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Original Article

Decadal Analysis of Air Quality in Kolhapur City: Trends, Exceedance Factors, and Statistical Modelling

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Abstract

In most Indian cities, exposure to ambient air pollution poses a serious risk to public health. Recent studies shows that more than 75% of Indians, are exposed to pollution levels that are higher than the national ambient air quality standards in India and much higher than those advised by the World Health Organisation. Air Quality Index in the Kolhapur city, Maharashtra was carried out based on monitoring of three ambient air quality parameters like PM_{10}, SO_2 and NO_2 at Dabholkar Corner, Mahadwar Road and Shivaji University. Dabholkar Corner location is situated around commercial area, Mahadwar Road around residential and commercial area and Shivaji University is considered as background area. Monitoring was carried out for ten years starting from January, 2014 to December 2023. APM-460 DXNL Respirable Dust Sampler is used followed by cyclonic and impactor-based technique for measurement of PM_{10}. The highest annual average concentration of PM_{10} was found in the years 144.54 µg/m³ (2019), 107.89 µg/m³ (2015) and 66.58 µg/m³ (2018) at Dabholkar corner, Mahadwar road and Shivaji University. The highest annual average concentration of NO_2 was 51.79 µg/m³ (2014), 39.75 (2015) µg/m³, 22.90 (2018) µg/m³ at respective locations and the highest annual average concentration of SO_2 was 30.06 µg/m³ (2020), 23.98 µg/m³ (2014) and 8.70 µg/m³ (2020) at respective locations. The exceedance factors for PM_{10} varied from 'moderate pollution at the background location and 'critical pollution' at the commercial and residential location. To investigate the relationship and perform statistical modeling between PM_{10} concentration, SO_2 and NO_2 levels, correlation and linear regression analysis was carried out. The purpose of this study is to understand the relationship between air pollution levels and how they affect PM_{10} levels in different locations.

Keywords: *Exceedance factor, Regression analysis, Particulate matter, Sulphur Dioxide, Nitrogen dioxide, AQI, Correlation, Regression Analysis*

Introduction

An increasing number of variables, including increased urbanisation, industrial pollutants, traffic emissions, agriculture, and energy consumption, are contributing to the global concern of rising air pollution levels Kumar *et al.*, 2015. Lim *et al.*, 2012 revealed that air pollution has a major impact on mortality worldwide. The majority of people in India live in locations where air quality exceeds even the less strict limitations specified by the Indian National Ambient Air Quality Standard (NAAQS) (CPCB, 2009) for PM, and nearly the entire population lives in areas that exceed the WHO Air Quality Guidelines Greenstone *et al.*, 2015. Despite the low quality of the air, large Indian cities have ambient air quality monitoring stations and they are running, while small towns and rural areas essentially lack monitoring stations. In India 804 stations are run by the Central Pollution Control Board and State Pollution Control Board. For a nation, this number of monitoring sites is insufficient. Prior to 2015, the National Air Monitoring Programme (NAMP) was exclusively monitoring PM_{10}, Nitrogen dioxide, and Sulphur dioxide Kumar *et al.*, 2014. The majority of India's air pollution statistics come from cities with a population of one million or more. As per 2011 census approximately 230 million of India's urban population reside in towns and cities with fewer than a million residents (Census of India, 2011). The primary goal of the work is to comprehend the state of air quality in small towns and cities and to develop action plan for future.

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This work is a component of a wider initiative that aims to give local planners and administrators the capacity to assess the effects of measures intended to raise air quality and meet National Clean Air Programme criteria. According to Johnson *et al.*, 1997 air quality is the state of the air in relation to the needs of one or more biotic species as well as any need or purpose that humans may have. One of the key methods for assessing and consistently portraying the state of air quality is the air quality index. Kolhapur city air relative change in the amounts of various pollutants can be evaluated using the Air Quality Index (AQI). The majority of diesel-powered vehicles in metropolitan areas, such as cars, buses, light motor vehicles, etc., release more particulate matter into the air (Bathmanabhan and Madanayak, 2010). According to reports, traffic volume, vehicle speed, city population, and other factors account for the majority of particulate matter sources in most cities worldwide (Ganguly *et al.*, 2015; Karner *et al.*, 2010). Particulate matter is the composition of various other pollutants which could be generated by human activities and various natural sources (Menzel and Ryther, 1964). In various studies, it is seen that particulate matter mostly affects human, plants and animals (Zhang *et al.*, 2017, Saini *et al.*, 2023 a, b). All the metropolitan cities in India are experiencing declining air quality year by year mostly because of various vehicular activities, industrialization, and huge construction activities. There are other sources of these pollutants, for example, marine in Mumbai (Chelani *et al.*, 2008; Kothai *et al.*, 2008; Kumar *et al.*, 2001), biomass burning in Delhi (Shridhar *et al.*, 2010), coal combustion in Kolkata (Chowdhury *et al.*, 2007) and Jorhat (Khare and Baruah, 2010) generate PM_{10} and $PM_{2.5}$. PM_{10} generation due to solid waste burning has been reported in Mumbai (Karar and Gupta, 2007) and Agra (Kulshrestha *et al.*, 2009). PM_{10} particles in Delhi (Balachandran *et al.*, 2000) and Mumbai (Kothai *et al.*, 2008) are reported due to vehicular activity. Industries emit PM_{10} in the air in Tirupati (Chandra *et al.*, 2006), Kanpur (Chakraborty and Gupta, 2009) and Mithapur city (Basha *et al.*, 2010). It is also generated due to the crushing dust or road dust, and also burning refuse oil (Shridhar *et al.*, 2010), PM_{10} and $PM_{2.5}$ generated due to various industries also seen in Chennai city (Bathmanabhan and Madanayak, 2010), due to various type of dust emits PM_{10} particles in Jaipur city of Rajasthan (Soni *et al.*, 2018).

Kolhapur city is a non-attainment city declared by CPCB, New Delhi, India. It is expected that the quality of ambient air should be within the standards mentioned in National Ambient Air Quality Standards (NAAQS) 2009. Various studies have been conducted by various researchers regarding particulate matter, like various traffic studies (Patni and Gupta, 2017), various disease generation (Patel *et al.*, 2001) and the outbreak of the virus in children, and heavy metal pollution (Chaudhari *et al.*, 2012). The studies regarding the pollution pattern in Kolhapur city have not been reported yet, hence the present work has been planned to study the air pollution pattern in Kolhapur city by considering a span of 10 years from 2014 to 2023. During this period there was a lot of development works have taken place in the city. The air pollution data for the above duration has been analysed to assess and find the quality of air at background, residential, and commercial locations. The annual variation in concentration of these three pollutants at all locations was studied.

