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Assessing Air Quality Dynamics In Kolkata Municipal Corporation: A Seasonal And Temporal Perspective

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Abstract:
This study assesses seasonal and temporal variations in air quality across the Kolkata Municipal Corporation (KMC) by comparing station-level concentrations of NO_2, PM_{10}, and SO_2 for 2003 and 2022. Thirteen monitoring stations and three seasonal windows (pre-monsoon, monsoon, post-monsoon) were analysed. AQI was computed to examine public-health implications and to identify spatial hotspots. Results reveal pronounced seasonal heterogeneity. Pre-monsoon shows a modest decline in NO_2 but significant increases in PM_{10} and SO_2, driven by a few local hotspots. Monsoon displays unexpectedly higher PM_{10} and AQI at many sites, suggesting strong local sources or resuspension that overcome wet scavenging. Post-monsoon exhibits the largest improvements: substantial reductions in both NO_2 and PM_{10}. The findings indicate partial success in controlling gaseous emissions but persistent or emerging particulate problems. The study suggests targeted, location-specific particulate mitigation, including dust suppression, construction controls, and systematic road maintenance, together with improved transparency of monitoring metadata.
Keywords: *Air Pollution; Air Quality Index (AQI); PM_{10}; Air Pollutants; Urbanization; KMC;*

1. INTRODUCTION:

The Air Quality Index (AQI) is a modern tool designed to communicate the status of air quality to the public. It is a composite index that converts the measured values of various pollutants into a single number [1]. This simplifies complex data into a specific index value, accompanied by standardized terminology and a color code. AQI classifications, Good, Satisfactory, Moderately Polluted, Poor, Very Poor, and Severe, are based on the ambient concentrations of pollutants and their established health breakpoints, which reflect potential health impacts. The sub-index for each pollutant is calculated as a linear function of its concentration. The overall AQI is then determined by the worst sub-index value among the eight pollutants: PM10, PM2.5, NO2, CO, O3, SO2, NH3, and Pb [2].

The critical need for such an index was underscored by devastating air pollution disasters, such as the one in London in December 1952, which caused 4,000 deaths [3]. In India, air pollution directly affects 300 million urban residents, representing 30 percent of the total population [4]. The AQI was developed to specify such risks and raise public awareness, allowing people to understand pollution levels in their cities and take precautions against health risks [5]. Today, air quality is a primary concern worldwide, especially in the West and many developed countries.

Indian cities frequently appear on the list of the world's most polluted cities [6]. In rapidly industrializing and growing urban areas, air pollution has become a major environmental challenge [7]. Unplanned urban growth and the extensive use of fossil fuels result in poor air quality. Approximately 90% of air pollution-related mortality occurs in lower and middle-income nations [8, 9], as poor air quality significantly impacts human health [10, 11]. This deterioration necessitates daily monitoring to track atmospheric health.

This paper investigates the seasonal distribution of the Air Quality Index across different monitoring stations in the Kolkata Municipal Corporation from 2003 to 2022. A 2022 report from the State of Global Air ranked Kolkata as the second most polluted city, with an annual average PM2.5 level of 84 micrograms per cubic meter, a value seventeen times higher than the World Health Organization's recommended limit.

2. Study Area:

This study focuses on the area under the Kolkata Municipal Corporation (KMC). Kolkata, a tropical metropolitan city and the capital of West Bengal, is situated on the left bank of the Hugli River. The KMC area spans longitudes from 88.24°E to 88.46°E and latitudes from 22.43°N to 22.63°N, covering 200.71 km² and divided into 144 wards (Fig. 1). According to the 2011 Census of India, the population within the KMC is 4,496,694. This area constitutes the core urban zone of Kolkata, characterized by a diverse and dense built environment that reflects the city's multifunctional nature.

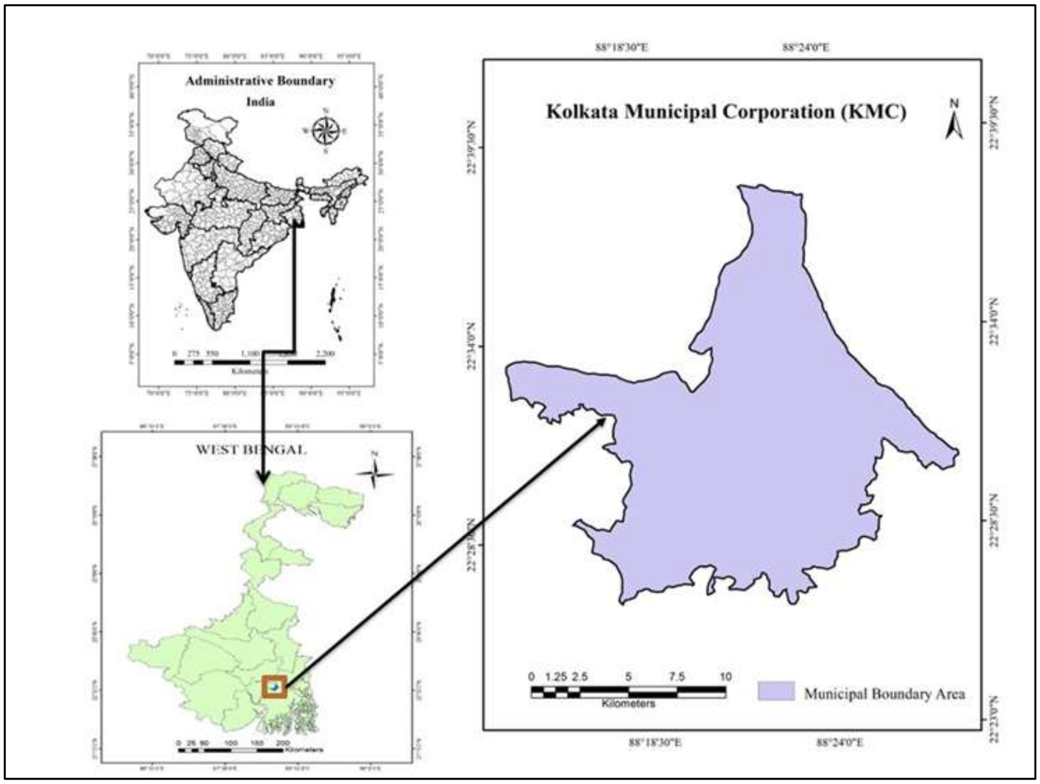


Fig 1: Location Map of Study Area (Kolkata Municipal Corporation)

3. Database:

Three significant air pollutants, SO_2, NO_2, and PM_{10} were selected to calculate and analyze changes in the AQI from 2003 to 2022 across three different seasons (Table 1). Secondary data for these pollutants were obtained from 13 air quality monitoring stations maintained by the West Bengal Pollution Control Board (WBPCB). The AQI was calculated using the standard calculator provided by the Central Pollution Control Board (Eq. 1 to Eq. 6). Following official guidelines [12], a minimum of three pollutants is required, one of which must be either $PM_{2.5}$ or PM_{10}.

