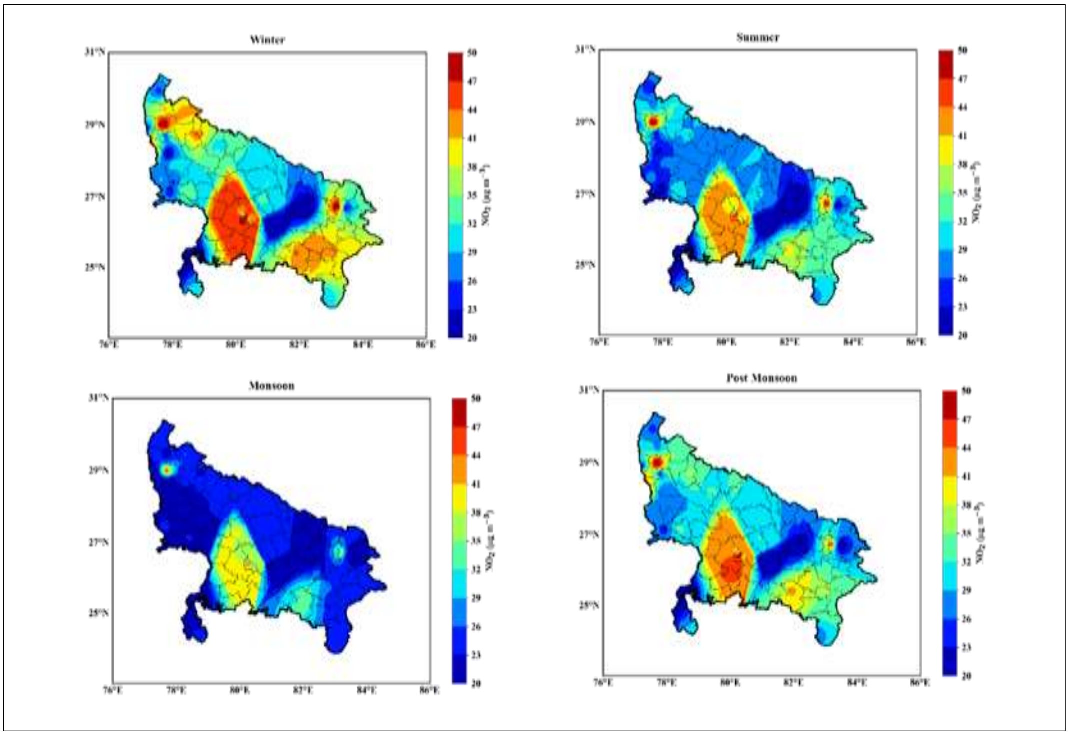

Figure 4 Inverse distance weighted (IDW) technique-based NO2 seasonal variation plot

