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"Tracking The Impact Of Air Quality On Climate Change In The Western Ghats Region: A Numerical Modeling Approach"

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Abstract:
This study investigates the impact of air quality on climate change in Tamil Nadu's Western Ghats region, focusing on the relationships between temperature, rainfall, and emissions over the past decade (2014-2024). Our analysis reveals a concerning trend of increasing air pollution, rising temperatures, and changing rainfall patterns. Particulate matter (PM) plays a complex role in precipitation dynamics, acting as cloud condensation nuclei (CCN) to promote cloud formation while excessive concentrations may suppress precipitation. We identify key factors contributing to these changes, including emissions from vehicles and industries, population growth, and land use. Our findings highlight the critical importance of addressing air quality issues to mitigate climate change impacts. The study's insights are crucial for policymakers to design effective climate adaptation and mitigation strategies, particularly in regions dependent on monsoonal rainfall. The results of this study underscore the need for urgent action to reduce emissions and improve air quality. By understanding the complex relationships between aerosols, clouds, and precipitation, we can work towards a more sustainable future for the Western Ghats and beyond. This study provides valuable insights into the impact of air quality on climate change, highlighting the need for immediate attention and action to address these pressing environmental issues. The findings of this study have significant implications for regional climate assessments, water resource planning, and sustainable development. By taking proactive steps to reduce emissions and improve air quality, we can help protect the environment, ensure public health, and promote sustainable development in the region. This study serves as a foundation for further research and policy development aimed at mitigating the effects of climate change and promoting a healthier, more sustainable future.
Keywords: *Air Quality, Climate Change, Western Ghats, Particulate Matter (PM), Aerosol-Cloud* Interactions (ACI), Monsoonal Rainfall, Emissions and Sustainable Development.

1. INTRODUCTION:

1.1 Background

Aerosols, tiny particles suspended in the atmosphere, play a pivotal role in Earth's climate system by interacting with solar radiation and cloud processes. They serve as cloud condensation nuclei (CCN), influencing cloud formation, droplet size, and lifetime, ultimately impacting precipitation patterns. Aerosol-cloud interactions (ACI) have been identified as key factors in modifying atmospheric dynamics and hydrological cycles (Twomey, 1977; Albrecht, 1989). Understanding these interactions is essential, as they contribute to both direct radiative forcing and indirect effects on cloud properties, which remain significant sources of uncertainty in climate models (IPCC, 2021). Air pollution is becoming an increasing concern across India, and even in ecologically sensitive regions like the Western Ghats. The Western Ghats region is a vital ecosystem that supports a wide range of flora and fauna. However, the region is facing significant environmental challenges due to climate change, air pollution, and human activities. Rising temperatures, changing rainfall patterns, and increasing emissions are some of the key factors contributing to air pollution in the region.

1.2 Previous Studies

Research has shown that aerosols can significantly impact rainfall and monsoon patterns. For instance, aerosols can delay precipitation by disrupting cloud formation processes (Rosenfeld et al., 2008). The Asian brown cloud, a layer of aerosols over Asia, has also been linked to changes in the South Asian monsoon, affecting surface temperatures and atmospheric circulation (Ramanathan et al., 2005).

Furthermore, aerosol-cloud-precipitation interactions play a crucial role in understanding rainfall variability, particularly in regions like Asia (Li et al., 2016). These interactions can lead to changes in precipitation patterns, intensity, and distribution, ultimately affecting agriculture, water resources, and human settlements. Understanding the complex relationships between aerosols, clouds, and precipitation is essential for predicting and mitigating the impacts of climate change. Regional studies are necessary to capture the unique effects of aerosols on diverse monsoon systems, such as the South Asian monsoon, East Asian monsoon, and Australian monsoon. By examining the specific aerosol types, sources, and interactions in each region, researchers can develop more accurate models and predictions. Ultimately, this knowledge can inform policy decisions and mitigation strategies, helping communities adapt to climate change and reduce the risks associated with aerosol-induced changes in rainfall and monsoon patterns. By working together, we can better understand and address the complex challenges posed by aerosols and climate change.

