Breathing Numbers: What PM2.5 Data Reveals About Air Quality

Introduction

Pollution is one of the most prevalent yet underrated challenges of the modern world. Driven by rapid urbanization, industrial growth, and energy demands, pollutants have become an indistinguishable part of our daily lives.

The hazard of air pollution lies in its persistence. Particulate matter accumulates in the environment, influenced by weather patterns and geography, leading to severe health outcomes. Long-term exposure is linked to respiratory distress, cardiovascular disease, and reduced life expectancy. This report explores the state of air quality in 2024, focusing specifically on Kolkata's PM2.5 levels and their implications for public health.

Data Description

In this project, we will analyze the pollution levels of different cities for the year 2024. The data consists of AQI of different cities in the year 2024. Next, we will analyze the PM2.5 level of Kolkata since it is where we live and impacts our daily lifestyle and health. The data consists of the PM2.5 level of Kolkata and also of different stations in Kolkata. We have three years of data in hand from 2022-2024.

SOURCE:
https://airquality.cpcb.gov.in/ccr/#/caaqm-dashboard-all/caaqm-landing
https://airquality.cpcb.gov.in/AQI_India/

AQI

The Air Quality Index (AQI) is an easy way of knowing the quality of the air and the corresponding health risks posed by the air. The AQI is calculated using the concentration of the six major air pollutants. They are PM2.5, PM10, nitrogen dioxide (NO_2), sulfur dioxide (SO_2),

carbon monoxide (CO), and ground-level ozone (O_3). Out of these six pollutants, PM2.5 is the major contributor when it comes to the AQI of the air.

National City-wise AQI Comparison (2024)

To contextualize the air quality in Kolkata, we compared its 2024 average AQI against other major Indian cities and regional capitals. By visualizing this data through a bar plot, we can clearly see the impact of geography and urbanization on the air we breathe.

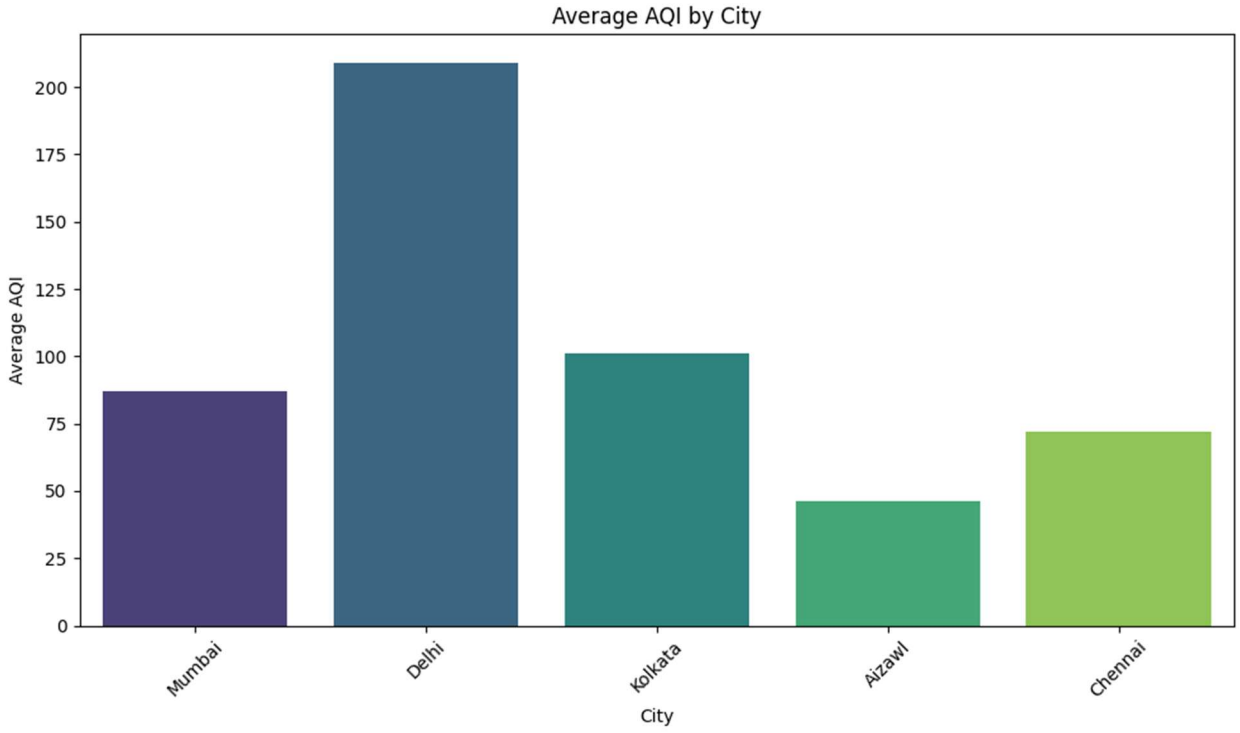

Fig 1.1

Comparative Analysis

The data reveals a contrast in air quality across the Indian subcontinent:

- **Delhi:** Remains the epicenter of the crisis, with AQI levels more than double those of other metros.