Material and methods

1. **Location of Monitoring Stations**

Ambient air quality monitoring was conducted at three distinct locations representing different land-use categories: Background (Station-I), Commercial (Station-II), and Residential (Station-III) areas. Station-I (SUK), situated within an educational zone, is located at the Department of Environmental Science, Shivaji University, Kolhapur, India (Station Code: 508; Latitude: 16°40'36.27"N; Longitude: 74°15'10.26"E). Station-II (DC), representing a commercial area, is positioned at Dabholkar Corner near the State Transport (ST) stand (Station Code: 509; Latitude: 16°42'15.38"N; Longitude: 74°14'30.23"E). Station-III (MR), indicative of a residential setting, is located at Mahadwar Chowk, Kolhapur (Station Code: 510; Latitude: 16°41'40.19"N; Longitude: 74°13'18.66"E). The monitoring and operation of all three stations was carried out by the Department of Environmental Science, Shivaji University, Kolhapur, as part of the Central Pollution Control Board's (CPCB) National Air Quality Monitoring Programme (NAMP), with financial support from the Maharashtra Pollution Control Board (MPCB), Mumbai, Maharashtra, India.

2. **Monitoring programme**

Ambient air quality monitoring at the three stations follows the guidelines established by the Central Pollution Control Board (CPCB), wherein air samples are collected on a 24-hour basis twice a week at uniform intervals. The annual arithmetic mean is derived from a minimum of 104 measurements per year. Three key air pollutants - Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), and Respirable Suspended Particulate Matter (RSPM or PM_{10}) are monitored across all three locations. The sampling protocol involves the collection of PM_{10} over a 24-hour period with 8-hourly intervals, resulting in three observations per day. Similarly, NO_2 and SO_2 are collected over 24-hour period with 4-hourly intervals, yielding six observations per day, twice a week.

Air pollutant sampling is conducted using a Respirable Dust Sampler (RDS) APM460, which comprises a protective casing, a blower, a voltage stabilizer, a time totalizer, a rotameter, and a filter holder designed to accommodate a 20.3 × 25.4 cm glass fibre filter. A cyclone separator, utilizing centrifugal force, is employed to remove larger dust particles prior to sample collection. The airflow rate for pollutant collection is maintained at 1.1 m^3/min to ensure consistent and representative sampling of ambient air quality.

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The concentration of particulate matter gravimetrically is determined as follows in equation (1). (IS 5182-4 1999):

$$PM_{10}(\mu g/m^3) = \frac{(W_f - W_i)}{V} \times 10^6 \quad (1)$$

where,
PM_{10} is the concentration of particulate matter in $\mu g/m^3$
W_i – initial weight of filter, g
W_f – final weight of filter, g
V– Volume of air sampled, m^3

Sulphur dioxide (SO_2) concentration in the air is determined by Improved West and Gaeke method (IS 5182-2 2001) using APM460 respirable sampler with the gaseous sampling instrument attached to it.

Nitrogen dioxide (NO_2) concentration in air is determined by using dust Jacob and Hochheiser Method (IS 5182-6 2006) using APM460 respirable dust sampler with the gaseous sampling instrument attached to it.

3. Analysis

Various statistical techniques have been employed to analyse the interrelationships among air pollutants, including the assessment of annual pollutant concentrations over a ten-year period across all three monitoring sites. Additionally, the exceedance factor (EF) has been calculated to evaluate air quality trends over time.

The exceedance factor (EF) serves as a key criterion for categorizing the current air quality status. It is defined as the ratio of the annual average concentration of a given pollutant to its respective standard concentration, as expressed mathematically in Equation (2) (CPCB 2016).

$$EF = \frac{C_0}{C_s} \quad (2)$$

where,
EF = Exceedance Factor
C_0 = Observed annual mean concentration of pollutant, $\mu g/m^3$
C_S = Standard annual mean concentration of pollutant, $\mu g/m^3$

Based on the value of the exceedance factor, the air quality has been divided into four categories as given in Table 1. As per the prescribed equation by the world health organization and national ambient air quality standard, an increase in the percentage of PM_{10} annual mean concentration can be calculated by the following equation (3) (CPCB 2016).

$$\text{Annual mean pollutant concentration} = \frac{(C_0 - C_S)}{C_s} \times 100 \quad (3)$$

Table No. 1. Exceedance factor as per the CPCB guidelines

Sr. No.	Exceedance factor range	Pollution level
1	Greater than 1.5	Critical pollution
2	1 to 1.5	High pollution
3	0.5 to 1	Moderate pollution
4	Less than 0.5	Low pollution

Air Quality Index (AQI)

The Air Quality Index (AQI) was developed as a standardized measure to assess air quality by representing pollution levels as a numerical value or ratio. As a widely used monitoring tool, AQI serves as an indicator of environmental air quality within urban areas, enabling rapid assessment of pollution's impact on human health. By providing a clear representation of local pollution levels, AQI allows individuals to understand the potential health risks associated with air quality. The AQI value is used to classify pollution levels into distinct categories, each corresponding to specific health implications. A detailed description of these categories and their associated health effects is presented in Table 2. The AQI (I_p) is calculated using the following equation:

$$I_p = \left\{\frac{(I_{HI} - I_{LO})}{(B_{HI} - B_{LO})} \times \left(C_p - B_{LO}\right)\right\} + I_{LO} \quad (3)$$

where,
B_{HI} is the breakpoint concentration greater or equal to given concentration.
B_{LO} is the breakpoint concentration smaller or equal to given concentration.
I_{HI} = AQI value corresponding to B_{HI}
I_{LO} = AQI value corresponding to B_{LO}
C_p = Pollutant concentration
AQI = Max (Ip) (where p = 1, 2, 3. . .n; denotes n pollutants range).

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Table No. 2. Air Quality Index Categories

AQI Category	AQI	PM_{10}	$PM_{2.5}$	NO_2	SO_2	O_3	NH_3	CO	Pb
Good	0 - 50	0 - 50	0 - 30	0 - 40	0 - 40	0 - 50	0 - 200	0 - 1	0 - 0.5
Satisfactory	51 - 100	51 - 100	31 - 60	41 - 80	41 - 80	51 - 100	201 - 400	1.1 - 2.0	0.5 - 1.0
Moderately polluted	101 - 200	101 - 250	61 - 90	81 - 180	81 - 380	101 - 168	401 - 800	2.1 - 10	1.1 - 2.0
Poor	201 - 300	251 - 350	91-120	181 - 280	381 - 800	169 - 208	801 - 1200	10 - 17	2.1 - 3.0
Very poor	301 - 400	351 - 430	121 - 250	281 - 400	801 - 1600	209 - 748	1200 - 1800	17 - 34	3.1 - 3.5
Severe	401 - 500	430 +	251 +	400 +	1600 +	748 +	1800 +	34 +	3.5 +

The Air Quality Index (AQI) is an environmental indicator that quantifies the overall status and trends of ambient air quality in a given location based on established standards. It is calculated as the ratio of pollutant concentration to the corresponding air quality standard, providing a comprehensive measure of air pollution levels. The AQI values for the monitoring sites under consideration were derived using the standardized computational approach outlined in previous studies. A higher AQI value indicates a greater level of air pollution, thereby posing a more significant risk to public health.