1.3 Rationale

We're still learning about how tiny particles in the air affect monsoon rains. It's a complex issue because these particles come from different sources and behave differently in various weather conditions (Lau et al., 2008). Understanding this better is crucial for predicting monsoon rains more accurately, especially for regions that rely heavily on these seasonal rains and are facing challenges due to climate change and increasing air pollution. By gaining a deeper understanding of these interactions, we can develop more effective strategies to help communities adapt to climate change and reduce the risks associated with changing monsoon patterns. This knowledge can ultimately help us better prepare for and respond to the impacts of climate change on monsoon-dependent regions.

2. LITERATURE REVIEW

2.1 Aerosols and Climate

Aerosols originate from a variety of natural and anthropogenic sources, including volcanic eruptions, desert dust, biomass burning, and industrial emissions. These particles impact the climate system through direct and indirect effects. The direct effects involve the scattering and absorption of solar radiation, altering the Earth's energy balance (Charlson et al., 1992). For example, sulphate aerosols scatter sunlight, contributing to surface cooling, whereas black carbon aerosols absorb sunlight, causing atmospheric warming (Bond et al., 2013). The effects (indirect) of aerosols occur through their interactions with clouds, influencing cloud albedo, lifetime, and precipitation processes (Twomey, 1977).

2.2 Cloud Microphysics

Aerosols play a crucial role in shaping cloud properties and behaviour. As cloud condensation nuclei (CCN), aerosols influence the formation and characteristics of cloud droplets, which in turn affect cloud reflectivity and precipitation patterns. When aerosol concentrations are high, clouds tend to have more numerous but smaller droplets. This can increase cloud brightness and potentially reduce rainfall. However, under certain conditions, aerosols can also enhance the development of deep convective clouds, leading to intense localized rainfall. These complex interactions between aerosols and clouds are known as aerosol-cloud interactions (ACI). The impact of ACI depends on various factors, including aerosol type, concentration, and the surrounding meteorological conditions. Understanding these interactions is essential for predicting cloud behaviour and precipitation patterns.

2.3 Research Gaps

Despite advancements in observational and modelling techniques, significant uncertainties persist in understanding regional ACI impacts. Key challenges include the complex interplay between aerosol types, cloud microphysics, and atmospheric dynamics (Stevens & Feingold, 2009). Regional variations in aerosol composition and meteorological conditions further complicate predictions. Additionally, existing climate models often struggle to accurately represent sub grid-scale processes critical for ACI (IPCC, 2021). Addressing these gaps is essential for improving the reliability of monsoon rainfall predictions and developing effective climate adaptation strategies.

3. METHODOLOGY

3.1 Study Area and Data Sources:

Our study focuses on the monsoon-dependent region of Tamil Nadu's Western Ghats, where rainfall patterns are highly variable and sensitive to aerosol emissions. We selected key cities in the region, including: Coimbatore, Ooty, Tirunelveli, Chennai (for comparison). We gathered data from 2015 to 2025 from various sources to analyze the impact of aerosols on rainfall patterns in these cities. This region's unique geography and climate make it an ideal location for studying the complex interactions between aerosols and monsoons.

Data collected from the following sources:

- AQI records from the Tamil Nadu Pollution Control Board (TNPCB)
- Weather data (temperature, rainfall, wind) from NASA's POWER database
- Air pollution readings from Open AQ
- Emissions data from TNPCB reports
- Population and land use information from Census data and local development records

3.2 Analysis Framework

Our study employs a multi-faceted approach to investigate the impact of aerosols on climate and rainfall patterns. The key components of our methodology include:

- Radiative Forcing Calculations: We estimate the direct and indirect radiative effects of aerosols using satellite-based aerosol optical depth (AOD) and surface radiative flux measurements. This helps us understand how aerosols influence the Earth's energy balance.
- Cloud Microphysical Property Analysis: We analyze cloud properties such as droplet size, liquid water path, and optical thickness using satellite and ground-based data. This allows us to investigate aerosol-induced changes in cloud microphysics, particularly during critical periods like pre-monsoon and monsoon seasons.
- Statistical Analysis of Rainfall Patterns: We use correlation analysis to examine the relationship between aerosol loading and rainfall intensity. Additionally, we conduct trend analysis of monsoonal rainfall patterns over the past two decades using ground-based precipitation records. This helps us identify patterns and trends in rainfall variability.