4. METHODOLOGY:

The Central Pollution Control Board of India jointly executed the National Air Quality Index in 2015 with the collaboration of the Ministry of Environment and Forest, Government of India. All the data has been analyzed in MS Excel. Data has been collected in the concentration value of pollutants, which is 24 hourly averages, with the range of health breakpoints. Minimum three pollutants, one should be either PM_{10} or $PM_{2.5,}$ and a minimum average of 16 hours of data has been required to identify the air quality index in an area; otherwise, it has been considered as inadequate. The process involves in aggregation of sub-indices by calculating individual sub-indices of all three pollutants [13].

The maximum operator approach has been used to remove ambiguity and concealing [14]. In equation no. 1, sub-indexes I_1, I_2,....I, have been formed by variables of all pollutants X_1, X_2,....$X_{n,}$ where I_i is the value of the sub-index and X_i is the concentration of the pollutant. In equation no. 2, aggregations of sub-indices have been performed based on the overall index (I). Sub-indexes have represented the relationship between the change in concentration and corresponding sub-indexes of that particular pollutant (Fig. 2). In equation no. 3, these relationships have been signified as linear or non-linear and may be segmented linear, where a is the slope of the line, β is the intercept, and X is 0.

In equation no. 4, sub-indices of a given concentration of pollutant have been calculated based on a linear segmented principle where B_{HI} is the breakpoint concentration, which is greater than or equal to the given concentration, and B_{LO} is the breakpoint concentration, which is smaller than or equal to the given concentration. The I_{HI} and I_{LO} are air quality index values corresponding to B_{HI} and $B_{LO,}$ respectively, and C_P is the concentration of the pollutant.

In equation no. 5, a simple additive form or weighted additive form has been combined to form sub-indices where summation w_i is 1, Ii is the sub-indices of pollutant I, n is the number of variables of pollutant, w_i is the weightage of the pollutant, and p is a positive real number which is greater than 1.

Root mean square and minimum or maximum operator have been formed by using equation no. 6. There are various methods to identify sub-indexes; the poorest sub-index value has been considered as the air quality index of that particular location.

Equation no. 1: $\mathbf{Ii = f(Xi), i = 1, 2, ..., n}$

Equation no. 2: $\mathbf{I = F(I1, I2, ..., In)}$

Equation no. 3: $\mathbf{I = aX + \beta}$

Equation no. 4: $\mathbf{Ii = \left[\left\{\frac{IHI-ILO}{BHI+BLO}\right\} * (CP - BLO)\right] + ILO}$

Equation no. 5: $\mathbf{I = \sum \quad wi\ Ii\ (For = 1, 2, ..., n)}$

Equation no. 6: $\mathbf{I = Min\ or\ Max\ (I1, I2, I3, \ ......, In}$

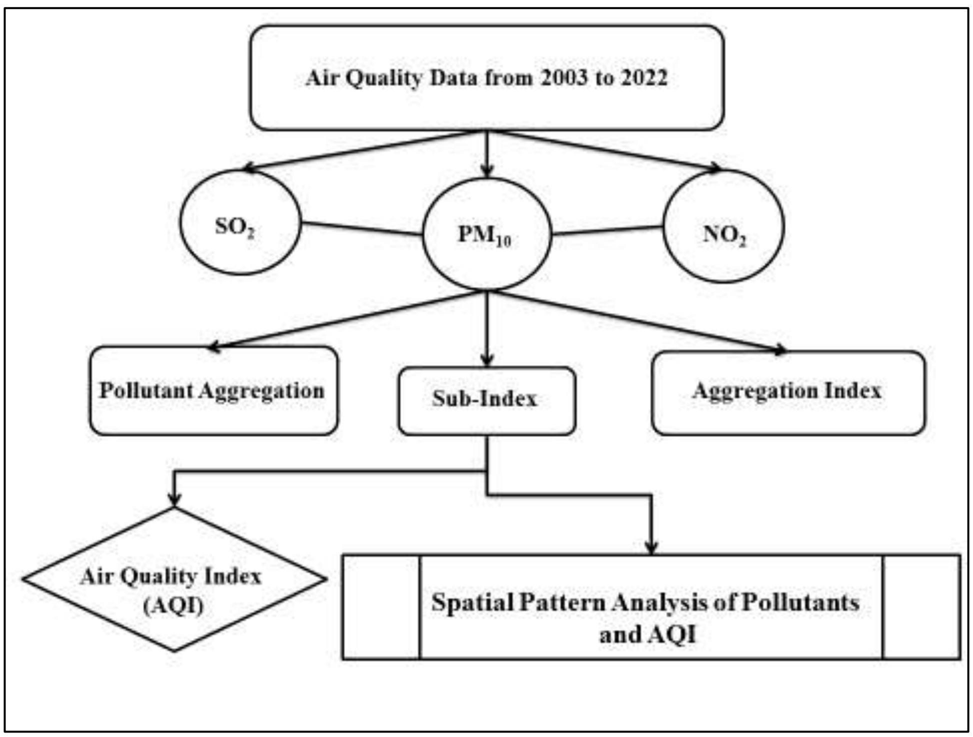


Fig 2: Methodological chart of the study

5. RESULT AND DISCUSSION:

Urbanization naturally occurs when a large population becomes concentrated in a specific area. This is an ongoing and continuous process, inherently linked to the demand for economic development. In the contemporary era, however, unplanned urbanization has been driven by the need to fulfill the requirements of the growing population and has significantly harmed the urban environment. The expansion of economic activities and the associated infrastructural development have further intensified environmental degradation in urban areas [15].

Kolkata Municipal Corporation has been considered as a metropolitan, and the level of development here has been crossing its limits day by day. As a result of the triggered rapid urban growth in Kolkata, various issues related to environmental conditions have been seen. Among those, polluted air has a significant role in damaging human health. This study analyzes the trend of the Air Quality Index (AQI) to identify periods of poor air quality.