Effective communication of air quality conditions and associated health risks, the AQI scale is categorized into five distinct levels, as detailed in Table 2. These classifications provide a clear framework for assessing pollution severity and potential health effects. Extensive research has been conducted on various aspects of ambient air quality, including air quality index modeling, air pollution climatology, air quality monitoring, and PM_{10} assessment, contributing to a deeper understanding of atmospheric pollution dynamics.

Correlation and Simple Linear Regression:

The degree and direction of the relationship between two variables are determined by correlation analysis. On the other hand, regression analysis is a statistical technique for examining the connection between variables. It helps to comprehend how changes in one variable are related with changes in another (Montgomery *et al.* 2021).The data is available of PM_{10}, SO_2 and NO_2 concentrations at three locations. The data can be fit in a simple linear regression model to the data available to predict PM_{10} concentration based on SO_2 and NO_2. The response variable (Y say) as PM_{10} concentration and repressor (X say) as either SO_2 concentration or NO_2 concentration. The general simple linear regression model (SLRM) is given by

$$y = \beta_0 + \beta_1 X + \epsilon \qquad (4)$$

where, β_0 is slope parameter, β_1 is regression parameter and ϵ is error term.
For more details on regression analysis one can refer to

Results and Discussion

To analyse the annual average concentrations of PM_{10}, SO_2, and NO_2 at the three monitoring locations, air quality data was collected by the Department of Environmental Science, Shivaji University, Kolhapur. The annual average concentrations for these pollutants are presented in Table 3 and illustrated graphically in Figures 1(a-c). The findings indicate that the annual concentration of PM_{10} exceeded the prescribed standard of 60 µg/m³ at two of the monitoring locations throughout the study period. At SUK, PM_{10} concentrations were observed to surpass this threshold in 2015, 2016, 2018, and 2019, whereas in 2014, 2017, 2020, 2021, 2022, and 2023, concentrations remained below the National Ambient Air Quality Standards (NAAQS). The highest PM_{10} concentration recorded at DC site was 144.54 µg/m³ in 2019. Additionally, the average levels of Respirable Suspended Particulate Matter (RSPM) at the DC and MR sites consistently exceeded the NAAQS limits established by the Central Pollution Control Board (CPCB), corroborating findings from previous studies (Mangalekar *et al.*, 2015). In contrast, the annual concentrations of SO_2 in Kolhapur city have consistently remained below the prescribed standard of 50 µg/m³ set by the CPCB. A decreasing trend in SO_2 levels was observed from 2014 to 2023, indicating an overall improvement in air quality concerning sulfur dioxide pollution. In 2013, SO_2 concentrations at all three monitoring sites were well within the regulatory limits (Mangalekar *et al.*, 2015).

Recognizing the need for further emission reductions, the Government of India has implemented policies promoting the use of low-sulfur fuels in vehicular

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transport. SO_2 emissions primarily originate from coal combustion in power plants, industrial activities, and fuel combustion in vehicles. However, over the past decade, India has witnessed a decline in SO_2 emissions due to the adoption of cleaner energy sources, the transition to low-sulfur fuels, and the implementation of flue gas desulfurization technologies (Kuttippurath *et al.*, 2022). Sulfur dioxide (SO_2) is a major air pollutant in India, primarily emitted from coal combustion in thermal power plants, industrial processes, petroleum refining, and vehicular emissions (Kuttippurath *et al.*, 2022; Guttikunda *et al.*, 2019). Over the past decade (2014-2023), SO_2 concentrations in India have shown a declining trend, largely due to policy interventions, technological upgrades, and changes in fuel use (Li *et al.*, 2017; UNEP, 2019). Delhi, Kolkata, and Mumbai saw a ~40% decline in SO_2 levels between 2014 and 2023, largely due to coal plant shutdowns and cleaner fuel adoption (Kuttippurath *et al.*, 2022). Industrial hubs like Chennai and Kolkata still exceed WHO limits but remain below NAAQS standards (Sharma *et al.*, 2020). These policy interventions have contributed to the observed decline in ambient SO_2 concentrations across urban and industrial regions. NO_2 is lower than the prescribed standards 40 µg/m³ respectively at Shivaji University and Mahadwar chowk. Annual concentration of NO_2 at Dabholkar corner is always higher than the prescribed standards (40 µg/m³) except in the year 2021 and 2022. In the year 2014, NO_2 annual concentration was all time high i.e. 51.79 µg/m³. The concentrations of NO_2 determined were below the prescribed limit set by the CPCB at all the three locations (Mangalekar *et al.*, 2015).

Nitrogen dioxide (NO_2) is a major urban air pollutant primarily emitted from vehicular emissions, power plants, industrial combustion, and biomass burning (Guttikunda *et al.*, 2019; Sharma *et al.*, 2022). Over the past decade, NO_2 levels in India have fluctuated, influenced by economic growth, transportation expansion, energy use, and policy interventions. While NO_2 levels increased between 2014 and 2019 and it declined significantly during the 2020 COVID-19 lockdowns but rebounded in 2021-2023 as industrial and transport activities resumed (Beig *et al.*, 2021; Sharma *et al.*, 2022). Delhi and Kolkata consistently exceed the NAAQS limit, with NO_2 levels above 50 µg/m³ in peak years (Jain *et al.*, 2021). Mumbai and Chennai often remain within NAAQS but exceed WHO standards, with high local variations near traffic hubs (Ganguly *et al.*, 2021). Bengaluru shows a declining trend post-2020, attributed to EV adoption and improved traffic management (Sharma *et al.*, 2022). Particulate Matter (PM_{10}) pollution remains a major environmental and public health concern in India, primarily originating from vehicular emissions, road dust, construction activities, industrial pollution, and biomass burning (Guttikunda *et al.*, 2019; CPCB, 2019). The concentration of PM_{10} has varied significantly over the past decade due to economic growth, urbanization, policy interventions, and meteorological conditions (Sharma *et al.*, 2022). While PM_{10} levels increased between 2014 and 2019, a temporary drop occurred in 2020 due to COVID-19 lockdowns. However, post-pandemic economic recovery led to a rebound in 2021-2023, although policy measures such as the National Clean Air Programme (NCAP) and stricter emission regulations have helped slow the rate of increase (Beig *et al.*, 2021).