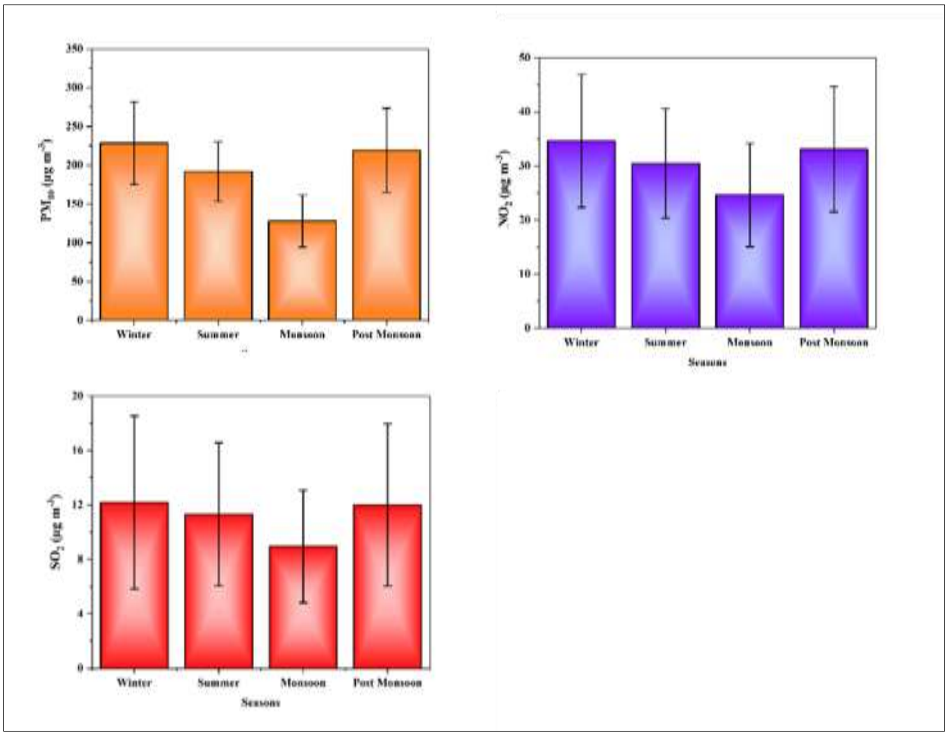

Figure 5 Seasonal average concentrations of pollutants over Uttar Pradesh during the study period (JAN 2016–NOV 2022). The Error Bars Represent the Standard deviation

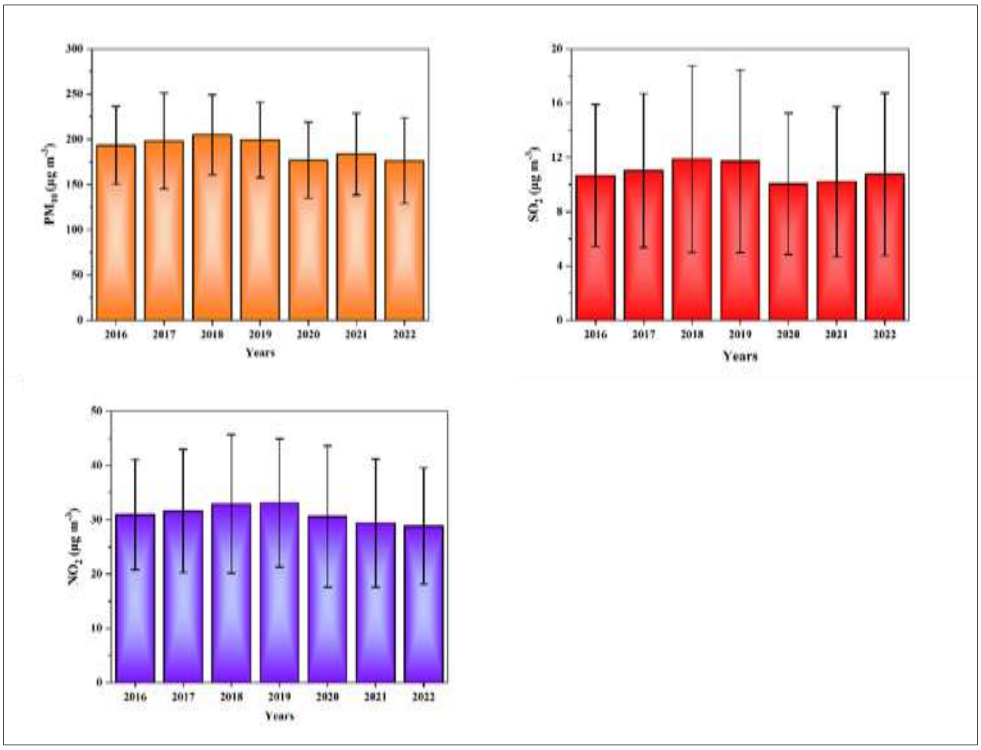

Figure 6 Yearly average concentrations of pollutants over Uttar Pradesh during the study period (JAN 2016–NOV 2022). The Error Bars Represent the Standard Deviation.

4. Conclusions

This study analyzed the temporal and spatial variations of PM_{10}, SO_2, and NO_2 concentrations in Uttar Pradesh, India. According to the study, gaseous contaminants were not as prevalent as particulate pollutant. The results imply that seasonal variations significantly affect the states pollution concentrations. Examining the temporal trends of air pollutants revealed that the monsoon season had the cleanest air, while the winter and post-monsoon seasons had the greatest levels of PM_{10} pollution. the findings reveal that the annual average concentration of particulate matter (PM_{10}) during each season exceeded the limits specified by the Central Pollution Control Board (CPCB). However, it's noteworthy that the concentrations of NO_2 and SO_2 in every season are within the reference standards of (40&50) $\mu g/m^3$.

The analysis of spatio-temporal trends in air pollutant variations serves as a robust scientific foundation for the management and regulation of air quality. This research offers valuable insights for urban planners and decision-makers, equipping them with the knowledge needed to efficiently oversee air quality control measures, benefiting both public health and the environment.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that they have no competing interests.

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