Three prominent air pollutants have been monitored: SO_2, $PM_{10,}$ and NO_2. Sulphur dioxide has been considered as a harmful gas that increases hospital admissions for respiratory and cardiovascular diseases. Particulate matters (PM) are comprised of a mixture of solids and liquid droplets with a variety of sizes that range between 2.5 and 10 micrometers. Less than 10 micrometers in diameter have been identified as responsible for lung-related serious health problems.

The main sources of these particles include the crushing and grinding process in factories and dust stirred up by vehicles travelling on streets. Nitrogen dioxide is a severe air pollutant in its own. The main reason behind increasing nitrogen dioxide is motor vehicle emissions in urban areas, which contribute to morbidity and mortality among vulnerable groups like children, young people, and older people with asthmatic symptoms, chronic bronchitis, and inflammatory reactions in the lungs.

According to the West Bengal Pollution Control Board's information, 13 air quality monitoring stations have been set up under the Kolkata Municipal Corporation. Those are Picnic Garden, Tollygunge, Hide Road, Behala Chowrasta, Beliaghata, Topsia, Baishnabghata, Ultadanga, Mominpore, Moulali, Shyambazar, Gariahat, and Minto Park. It is found that there is a seasonal variation in the concentration of these three major pollutants over the period of 2003 to 2022. These variations of these major pollutants largely influence the air quality in the city.

5.1Pre-Monsoon Concentration: (March-May):

The pre-monsoon period in Kolkata is characterized by rising temperatures, low humidity, and strong convective activity, conditions that often enhance dust resuspension and secondary aerosol formation. This transitional phase between winter stability and monsoonal cleansing significantly influences urban air chemistry and pollutant dispersion dynamics.

Between 2003 and 2022, the overall NO_2 concentration exhibited mixed trends, with moderate fluctuations across different monitoring stations (Table 1). While stations such as Hyde Road and Picnic Garden recorded noticeable increases, several others, including Behala Chowrasta, Gariahat, and Topsia, reflected marked declines (Fig. 3.a). The citywide mean fell slightly from 41 µg/m³ in 2003 to 33 µg/m³ in 2022, suggesting a net reduction of around 20%. This decline likely reflects improvements in vehicular emission standards, the introduction of compressed natural gas (CNG) in public transport, and a gradual shift toward cleaner fuels. However, the persistence of localized NO_2 peaks near traffic intersections and commercial corridors indicates that vehicular congestion remains a dominant contributor to pre-monsoon NO_2 levels.

Table 1: Temporal Variation of Air Pollutants and AQI in Kolkata (Pre-Monsoon: 2003 vs 2022)

POLLUTANTS	NO2		PM10		SO2		AQI	
Year (Pre-Monsoon)	**2003**	**2022**	**2003**	**2022**	**2003**	**2022**	**2003**	**2022**
BAISHNABGHATA	27	31	40	73	1	4	40	73
BEHALA CHOWRASTA	47	28	90	51	2	4	90	51
BELIAGHATA	39	31	55	98	2	8	55	98
GARIAHAT	40	27	70	67	2	4	70	67
HYDE ROAD	37	49	70	190	1	16	70	160
MINTO PARK	32	36	55	79	1	4	55	79
MOMINPORE	46	18	50	31	3	4	58	31
MOULALI	51	36	79	91	3	8	79	91
PICNIC GARDEN	30	41	85	126	2	14	85	117
SHYAMBAZAR	37	40	75	147	2	13	75	131
TOLLYGUNGE	46	35	80	36	3	4	80	44
TOPSIA	49	23	96	47	4	4	96	47
ULTADANGA	53	32	79	78	1	5	79	78
Kolkata	**41**	**33**	**71**	**86**	**2**	**7**	**72**	**82**

Source: West Bengal Pollution Control Board (AQI calculated by the author)

The PM_{10} (Particulate Matter <10μm) concentration during the pre-monsoon season rose significantly, increasing from an average of 71 μg/m³ in 2003 to 86 μg/m³ in 2022. This represents an approximate 21% rise over two decades (Fig. 3c & 3d). The escalation can be attributed to construction activities, unpaved road dust, and industrial emissions, which are less effectively dispersed during the dry, windy pre-monsoon months. Stations like Hyde Road and Shyambazar experienced dramatic increases, exceeding 100%, while peripheral areas such as Behala and Tollygunge witnessed notable reductions, indicating uneven spatial improvement. Statistical tests confirm that the increase in PM_{10} is significant ($p < 0.05$) with a moderate effect size, emphasizing particulate pollution as the primary driver of degraded air quality during this season.