Delhi has consistently recorded the highest PM_{10} levels, exceeding 250 µg/m³ during peak years, with a partial decline post-2020 due to NCAP measures (Guttikunda *et al.*, 2019).

Kolkata and Mumbai have shown gradual improvements, but localized pollution hotspots remain near industrial zones (Sharma *et al.*, 2022). Bengaluru and Chennai have lower PM_{10} levels compared to northern cities but continue to face high seasonal variations (Jain *et al.*, 2021).

Table No. 3: Annual average of air pollutants in Kolhapur city during the years 2014 to 2023

Year	NAAQS (2009)	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
		Annual average concentration of SO_2 in µg/m³									
SUK	50	12.20 ±2.89	13.90 ±2.45	11.22 ±2.53	12.25 ±2.08	13.18 ±4.33	10.44 ±4.45	10.05 ±3.56	10.11 ±2.51	8.70 ±1.34	8.90 ±1.54
DC		29.09 ±7.57	26.74 ±7.31	27.10 ±5.49	28.07 ±5.98	26.87 ±5.12	27.63 ±5.12	30.06 ±6.81	23.40 ±7.03	19.88 ±2.65	19.28 ±4.12
MR		23.98 ±6.12	21.94 ±6.16	21.48 ±4.68	20.97 ±5.15	21.58 ±4.70	22.43 ±4.66	17.89 ±5.91	17.71 ±5.73	13.82 ±1.71	13.57 ±2.93
		Annual average concentration of NO_2 in µg/m³									
SUK	40	21.80 ±4.47	22.87 ±5.33	20.60 ±5.24	21.23 ±5.51	22.90 ±9.81	19.38 ±5.05	16.67 ±8.29	15.66 ±3.44	14.79 ±2.20	16.62 ±3.03
DC		51.79 ±15.93	51.76 ±13.44	51.21 ±11.36	49.56 ±15.20	44.40 ±13.23	51.39 ±12.92	45.86 ±19.03	39.21 ±14.63	37.74 ±8.42	46.37 ±4.20
MR		38.02 ±10.68	39.75 ±11.43	38.51 ±10.16	35.18 ±10.01	36.99 ±12.04	38.94 ±12.23	30.50 ±15.35	28.69 ±10.53	24.84 ±2.67	25.71 ±3.13
		Annual average concentration of PM_{10} in µg/m³									

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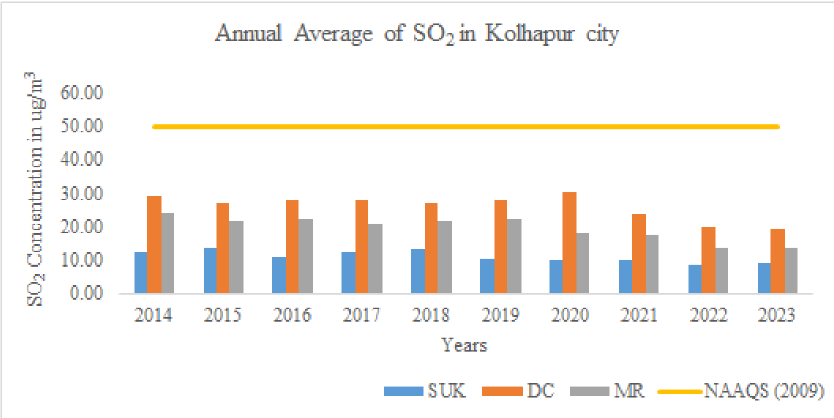
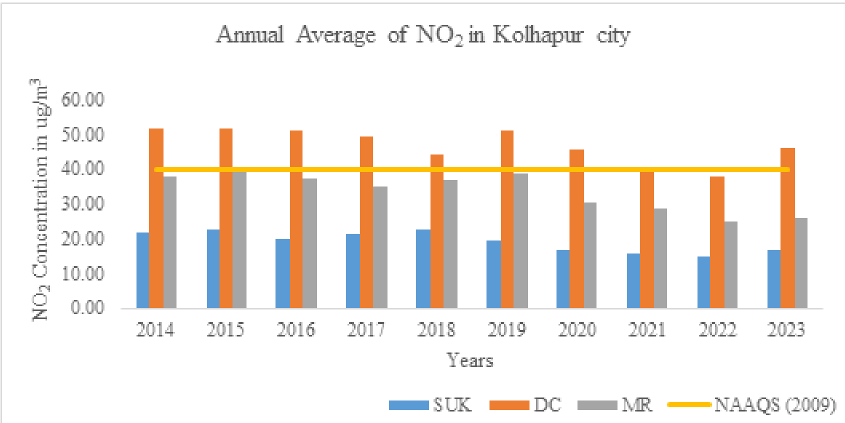
SUK	60	59.79 ±11.27	62.99 ±8.75	61.35 ±8.26	57.12 ±11.29	66.58 ±17.17	62.76 ±8.37	50.67 ±13.90	54.01 ±7.94	48.90 ±6.39	50.93 ±5.27
DC		133.55 ±45.12	122.27 ±20.23	116.68 ±20.49	117.79 ±26.35	113.69 ±16.40	144.54 ±18.03	119.06 ±28.28	111.48 ±22.28	116.37 ±21.10	122.75 ±14.61
MR		107.89 ±26.38	107.58 ±15.88	99.13 ±15.35	90.77 ±19.93	94.27 ±16.37	98.89 ±18.10	82.16 ±23.82	87.18 ±16.44	78.33 ±7.33	73.71 ±9.17

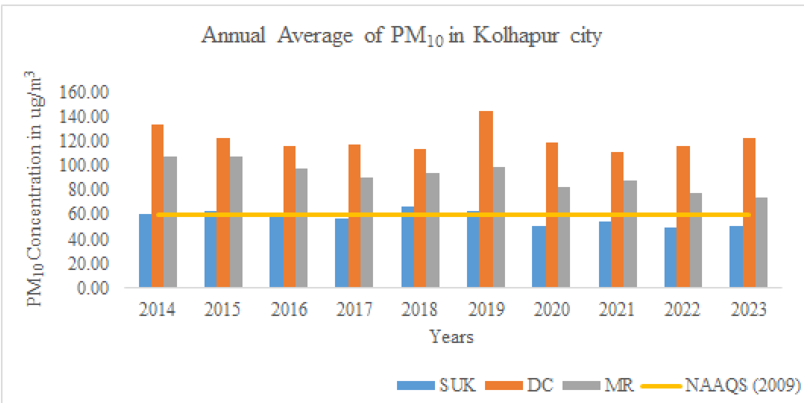
Graph No. 1a: Annual average of SO_2 in Kolhapur city during the years 2014 to 2023.