- **Kolkata:** Ranks as the second most polluted in this group. Crossing the 100-mark is a critical threshold, transitioning from "Satisfactory" to "Moderately Polluted," which poses risks to vulnerable groups.
- **Coastal Cities:** Mumbai and Chennai benefit from sea breezes that disperse particulate matter.
- **Aizawl:** Serves as the benchmark for clean air due to high altitude and low industrial density.

Key Takeaway

The data confirms that Kolkata's air quality is a significant concern compared to other coastal or high-altitude cities. While it has not reached the extreme levels seen in Delhi, an average AQI above 100 indicates that the city's population is frequently exposed to pollutants that exceed healthy limits.

PM2.5 – The Most Harmful Pollutant

PM2.5 refers to fine particulate matter with a diameter of **2.5 micrometers or smaller**. Because these particles are extremely small, they can penetrate deep into the lungs and enter the bloodstream, making them one of the most harmful air pollutants. Exposure to PM2.5 can worsen asthma, reduce lung function, increase cancer risk, cause cardiovascular diseases, affect fetal development, and aggravate existing respiratory and circulatory conditions.

Graphical Representation of Kolkata's PM2.5

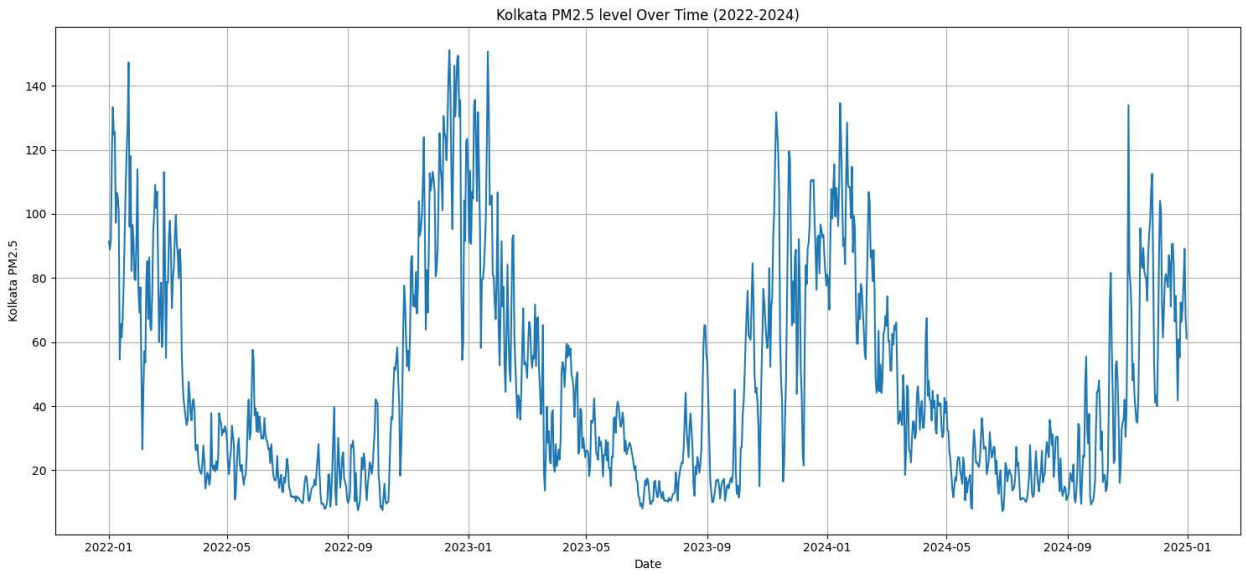

Fig 1.2

Kolkata's PM2.5 levels from 2022 to 2024 show a clear seasonal pattern, with severe pollution during winter months (November–January) and significantly lower concentrations during the monsoon season (June–September). Winter peaks frequently exceed safe air quality limits, indicating recurring pollution episodes likely driven by meteorological conditions and emission sources. Despite short-term fluctuations, there is no strong evidence of long-term improvement in air quality, highlighting persistent environmental and public health concerns.