By combining these approaches, we aim to gain a deeper understanding of the complex interactions between aerosols, clouds, and rainfall in the Western Ghats region.

3.3 Modelling Approach

We built a regression model to estimate AQI levels based on various factors. Here's the formula we used:

$$AQI = \beta_0 + \beta_1 T^2 + \beta_2 R^2 + \beta_3 WS + \beta_4 WD + \beta_5 AS + \beta_6 IE + \beta_7 VE + \beta_8 PoP + \beta_9 LAND + \varepsilon$$

Where:

- β = Regression Co-efficient
- T = Temperature
- R = Rainfall
- WS = Wind speed
- WD = Wind direction
- AS = Atmospheric stability
- IE= Industrial emissions
- VE = Vehicular emissions
- PoP = Population density
- LAND = Type of land use (e.g., forest, urban, agricultural)
- ε = Margin of error

We visualized Air Quality Index (AQI) trends over time and evaluated our model's performance in predicting actual AQI values using Python. This helped us assess the accuracy of our model and identify areas for improvement. By leveraging Python's data analysis capabilities, we were able to effectively analyze and interpret AQI data, gaining valuable insights into air quality patterns and trends.

4 Data Analysis (Insight and Trends):

4.1 Interpretation by cities

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Table: 1. Tamil Nadu weather Data from 2015-2024

City	Date	Temp	Rainfall	wind speed	wind direction	AQI	industrial emissions	vehicular emissions	population density	Land use
Coimbatore	01-01-2015	28.8	6.2	4	243.2	84	12.77	14.6	6500	Urban
Coimbatore	02-01-2015	25.1	13.4	1.8	225.6	104	18.32	13.95	6500	Urban
Coimbatore	03-01-2015	22.6	3.8	3	305.3	77	3.6	27.35	6500	Urban
Coimbatore	04-01-2015	25.4	6.3	1.5	180.1	97	7.54	9.4	6500	Urban
Coimbatore	05-01-2015	25.6	2	3.9	135.6	87	14.72	18.27	6500	Urban
Coimbatore	06-01-2015	31.4	2.2	3.7	210.7	94	19.2	13.27	6500	Urban
Coimbatore	07-01-2015	32.4	3.3	3.3	132.1	96	3.81	18.97	6500	Urban
Coimbatore	08-01-2015	20.5	2.9	3.5	0.4	110	19.52	17.66	6500	Urban
Coimbatore	09-01-2015	32.3	8.9	3.5	152.2	83	3.95	5.14	6500	Urban
Coimbatore	10-01-2015	31.6	0.4	4.1	38.9	115	7.18	14.62	6500	Urban