Graph No. 1b: Annual average of NO_2 in Kolhapur city during the years 2014 to 2023.



Graph No. 1c: Annual average of PM_{10} in Kolhapur city during the year 2014 to 2023.



Annual Exceedance factor

The annual exceedance factor has been summarized in Table 4. According to the exceedance factor, it is observed that the SO_2 pollution level at SUK and MR is low pollution and DC is moderate pollution. The maximum value of pollution is found in the year 2020, which is 0.60. It is found that the NO_2 pollution level at SUK is moderate to low pollution, after that at DC pollution level is high pollution because of dense traffic activity. PM_{10} pollution level at SUK is moderate to high pollution, DC PM_{10} pollution level is critical pollution and MR Pollution level is at critical pollution level. Kumar *et al.*, 2014 found that EF value in the different study locations shows low pollution areas. In residential and commercial areas the particulate matter mainly emitted from massive constructional activities, vehicles and road shoulders. SO_2 and NO_2 indicate that these pollutants are present in low polluting range (Roy and Singha, 2020). It is observed that all three locations in Kolhapur city PM_{10} concentrations are above the Central Pollution Control Board standards.

Post-2019 reductions due to Flue Gas Desulfurization (FGD) implementation in power plants (CPCB, 2019). SO_2 levels have remained low in most Indian cities due to cleaner fuels and improved emission controls. Coal-based power plants, refineries, and industrial clusters remain major SO_2 contributors in cities like Delhi, Mumbai, and Chennai (Kuttippurath *et al.*, 2022). Delhi and Kolkata consistently exceed the NAAQS limit for NO_2, with EF > 1.0 in peak years (Jain *et al.*, 2021). Mumbai and Chennai stay within NAAQS but exceed WHO guidelines (WHO, 2021). Bengaluru shows a declining trend post-2020, attributed to EV adoption and better traffic management (Sharma *et al.*, 2022). PM_{10} remains the most critical air pollutant in Indian cities, exceeding NAAQS levels in most cases. Delhi, Kolkata, and Mumbai have consistently exceeded PM_{10} limits since 2014 (Ganguly *et al.*, 2021). COVID-19 lockdown (2020) caused a temporary reduction, but levels rebounded in 2021-2023 (Beig *et al.*, 2021). Vehicular Emissions is major contributor to NO_2 exceedance in Delhi, Mumbai, and Kolkata (Sharma *et al.*, 2022). Industrial Activities like Power plants, refineries, and manufacturing units contribute to SO_2 and PM_{10} exceedance in Mumbai, Chennai, and Kolkata (CPCB, 2019). Seasonal Effects like winter months worsen pollution due to temperature inversion and stagnation (Beig *et al.*, 2021).

Table No. 4 Exceedance factor for monitoring stations in Kolhapur city during the year 2014 – 2023

Site Name	SUK	DC	MR	SUK	DC	MR	SUK	DC	MR
Parameters	**SO_2**			**NO_2**			**PM_{10}**		
2014	0.24	0.58	0.48	0.55	1.29	0.95	1.00	2.23	1.80
	Low pollution	Moderate pollution	Low pollution	Moderate pollution	High pollution	Moderate pollution	Moderate pollution	Critical pollution	Critical pollution
2015	0.28	0.53	0.44	0.57	1.29	0.99	1.05	2.04	1.79
	Low pollution	Moderate pollution	Low pollution	Moderate pollution	High pollution	Moderate pollution	High pollution	Critical pollution	Critical pollution
2016	0.22	0.55	0.44	0.50	1.28	0.93	1.00	1.93	1.63
	Low pollution	Moderate pollution	Low pollution	Low pollution	High pollution	Moderate pollution	Moderate pollution	Critical pollution	Critical pollution
2017	0.25	0.56	0.42	0.53	1.24	0.88	0.95	1.96	1.51
	Low pollution	Moderate pollution	Low pollution	Moderate pollution	High pollution	Moderate pollution	Moderate pollution	Critical pollution	Critical pollution
2018	0.26	0.54	0.43	0.57	1.11	0.92	1.11	1.89	1.57
	Low pollution	Moderate pollution	Low pollution	Moderate pollution	High pollution	Moderate pollution	High pollution	Critical pollution	Critical pollution
2019	0.21	0.55	0.45	0.48	1.28	0.97	1.05	2.41	1.65
	Low pollution	Moderate pollution	Low pollution	Low pollution	High pollution	Moderate pollution	High pollution	Critical pollution	Critical pollution
2020	0.20	0.60	0.36	0.42	1.15	0.76	0.84	1.98	1.37
	Low pollution	Moderate pollution	Low pollution	Low pollution	High pollution	Moderate pollution	Moderate pollution	Critical pollution	High pollution
2021	0.20	0.47	0.35	0.39	0.98	0.72	0.90	1.86	1.45
	Low pollution	Low pollution	Low pollution	Low pollution	Moderate pollution	Moderate pollution	Moderate pollution	Critical pollution	High pollution
2022	0.17	0.40	0.28	0.37	0.94	0.62	0.82	1.94	1.31
	Low pollution	Low pollution	Low pollution	Low pollution	Moderate pollution	Moderate pollution	Moderate pollution	Critical pollution	High pollution
2023	0.18	0.39	0.27	0.42	1.16	0.64	0.85	2.05	1.23
	Low pollution	Low pollution	Low pollution	Low pollution	High pollution	Moderate pollution	Moderate pollution	Critical pollution	High pollution

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Sub-indices for individual parameters (AQIs)

Annual Air Quality sub-indices at all stations

The individual Air Quality sub-index for the three monitoring stations was calculated and is presented in Table 5, with its graphical representation illustrated in Figures 2(a–c). A comparative analysis of Tables 2 and 4 reveals variations in sub-indices across the three monitoring sites. The overall Air Quality Index (AQI) for Kolhapur city is provided in Table 6, with its corresponding graphical representation shown in Figure 3.

The air quality sub-indices for three monitoring locations in Kolhapur city were determined based on three primary pollutants: Sulfur dioxide (SO_2), Nitrogen dioxide (NO_2), and Particulate matter (PM_{10}). At the SUK monitoring station, air quality remained within the "good" category throughout the year. Similarly, the MR location exhibited consistently good air quality across all observed years. In contrast, air quality at the DC station was predominantly classified as "moderate" year-round. The overall Air Quality Index (AQI), calculated using the Central Pollution Control Board (CPCB) methodology, ranged between 79 and 97, categorizing the air quality as "satisfactory," with potential for minor respiratory discomfort among sensitive individuals.