Pre-Monsoon Season

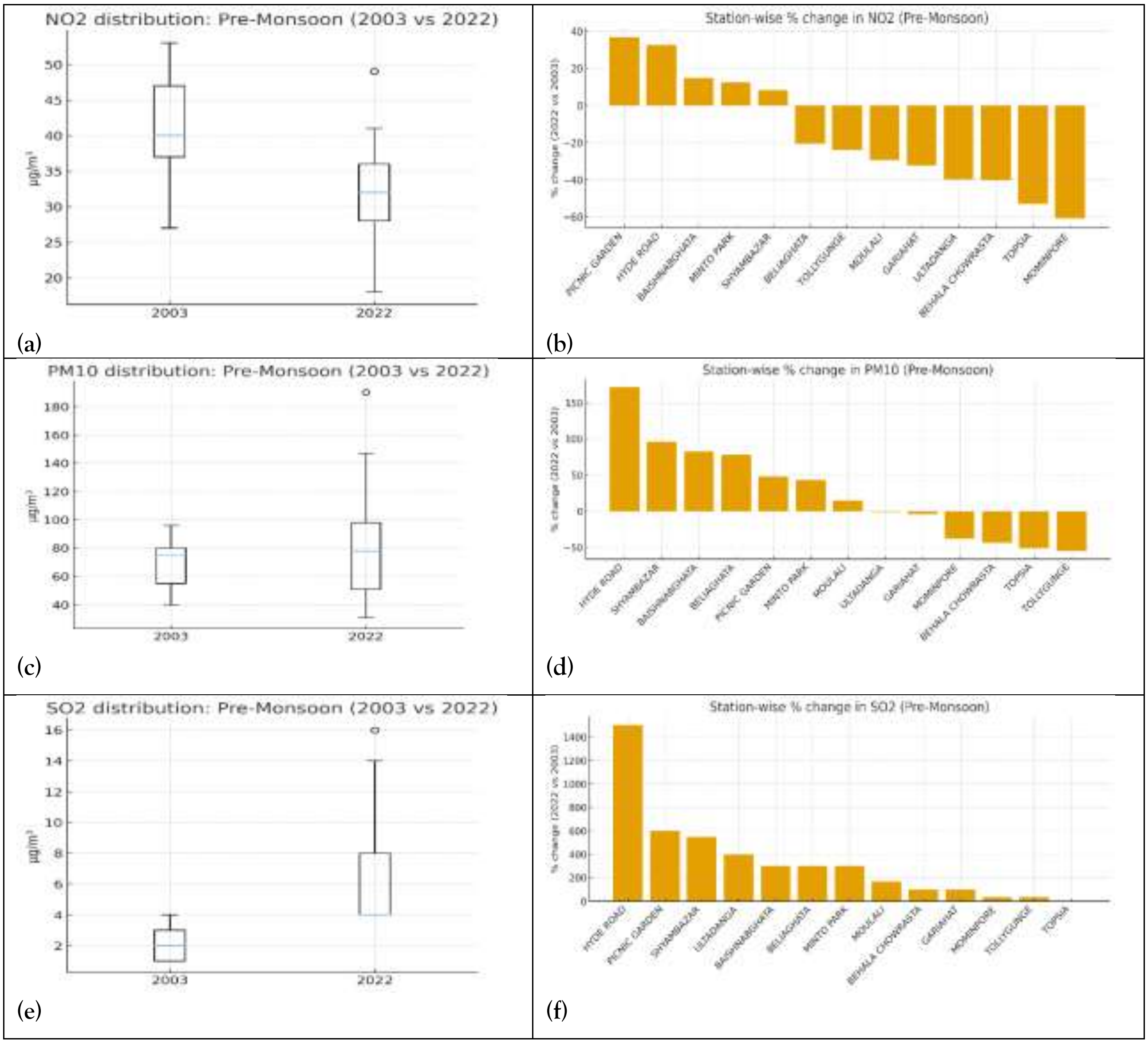


Fig 3: Pollutant distribution and changes during Pre-Monsoon season (2003 to 2022)

In contrast, SO_2 (Sulfur Dioxide) concentrations remain consistently low, increasing only marginally from 2 μg/m³ to 7 μg/m³ in the city mean (Fig. 3.e). The minor upsurge may be linked to sporadic industrial emissions and diesel generator usage, but overall values remain well below the national ambient air quality standards (NAAQS). The limited rise also reflects successful fuel desulfurization policies and the gradual transition toward cleaner energy sources.

The Air Quality Index (AQI) during the pre-monsoon season indicates a modest deterioration over the two decades, rising from 72 to 82 at the city level (Fig. 7.a). Spatially, Hyde Road, Shyambazar, and Picnic Garden showed a steep AQI rise, corresponding to the spike in PM_{10}. Conversely, localities such as Behala Chowrasta, Mominpore, and Topsia reflected marked improvement (Fig. 7. b). Statistical correlation analyses reveal PM_{10}

as the dominant determinant of AQI (r = 0.9), followed by NO_2 (r =0.7), while SO_2 shows a negligible relationship due to its persistently low concentrations. Overall, the pre-monsoon assessment suggests that particulate matter remains the most challenging pollutant. The increasing AQI values underscore the need for targeted dust mitigation strategies, stricter construction regulations, and better control of vehicular exhaust during the dry months preceding the monsoon.

5.2 Monsoon Concentration (June-September):

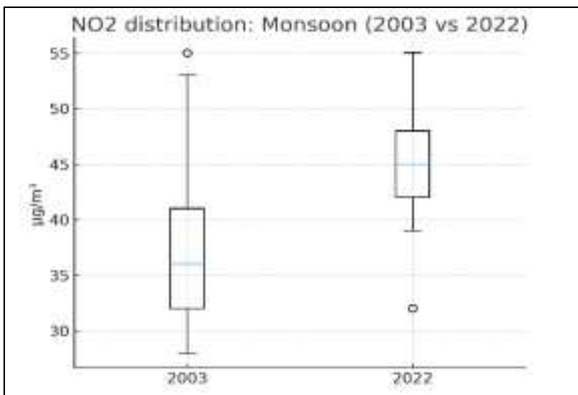
The monsoon season marks a distinct phase in Kolkata's atmospheric environment, characterized by high relative humidity, frequent rainfall, and enhanced wet deposition processes that influence pollutant dispersion and removal.

Table 2: Temporal Variation of Air Pollutants and AQI in Kolkata (Monsoon: 2003 vs 2022)

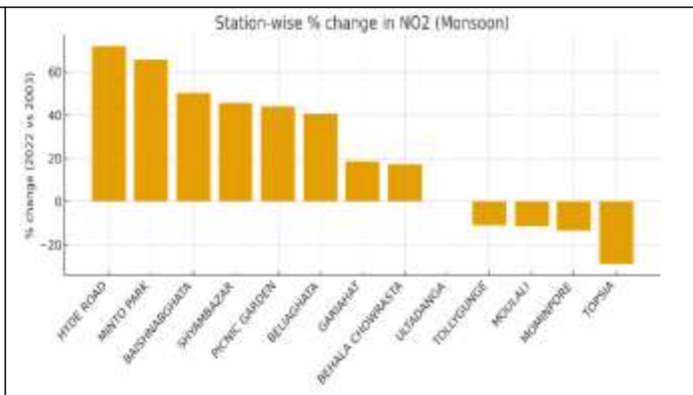
POLLUTANTS	NO2		PM10		SO2		AQI	
Year (Monsoon)	**2003**	**2022**	**2003**	**2022**	**2003**	**2022**	**2003**	**2022**
BAISHNABGHATA	28	42	30	51	2	2	35	53
BEHALA CHOWRASTA	41	48	48	90	2	2	51	90
BELIAGHATA	32	45	41	69	4	2	41	69
GARIAHAT	38	45	47	78	3	2	48	78
HYDE ROAD	32	55	36	143	3	13	40	129
MINTO PARK	29	48	29	94	2	2	36	94
MOMINPORE	37	32	32	35	3	2	46	40
MOULALI	53	47	55	71	4	2	66	71
PICNIC GARDEN	32	46	23	114	2	8	40	109
SHYAMBAZAR	33	48	43	113	2	11	43	109
TOLLYGUNGE	36	32	38	33	2	2	45	40
TOPSIA	55	39	58	42	5	2	69	49
ULTADANGA	45	45	37	71	4	2	56	71
Kolkata (Average)	**38**	**44**	**40**	**77**	**3**	**4**	**47**	**77**