Statistical Decomposition of PM2.5 in Kolkata (2022–2024)

To look beyond daily fluctuations, we applied an **STL Decomposition** to the Kolkata PM2.5 dataset. This allows us to separate the "noise" of daily weather from the underlying **Trend** (long-term direction) and **Seasonality** (repeating yearly patterns).

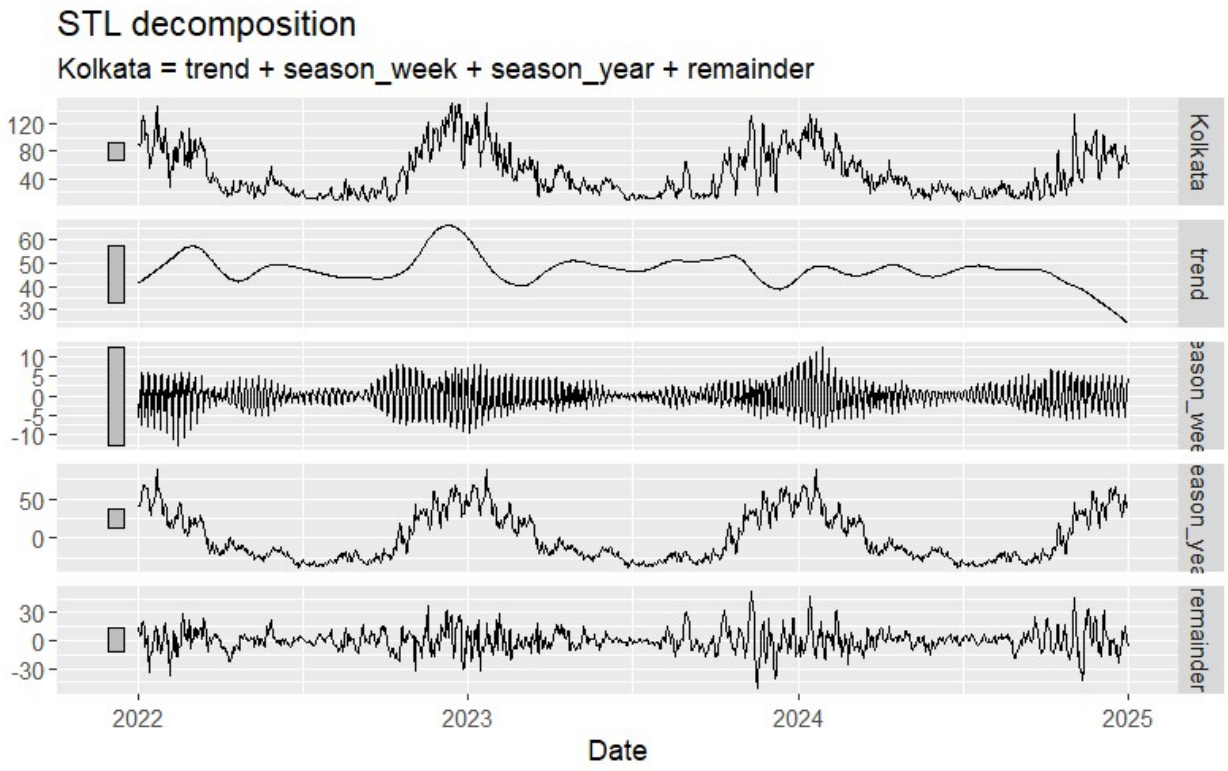

Fig 1.3

1. Strength of Components

The STL feature analysis provides two critical "Strength" scores (ranging from 0 to 1) that tell us what actually drives pollution in the city:

- **Yearly Seasonal Strength (0.835):** This is a very high score. It confirms that air quality in Kolkata is **heavily dictated by the time of year**. The peak occurs around day 21 (January), while the trough (cleanest period) occurs around day 178 (late June/July), perfectly aligning with the arrival of the Monsoon.
- **Trend Strength (0.927):** This exceptionally high value indicates a very strong, non-random direction in the data over the three-year period. It suggests that the changes we see aren't just "luck"—there is a systematic movement in the city's baseline pollution.

```
> data_ts %>% features(Kolkata, feat_stl)
# A tibble: 1 × 9
  trend_strength seasonal_strength_week seasonal_peak_week seasonal_trough_week spikiness linearity
           <dbl>                  <dbl>              <dbl>                <dbl>      <dbl>      <dbl>
1          0.927                  0.159                  2                    3     0.0302      -87.9
# i 3 more variables: curvature <dbl>, stl_e_acf1 <dbl>, stl_e_acf10 <dbl>
> data_ts %>% features(Kolkata, feat_stl, .period = 365.25)
# A tibble: 1 × 9
  trend_strength seasonal_strength_365.25 seasonal_peak_365.25 seasonal_trough_365.25 spikiness
           <dbl>                    <dbl>                <dbl>                  <dbl>      <dbl>
1         0.0473                    0.835                   21                    178      0.110
# i 4 more variables: linearity <dbl>, curvature <dbl>, stl_e_acf1 <dbl>, stl_e_acf10 <dbl>
```