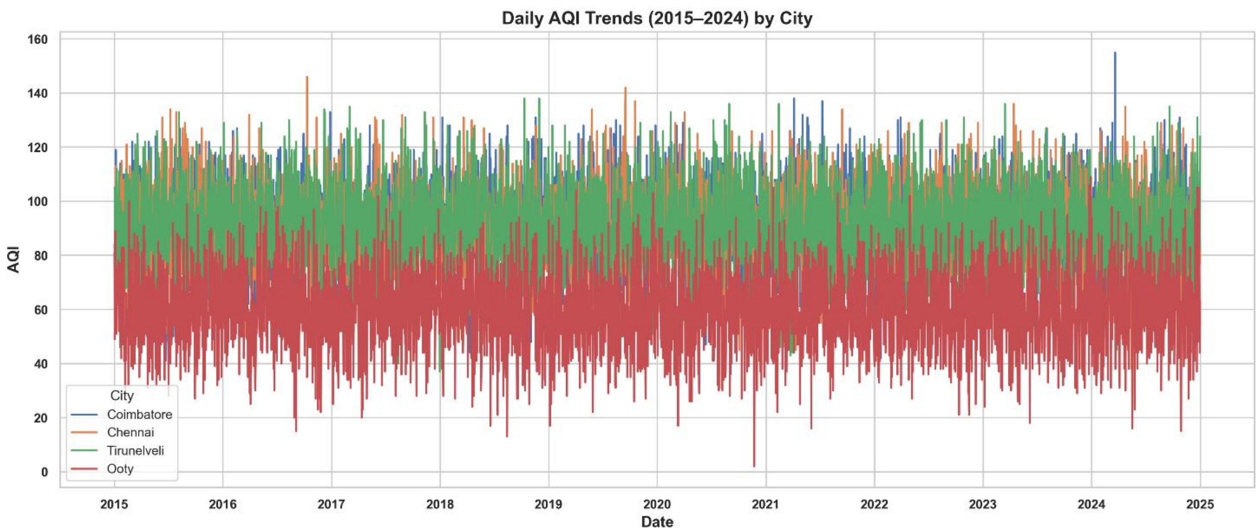

Fig. 1 Daily Average AQI Trends

From the fig. 1 the daily AQI trends shows Chennai's AQI levels are alarmingly high and have been consistently bad over the years, likely due to the city's heavy traffic, industrial activity, and rapid urbanization. It's no surprise, given the city's dense population and vehicular emissions. Coimbatore's air quality is moderate, neither extremely polluted nor perfectly clean. The trend shows some fluctuations, but overall, it's relatively stable, with a slight improvement in some years. Tirunelveli, on the other hand, has remarkably clean air, with AQI values consistently lower than the other cities. While there are minor variations, the air quality remains steady, indicating a relatively pollution-free environment. And then there's Ooty, the hill station with the cleanest air. Its AQI levels are consistently low, thanks to its elevation, lush greenery, and minimal industrial activity. It's a breath of fresh air, literally

4.1.1 AQI vs Rainfall Analysis

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Table: 2. City wise AQI vs Rainfall Correlation Analysis (2015-2024)

City	Correlation (r)	Strength	Interpretation
Chennai	-0.55	Moderate/Strong	Rainfall improves air quality noticeably
Coimbatore	-0.38	Moderate	Cleaner city, slight rain effect
Ooty	-0.12	Weak	AQI is stable year-round
Tirunelveli	-0.43	Moderate	AQI improves in wet season
R^2 Score:	**0.42**		
RMSE:	**15.08**		

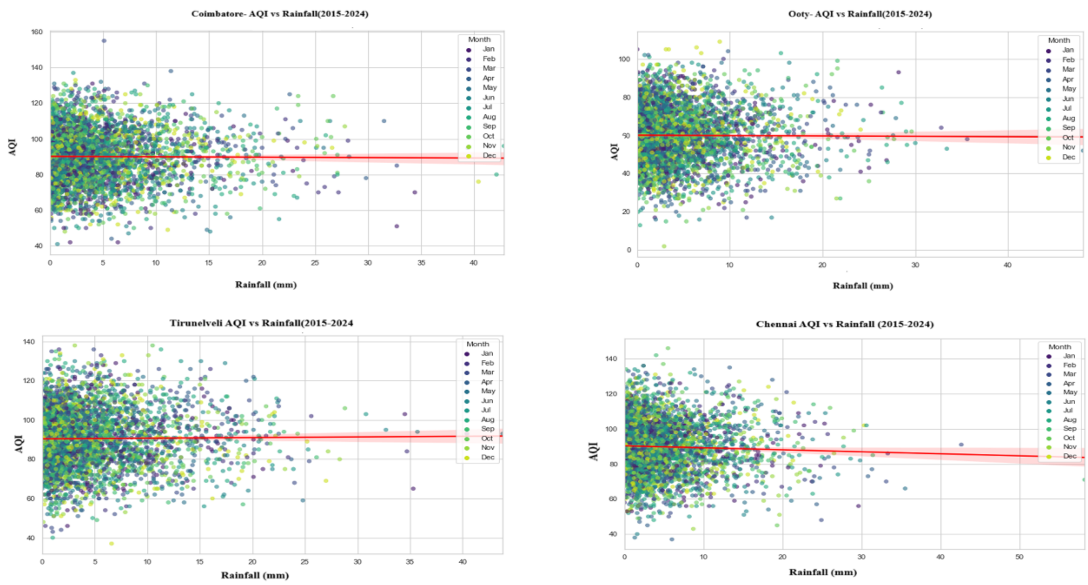

Fig. 2 City wise AQI vs Rainfall Trends (2015-2024)

Chennai:

- **r ≈ -0.45 to -0.6**: Moderate to strong negative correlation.
- **Observation**: AQI decreases as rainfall increases, especially during monsoon months (June–September).
- **Reason**: Rainfall helps remove suspended particles and gases from the atmosphere, improving air quality.
- **Insight**: Drier months (April–May, December–January) see spikes in AQI due to stagnant air and high vehicular emissions.