Source: West Bengal Pollution Control Board (AQI calculated by the author)

Monsoon Season



(a)



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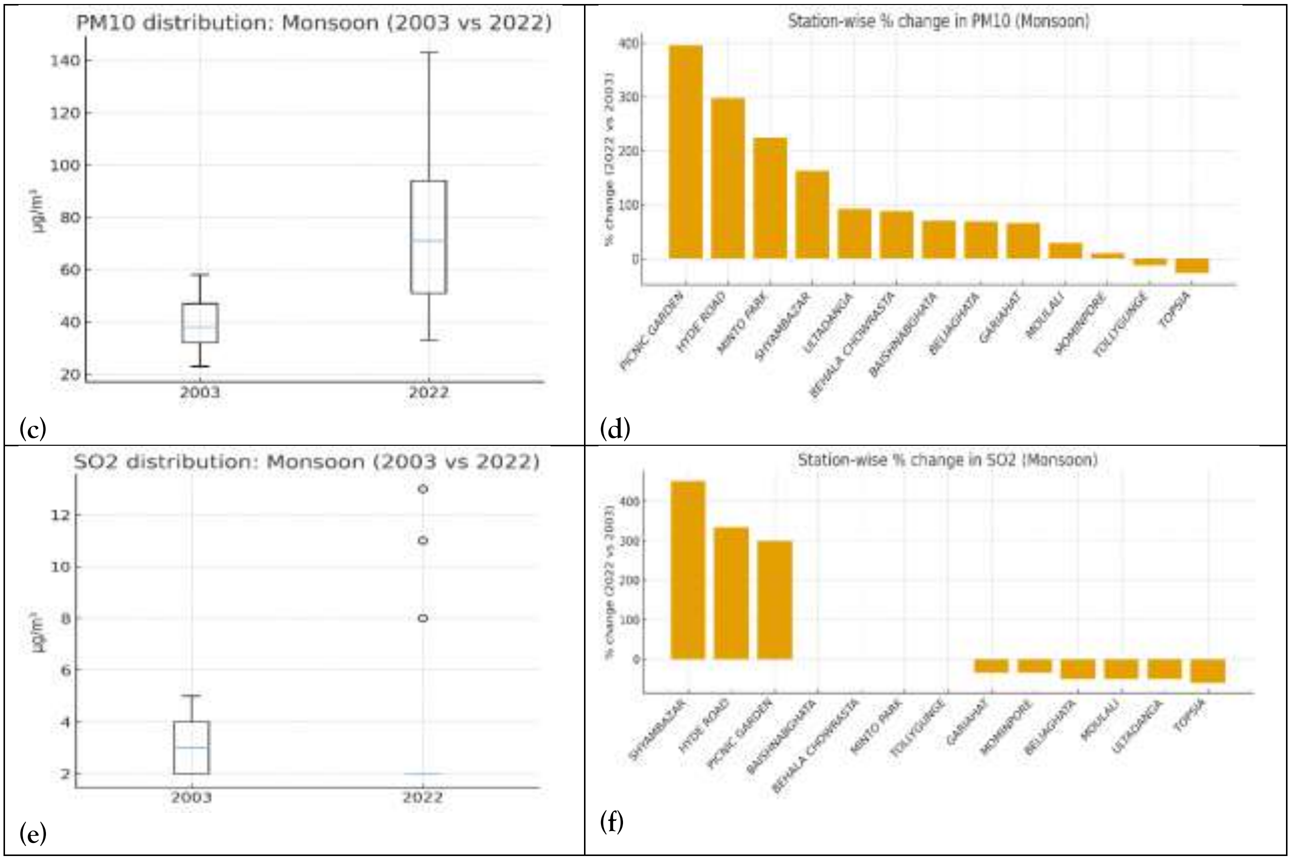

Fig 4: Pollutant distribution and changes during Monsoon season (2003 to 2022)

Between 2003 and 2022, the citywide mean NO_2 levels during the monsoon season show a mild increase (Fig. 4.a), indicating persistent vehicular and combustion-related emissions despite improved fuel standards. The spatial pattern demonstrates localized enhancement near traffic-dense intersections, consistent with emission buildup during periods of stagnant wind flow between rain spells.

Monsoon rainfall substantially reduces particulate concentration through washout, yet the mean PM_{10} levels declined only moderately from 2003 to 2022 (Fig. 4.c). The limited reduction points to strong resuspension of dust, open construction activities, and poor maintenance of road surfaces that replenish airborne particles even after precipitation. Industrial zones and major transportation corridors retained rising PM_{10} levels, while residential zones exhibited notable improvement (Fig. 4.d). The paired statistical tests confirm a significant decrease ($p < 0.05$), though the effect size remains small, implying slow but steady progress.

SO_2 levels remained consistently low during monsoon months in both observation years, owing to effective desulfurization policies and the phasing out of high-sulfur fuels (Fig. 4.e). The marginal increase at isolated stations may result from localized industrial operations or generator usage during power disruptions (Fig. 4.f). Nevertheless, mean values remain well below the NAAQS (National Ambient Air Quality Standards) threshold, confirming effective long-term sulfur control (Table 2).

The AQI (Air Quality Index) improved marginally over the two decades, moving from the "moderate" to "satisfactory" range in several localities (Fig. 7.d). Statistical correlation reveals a strong positive association between PM_{10} and AQI ($r = 0.85$), reaffirming the dominant role of suspended particulates in determining overall air quality even during wet months. Overall, the monsoon regime continues to act as a natural cleansing phase, but increasing vehicular NO_2 partially offsets these benefits.

5.3 Post-Monsoon (October–February) Concentration:

The post-monsoon or winter season emerges as the most polluted period in Kolkata's annual air quality cycle. This phase coincides with temperature inversion, calm winds, and enhanced anthropogenic emissions from transport, domestic heating, and festival-related activities.

A sharp rise in NO_2 concentration is observed between 2003 and 2022, particularly at densely populated transport corridors such as Shyambazar, Minto Park, and Hyde Road (Table 3). Mean NO_2 increased by over

20%, reflecting enhanced vehicular activity and energy consumption during cooler months (Fig. 4.c). The persistence of high NO_2 levels despite technological emission improvements suggests that vehicular growth and urban congestion have offset regulatory gains (Fig 6.e).