Fig 1.4

2. Key Statistical Insights

Metric	Value	Interpretation
Seasonal Peak (Yearly)	Day 21	Pollution consistently hits its worst levels in the **third week of January**.
Seasonal Trough (Yearly)	Day 178	The city breathes its cleanest air in **late June**, thanks to Monsoon wash-out.
Weekly Strength	0.159	Weekly patterns (like weekend vs. weekday traffic) have a **minor impact** compared to the massive influence of the seasons.
Spikiness	0.110	Indicates that while the trend is smooth, there are occasional "shocks" or extreme pollution events that deviate from the norm.

Intra-City Analysis: PM2.5 Distribution across Kolkata

While the city-wide average gives a general idea, the boxplot reveals significant variations in air quality depending on the specific location within Kolkata.

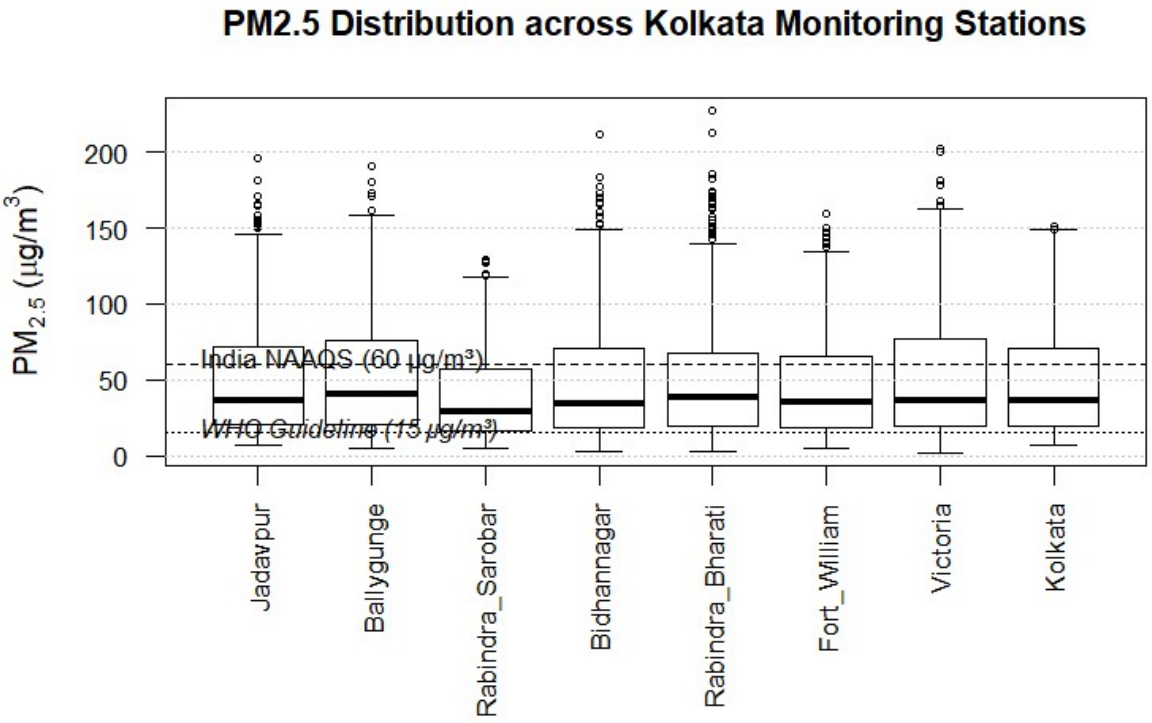

Fig 1.5

1. Median Levels vs. Safety Standards

A striking observation from the plot is that the **median PM2.5 level** at almost every station (represented by the thick black line inside the boxes) hovers around or below the Indian Limit of **60 µg/m^3**, but stays consistently **above the WHO Guideline of 15 µg/m^3**

- **Cleanest Zone: Rabindra Sarobar** stands out as the cleanest area, with the lowest median and the smallest "box" (Interquartile Range). This confirms that large water bodies and greenery act as significant buffers against pollution.