Delhi consistently records the highest levels of air pollution among Indian cities, with AQI levels frequently exceeding Very Poor (300–400) and reaching Severe (>400) levels in winter (Jain *et al.*, 2021). Mumbai and Chennai experience pollution spikes due to traffic emissions, industrial sources, and coastal meteorology (Ganguly *et al.*, 2021). Bengaluru has a relatively lower AQI, but congestion in Electronic City and Whitefield causes localized pollution (Sharma *et al.*, 2022). Kolkata's AQI worsens in winter, particularly in areas near Howrah and industrial belts (Guttikunda *et al.*, 2019).

Table No. 5 Location wise sub-indices for monitoring stations in Kolhapur city during the year 2014 to 2023

Parameters	SO_2				NO_2				PM_{10}			
Site Name	SUK	MR	DC	Avg. SO_2	SUK	MR	DC	Avg. NO_2	SUK	MR	DC	Avg. PM_{10}
2014	15.25	29.98	36.36	27.20	27.25	47.53	64.74	46.50	59.79	105.26	122.37	95.81
2015	17.38	27.43	33.43	26.08	28.59	49.69	64.70	47.66	62.99	105.05	114.85	94.30
2016	13.84	27.55	34.63	25.34	25.16	46.58	64.20	45.31	60.01	97.87	110.61	89.50
2017	15.31	26.21	35.09	25.54	26.54	43.98	61.95	44.15	57.12	90.77	111.86	86.58
2018	16.48	26.98	33.59	25.68	28.63	46.24	55.50	43.45	66.58	94.27	109.13	89.99
2019	13.05	28.04	34.54	25.21	24.23	48.68	64.24	45.71	62.76	98.89	129.69	97.11
2020	12.56	22.36	37.58	24.17	20.84	38.13	57.33	38.76	50.67	82.16	112.71	81.85
2021	12.63	22.14	29.24	21.34	19.58	35.86	49.01	34.82	54.01	87.18	107.65	82.95
2022	10.88	17.27	24.85	17.66	18.49	31.05	47.18	32.24	48.9	78.33	110.91	79.38
2023	11.12	16.96	24.10	17.39	20.78	32.14	57.97	36.96	50.93	73.71	115.17	79.94

Table No. 6 AQI for Kolhapur city during the year 2014 to 2023

Year	SO_2	NO_2	PM_{10}	AQI
2014	27.20	46.50	95.81	95.81
2015	26.08	47.66	94.30	94.30
2016	25.34	45.31	89.50	89.50
2017	25.54	44.15	86.58	86.58
2018	25.68	43.45	89.99	89.99
2019	25.21	45.71	97.11	97.11
2020	24.17	38.76	81.85	81.85
2021	21.34	34.82	82.95	82.95
2022	17.66	32.24	79.38	79.38

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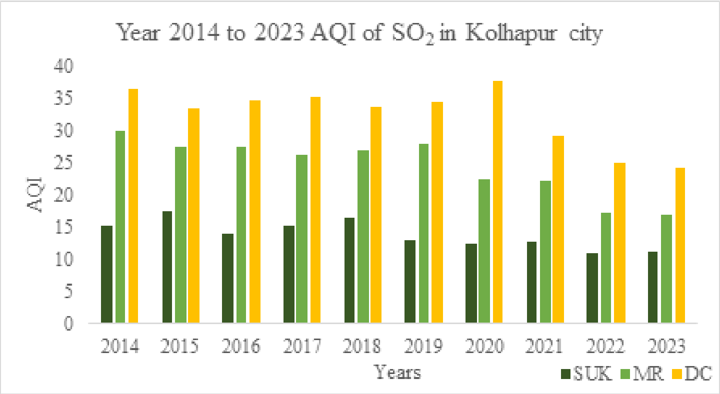
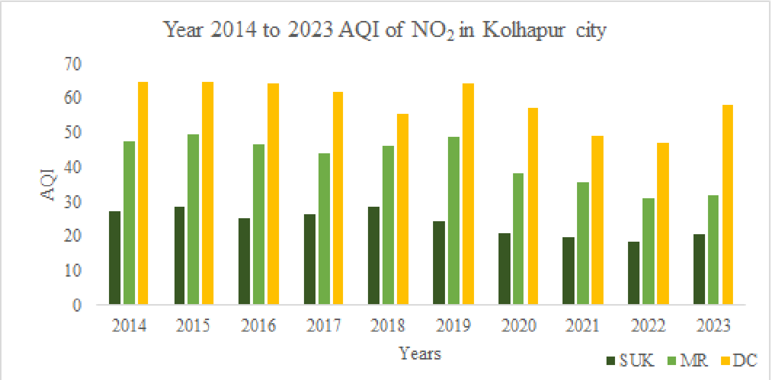
2023	17.39	36.96	79.94	79.94

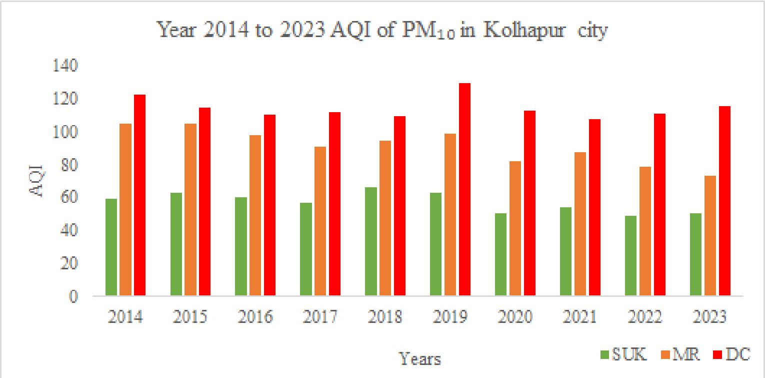
Graph No. 2a: Sub-index of SO_2 in Kolhapur city during the year 2014 to 2023.



Graph No. 2b: Sub- index of NO_2 in Kolhapur city during the year 2014 to 2023.



Graph No. 2c: Sub- index of PM_{10} in Kolhapur city during the year 2014 to 2023.



Graph No. 3: AQI of Kolhapur city during the year 2014 to 2023.