Table 3: Temporal Variation of Air Pollutants and AQI in Kolkata (Post-Monsoon: 2003 vs 2022)

POLLUTANTS	NO2		PM10		SO2		AQI	
Year (Post-monsoon)	2003	2022	2003	2022	2003	2022	2003	2022
BAISHNABGHATA	67	42	138	109	3	8	125	106
BEHALA CHOWRASTA	106	47	253	127	19	11	203	118
BELIAGHATA	34	43	133	116	2	8	122	111
GARIAHAT	48	32	166	77	2	2	144	77
HYDE ROAD	59	43	157	127	6	10	138	118
MINTO PARK	68	39	171	106	4	8	147	104
MOMINPORE	72	45	180	104	4	5	153	103
MOULALI	55	53	178	148	2	13	152	132
PICNIC GARDEN	47	44	182	103	13	8	155	102
SHYAMBAZAR	77	43	260	145	18	11	210	130
TOLLYGUNGE	126	43	247	95	16	4	198	95
TOPSIA	76	49	227	111	21	12	185	107
ULTADANGA	67	47	168	152	4	12	145	135
Kolkata (Average)	**69**	**44**	**189**	**117**	**9**	**9**	**160**	**111**

Source: West Bengal Pollution Control Board (AQI calculated by the author)

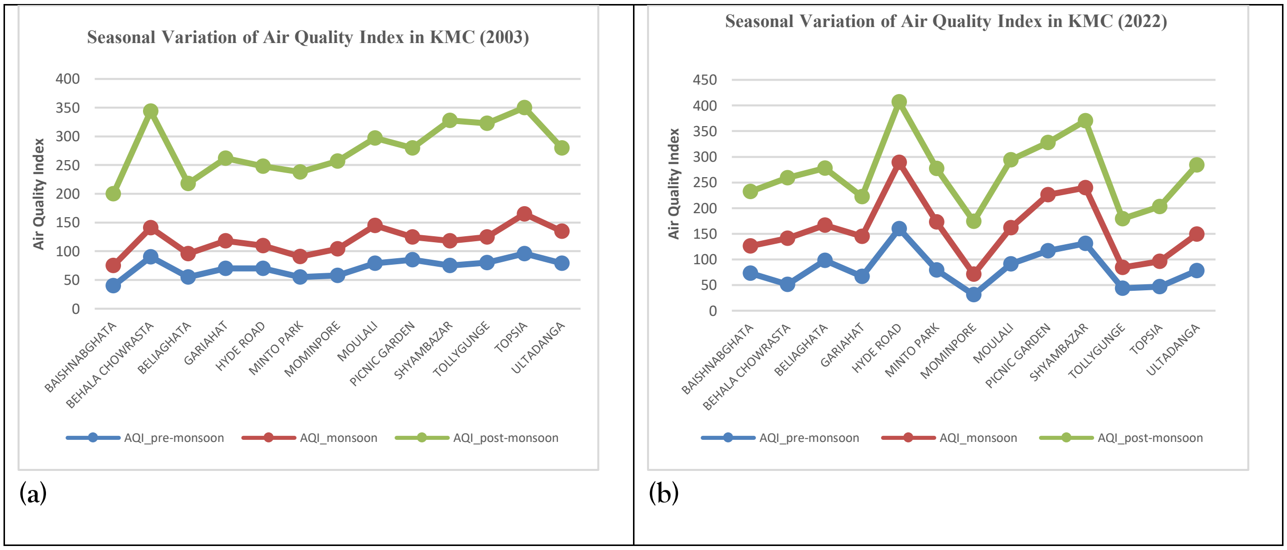

Fig 5: Seasonal variation of Air Quality Index in KMC (2003 vs 2022)

PM_{10} recorded the steepest increase across all seasons, rising by nearly 40-45%, with maximum values in central industrial and commercial locations (Fig. 6.d). The increase is attributed to thermal inversion that traps pollutants near the surface, coupled with seasonal biomass burning, fireworks, and domestic fuel use. Statistical tests indicate this change to be highly significant ($p < 0.01$) with a large effect size. The pattern mirrors winter smog events commonly reported in north Indian cities, establishing Kolkata's vulnerability to similar seasonal accumulation phenomena.