- **Most Polluted/Volatile Zones: Victoria**, **Bidhannagar**, and **Ballygunge** show higher 75th percentile values (the top of the box), indicating that residents in these areas are more frequently exposed to "Moderately Polluted" air.

2. The "Outlier" Problem

The numerous circles above the "whiskers" at every single station represent **outliers**—days of extreme pollution.

- **Rabindra Bharati** and **Bidhannagar** show extreme spikes reaching above **200 µg/m^3.**
- These spikes are likely linked to specific events like winter temperature inversions, festivals involving firecrackers, or localized construction activities.
- Even the relatively cleaner **Victoria** station shows outliers exceeding **200 µg/m^3**, proving that during peak pollution episodes, no part of the city is truly safe.

3. Summary of Station Dynamics

Station	Median PM2.5	Spread/Volatility	Risk Level
Rabindra Sarobar	Lowest (~30)	Very Low	Minimal (for Kolkata)
Fort William/Bidhannagar	Moderate (~30-35)	Moderate	Regular exposure
Victoria / Rabindra Bharati / Jadavpur	High (~35-40)	High	Frequent unhealthy days

Ballygunge	Highest (greater than 40)	Highest	Extreme risk during peaks

Conclusion from Local Data

The boxplot clearly shows that while the "average" day in Kolkata might seem manageable by national standards, the **frequency of extreme spikes** (outliers) is the real health hazard. The fact that the entire "Kolkata" aggregate box sits largely above the WHO guideline emphasizes that air quality remains a chronic health concern for the entire urban population.

Strategic Suggestions for a "Cleaner Kolkata"

1. The "Airshed" Management Strategy

Kolkata sits at the fringe of the Indo-Gangetic Plain and receives significant **transboundary pollution** from the north-west.

- **Regional Coordination:** Air quality cannot be managed by the Kolkata Municipal Corporation (KMC) alone. Suggestions include a unified "Airshed" regulatory body that coordinates with Howrah, Hooghly, and North 24 Parganas to sync industrial and crop-burning regulations.
- **Buffer Zones:** Establish "Green Belts" along the city borders to intercept incoming particulate matter from surrounding industrial clusters.

2. Combating "Secondary Aerosols"

Recent source-apportionment studies show that **32% of Kolkata's winter PM2.5** comes from secondary aerosols (gases reacting in the air).

- **Ammonia Reduction:** Target the chemical precursors of PM2.5 by strictly regulating solid waste and biomass burning, which release ammonia into the atmosphere.
- **Construction Protocols:** Enforce "Smart Construction" rules where all sites must have high-resolution dust screens and continuous water misting during the dry winter months (November–February).

3. Hyper-Local Green Interventions

Since station-wise data proves the benefit of "Green Lungs" like Rabindra Sarobar:

- **Miyawaki Micro-Forests:** Plant high-density, native micro-forests at traffic-heavy "hotspots" like **Bidhannagar and Ballygunge** to act as immediate particulate scrubbers.
- **Vertical Filtering:** Install vertical gardens on flyover pillars (e.g., Maa Flyover) and bus shelters to trap road dust at the breathing level of commuters.

4. Transitioning Roadside & Domestic Sources

- **Clean Fuel Subsidies:** Continue and expand the WBPCB initiative of providing gas-irons to cloth pressers and LPG connections to roadside eateries to eliminate coal/wood smoke in residential neighborhoods.
- **The "70 Threshold" Advisory:** Implement a **Public Health Alert System** that triggers mandatory health warnings (like the use of N95 masks) whenever the "STL model" predicts a breach of the 70 $\mu g/m^3$ toxicity limit.

5. Transport & Mobility

- **Low Emission Zones (LEZ):** Designate high-risk areas as identified from boxplot as LEZs, where commercial vehicles older than 15 years are restricted during peak winter pollution hours.
- **IoT Monitoring:** Deploy low-cost IoT sensors in every ward to provide residents with real-time, street-level data, fostering community-led accountability for pollution control.

Conclusion

The data confirms that while Kolkata’s air is manageable by national standards on "average" days, the frequency of extreme spikes and the high seasonal trend represent a chronic health

hazard. By shifting toward airshed management and hyper-local greening, Kolkata can begin to move its baseline toward the WHO's healthy limits.

References

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