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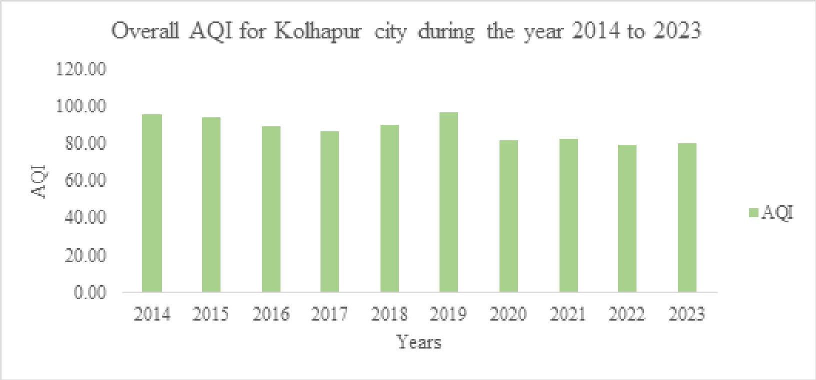
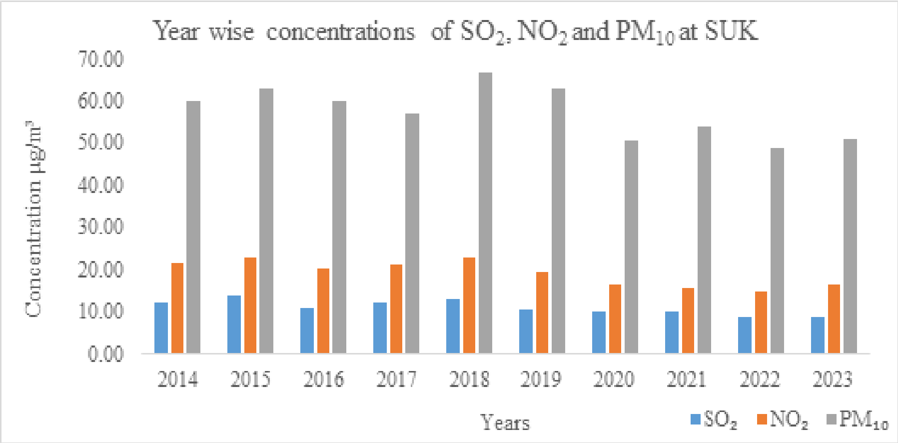
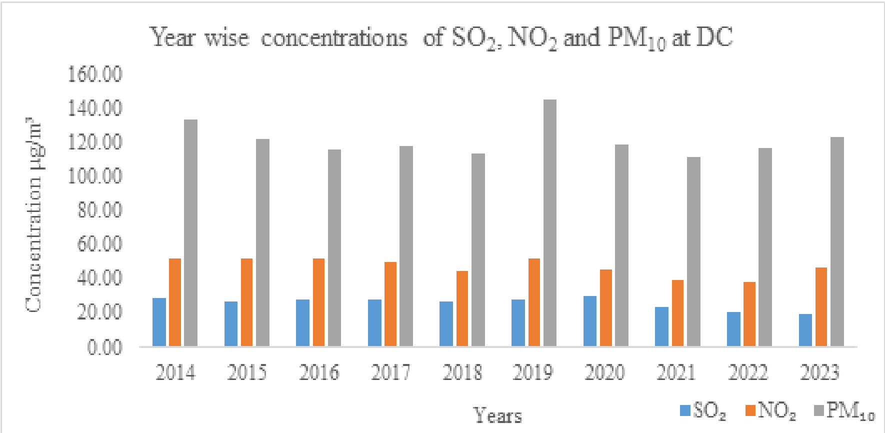


The following graphs (Figure 4 a, b, c) gives the idea about the variation in the PM_{10}, SO_2 and NO_2 concentration over the period of 2014 to 2023 at SUK, DC and MR respectively.

Graph No. 4a. Year wise concentrations of SO_2, NO_2 and PM_{10} at SUK



Graph No. 4b. Year wise concentrations of SO_2, NO_2 and PM_{10} at DC



Graph 4 c. Year wise concentrations of SO_2, NO_2 and PM_{10} at MR

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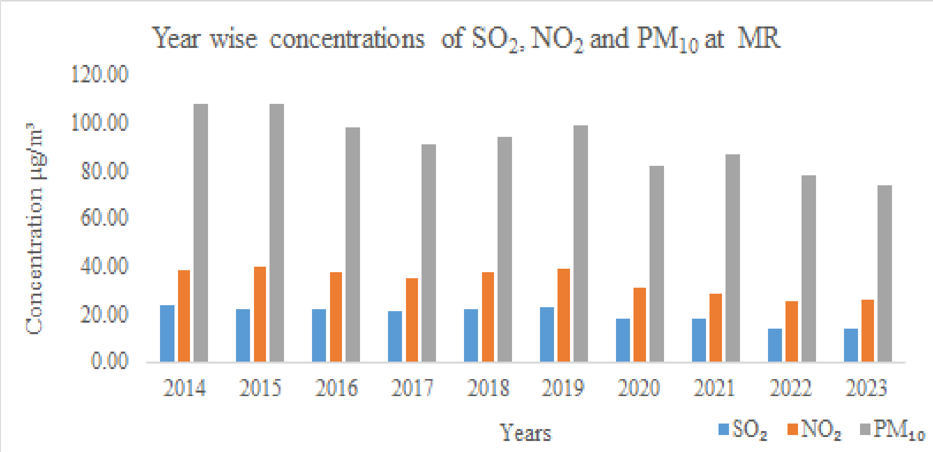

Correlation and Regression Analysis

The correlation analysis of PM_{10} with SO_2 and NO_2 across the three monitoring stations in Kolhapur city reveals distinct spatial variations in pollutant relationships. These differences highlight the influence of local emission sources, meteorological factors, and atmospheric chemistry in shaping air quality patterns.

Table No. 6. Correlation Analysis Results for SO_2 and NO_2 in Kolhapur city during the year 2014 -23

Area	Concertation	Value of Karl-Pearson's Correlation coefficient with PM_{10}
SUK	SO_2	0.8220
	NO_2	0.8844
DC	SO_2	0.2670
	NO_2	0.5836
MR	SO_2	0.9308
	NO_2	0.9263

At SUK, the strong positive correlations between PM_{10} and both SO_2 (0.8220) and NO_2 (0.8844) suggest that vehicular emissions and combustion processes are major contributors to air pollution in this area. Studies have shown that SO_2 and NO_2 are commonly associated with fossil fuel combustion, particularly from traffic and industrial sources, which also generate fine and coarse particulate matter (Guttikunda & Calori, 2019; Sharma *et al.*, 2020). These results align with research indicating that higher levels of gaseous pollutants in urban environments are often accompanied by elevated PM_{10} concentrations, driven by common emission sources and atmospheric reactions (Zhang *et al.*, 2021). At DC, the correlation between PM_{10} and SO_2 is relatively low (0.2670), whereas NO_2 exhibits a moderate correlation (0.5836). The weak relationship between SO_2 and PM_{10} may indicate that sulfur dioxide emissions in this area arise from sources that do not significantly contribute to particulate matter levels, such as industrial emissions that disperse before interacting with local particulate pollution (Cheng *et al.*, 2019). Conversely, the moderate correlation between NO_2 and PM_{10} suggests that traffic emissions remain a dominant source of air pollution, though local factors such as dispersion patterns or secondary pollutant formation may reduce the strength of the association (Kumar et al., 2021).