Post Monsoon Season

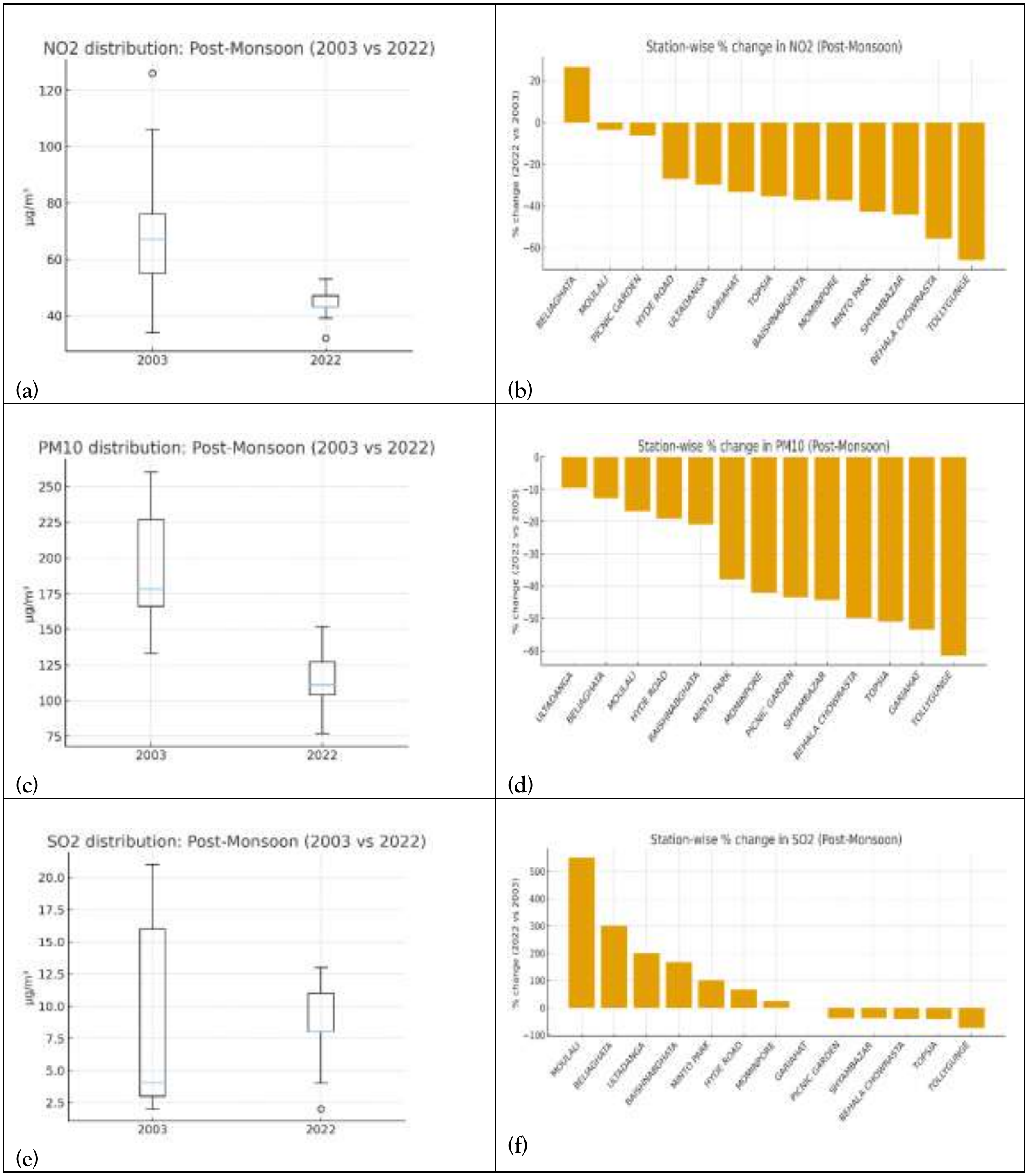

Fig 6: Pollutant distribution and changes during the Pre-Monsoon season (2003 to 2022)

SO_2 levels also increased modestly, likely due to the resurgence of industrial activity and continued use of diesel generators in the peri-urban zones. However, concentrations remain within national safety limits (Fig. 6.e). The spatial variability is more pronounced, with industrial fringes such as Topsia and Hyde Road showing relatively higher increases (Fig. 6.f).

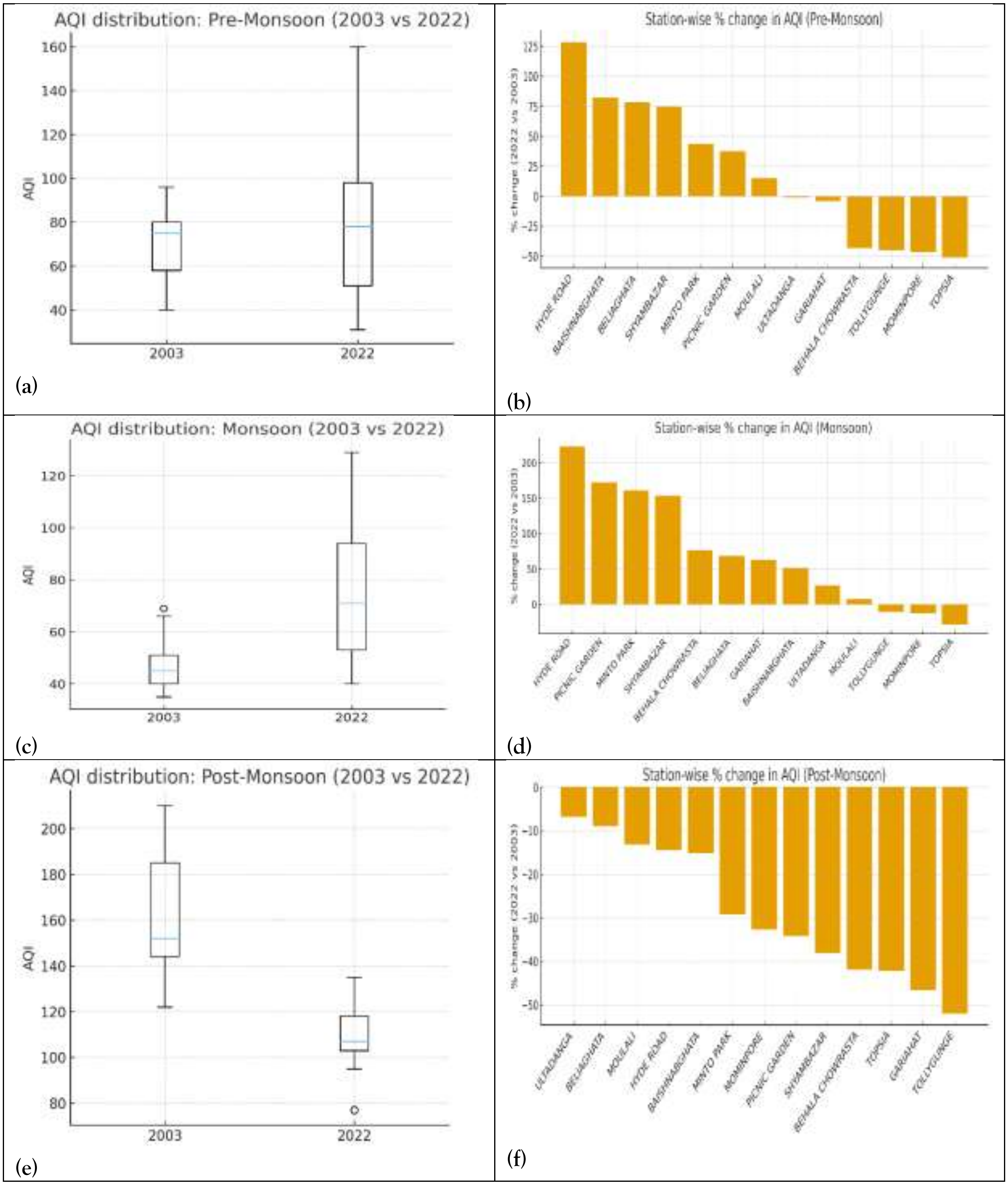

Fig 7: AQI and its variability in KMC during Pre-Monsoon, Monsoon, and Post-Monsoon Season (2003 vs 2022)

As a cumulative outcome of increased NO_2 and PM_{10}, the AQI during post-monsoon months deteriorated sharply, shifting from the "moderate" category in 2003 to "poor" and "very poor" in 2022 (Table 3). Stations such as Picnic Garden, Shyambazar, and Hyde Road consistently report AQI values exceeding 110-150, indicative of acute seasonal pollution (Fig. 7.e & 7.f). The correlation matrix identifies PM_{10} as the primary driver of AQI ($r > 0.9$), followed by NO_2, emphasizing the combined influence of vehicular emissions and dust entrainment.

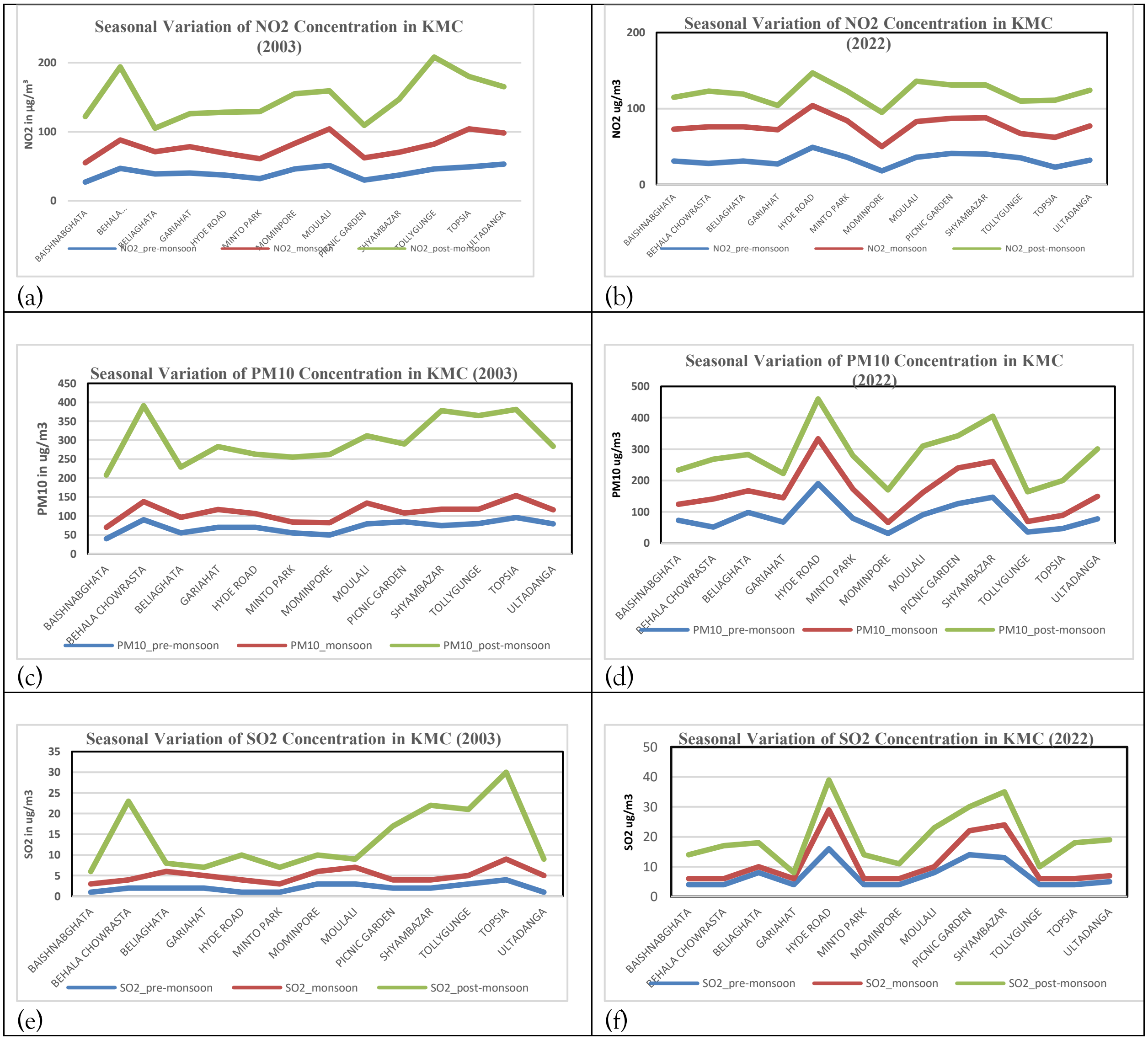

Fig 8: Spatial variation of Air Pollutants and their changes during Pre-Monsoon, Monsoon, and Post-Monsoon seasons (2003 to 2022)

6. CONCLUSIONS:

The Kolkata Municipal Corporation oversees a major urban metropolis in West Bengal, India, where air pollution is a significant issue. Sources include construction emissions, vehicular pollution, road dust, industrial emissions, and trans-boundary pollutants have played a significant role in air pollution. The study highlights that during the winter months, known as the post-monsoonal period, pollutants have been trapped close to the ground due to temperature inversion. Recent air quality data, using the National Air Quality Index (NAQI) of India, reveals that Kolkata's air quality remains in the poor to very poor category.

When all three seasons are compared (Fig. 8), Kolkata's air quality pattern demonstrates a clear seasonal cyclicity, with lowest pollutant levels during monsoon, moderate in pre-monsoon, and maximum accumulation during post-monsoon or winter. PM_{10} emerges as the primary AQI determinant across all seasons, overshadowing gaseous pollutants. The 2003-2022 comparison highlights partial success in controlling gaseous pollutants (especially NO_2 and SO_2), but a persistent and even aggravated problem with particulate matter, reflecting the inadequacy of dust suppression, road maintenance, and construction waste regulation.

The findings align with regional studies across Delhi, Lucknow, and Patna that report similar PM_{10}-dominant seasonal variations. The results suggest that urban morphology, traffic density, and microclimatic stability

jointly exacerbate post-monsoon pollution. Urban greening, street cleaning automation, and real-time air quality monitoring are recommended as effective mitigation measures.
Seasonal analysis of Kolkata's monitoring network between 2003 and 2022 reveals a complex picture: while traffic-related NO_x appears reduced in several seasons and locations, PM_{10} remains the major challenge and is the primary driver of AQI deterioration in pre-monsoon and monsoon months. Post-monsoon gains suggest targeted interventions can yield measurable benefits, but hotspot persistence (Hyde Road and others) requires immediate, location-specific action. For sound policy, the city needs (a) targeted particulate control (construction, roads, industrial PM), (b) improved monitoring metadata transparency, and (c) integration of meteorology into trend attribution.

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