Similar studies have reported variability in pollutant correlations based on urban topography and traffic intensity, where NO_2 often exhibits stronger correlations with PM_{10} in areas dominated by vehicular activity (Gao *et al.*, 2020). At MR, the exceptionally high correlations between PM_{10} and both SO_2 (0.9308) and NO_2 (0.9263) indicate that these pollutants likely originate from the same sources and follow similar dispersion patterns. Such strong associations are often observed in areas with heavy traffic congestion, high industrial emissions, and commercial activities that contribute both primary particulates and gaseous pollutants (Gupta & Kumar, 2021; Zhang *et al.*, 2022). Additionally, research suggests that high PM_{10} concentrations can enhance the retention of SO_2 and NO_2 in the atmosphere by acting as carriers for these gaseous pollutants, further reinforcing their correlation (Wu *et al.*, 2019). This could explain the stronger association at MR compared to DC, where local conditions might lead to different pollutant interactions. These variations in correlation strengths across Kolhapur city highlight the complexity of urban air pollution dynamics. Factors such as local emission inventories, meteorological conditions (e.g., wind patterns, humidity, and temperature), and secondary chemical transformations play a critical role in shaping pollutant interactions (Seinfeld & Pandis, 2016). The findings underscore the need for targeted air quality management strategies, where mitigation measures should be tailored to the specific pollution sources and characteristics of each location. Future research incorporating seasonal variations and source apportionment models would provide deeper insights into the underlying drivers of these correlations. The regression analysis results provide deeper insights into the relationship between PM_{10} and the gaseous pollutants SO_2 and NO_2 across the three study locations in Kolhapur. By assessing the R-squared (R^2) values and p-values, the study evaluates the predictive strength and statistical significance of these regression models, helping to identify key pollution sources and potential confounding factors. Results summarize in Table 7.

Table No. 7. Regression Analysis for Kolhapur city during the year 2014 – 2023

Area	Prediction of PM_{10} based on	Regression Equation: $PM^{10}Con. = \beta_0 + \beta_1 SO2\ Con.$	p- value of Overall Regression	R^2
SUK	**SO_2**	PM_{10} Con. = 26.13+2.82 * SO_2 Con.	0.0035	0.6757
	NO_2	PM_{10} Con. = 23.82+1.74 * NO_2 Con.	0.0007	0.7821
DC	**SO_2**	PM_{10} Con. = 103.14+0.72 * SO_2 Con.	0.3306	0.4557
	NO_2	PM_{10} Con. = 68.78+1.13 * NO_2 Con.	0.0765	0.3406
MR	**SO_2**	PM_{10} Con. = 34.79+2.96 * SO_2 Con.	0.00009	0.8663
	NO_2	PM_{10} Con. = 27.47+1.92 * NO_2 Con.	0.00011	0.8581

At Shivaji University, Kolhapur (SUK), the regression models for SO_2 (R^2 = 0.6757, p = 0.0035) and NO_2 (R^2 = 0.7821, p = 0.0007) are both statistically significant. This suggests that these pollutants explain a substantial portion of the PM_{10} variability in this region, indicating a strong relationship between vehicular and industrial emissions and particulate matter concentrations. The higher predictive power of NO_2 compared to SO_2 aligns with studies showing that NO_2 is often more strongly associated with PM_{10} in urban areas due to its role in secondary aerosol formation and traffic-related emissions (Gupta & Kumar, 2021; Zhang *et al.*, 2022). The significance of SO_2 also suggests contributions from fuel combustion processes, potentially from local industrial activities or biomass burning, which are known sources of both primary particulates and sulfur dioxide emissions (Tian *et al.*, 2022). At Dhabholkar Corner (DC), the regression models show weaker relationships, with R^2 values of 0.4557 (SO_2) and 0.3406 (NO_2) and higher p-values (0.3306 for SO_2, 0.0765 for NO_2). These results indicate that SO_2 and NO_2 alone do not adequately explain variations in PM_{10} concentrations at this location, suggesting that other factors—such as meteorological conditions (wind speed, humidity), resuspended road dust, or additional pollutants like CO and VOCs—might play a more dominant role (Hsu *et al.*, 2019). Similar findings have been reported in urban pollution studies where weaker R^2 values in regression models indicate a more complex mix of pollution sources, requiring multi-variable modeling approaches to improve predictive accuracy (Gholami *et al.*, 2020). The relatively higher p-value for SO_2 suggests that this variable is not a statistically significant predictor of PM_{10} in DC, reinforcing the idea that its presence may be influenced by regional atmospheric transport rather than local emissions (Cheng *et al.*, 2019).

At Mahadwar Road (MR), the regression models exhibit high predictive power, with R^2 values exceeding 0.85 and p-values close to zero, indicating strong statistical significance. This suggests that SO_2 and NO_2 are highly reliable predictors of PM_{10} levels in this area. The strong association aligns with research on air pollution hotspots, where high vehicular density, industrial activities, and commercial emissions create a strong link between gaseous pollutants and particulate matter (Seinfeld & Pandis, 2016). Studies have also found that in densely populated urban areas, NO_2 and SO_2 often show high predictive accuracy for PM_{10} due to their common origin from combustion sources (Wu *et al.*, 2020). Furthermore, atmospheric reactions involving NO_2 and SO_2 can contribute to secondary aerosol formation, reinforcing their strong correlation with particulate matter (Tian *et al.*, 2022).

Conclusions

The study provides a comprehensive assessment of air quality trends in Kolhapur city, highlighting persistent PM_{10} pollution, particularly at Dabholkar Corner (DC) and Mahadwar Road (MR), where concentrations frequently exceed NAAQS limits. In contrast, SO_2 and NO_2 levels generally remain within regulatory standards, with occasional exceedances at DC. Exceedance factor analysis indicates low to moderate SO_2 pollution, while NO_2 pollution varies from low to high across locations. PM_{10} pollution ranges from moderate to critical, with DC experiencing the highest pollution levels. AQI analysis classifies air quality as satisfactory, with PM_{10} as the dominant pollutant. Correlation and regression analyses reveal a strong relationship between PM_{10} and SO_2/NO_2 at SUK and MR, whereas DC shows weaker associations, suggesting additional influencing factors. These findings underscore the need for targeted mitigation strategies and localized studies to address air pollution in Kolhapur.

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