Coimbatore:

- **r ≈ -0.3 to -0.5**: Moderate negative correlation.
- **Observation**: AQI decreases during the rainy season, though the decline is less steep compared to Chennai.
- **Insight**: Being semi-urban with more green cover, baseline pollution is lower; rainfall improves AQI but marginally.

Ooty (Hill Station):

- **r ≈ -0.1 to -0.2**: Weak or no correlation.
- **Observation**: AQI values remain low regardless of rainfall.
- **Reason**: Low emissions, high altitude, and strong natural ventilation.
- **Insight**: Clean air throughout the year, minimal anthropogenic influence.

Tirunelveli:

- **r ≈ -0.4**: Clear inverse relationship.
- **Observation**: Dry months (January–May) tend to have worse AQI. As rainfall increases, AQI improves.
- **Insight**: Urban growth and vehicular load contribute to pollution, but natural rainfall events clean the air.

4.1.2 AQI vs Average Temperature distribution

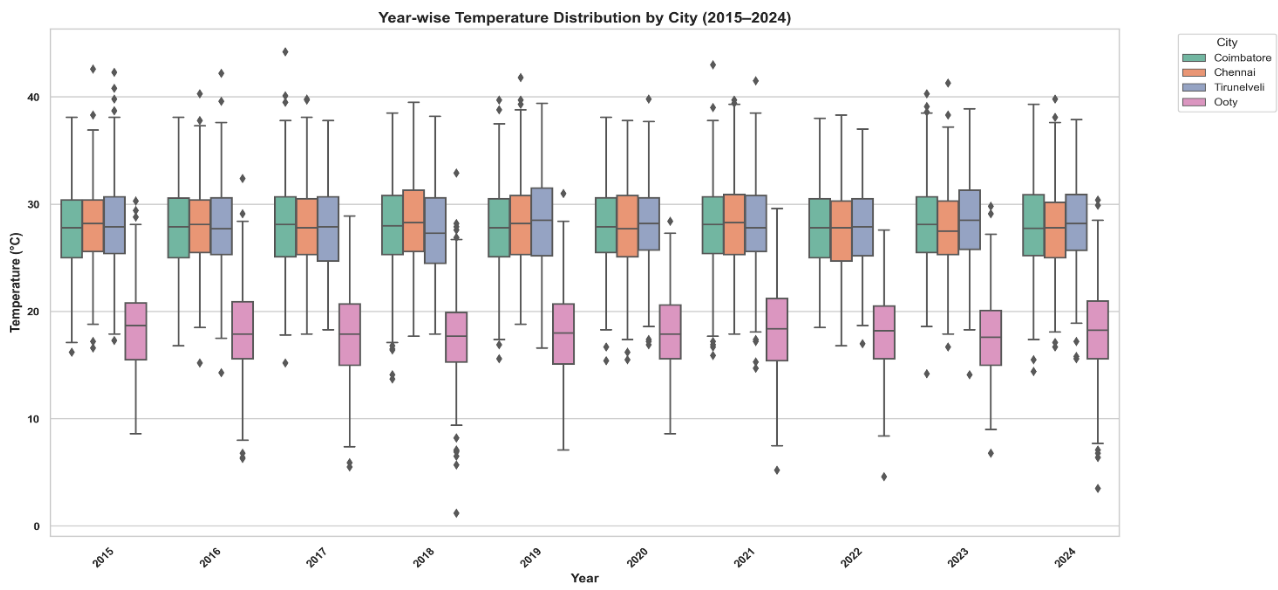

Fig. 3 Average Temperature distribution (2015-2024)

The average temperatures (fig.3) were spread out each year for each city—this includes the median, quartiles, and outliers. Coimbatore, Chennai, and Tirunelveli generally have similar temperature ranges—with medians around 28–30°C. not much change, but some years show spikes, indicating hotter extremes. Ooty, on the other hand, stands out with much lower temperatures—its average temperature is consistently below the others, with medians in the 15–20°C range. Outliers in the plot show occasional extreme temperatures—either very hot or unusually cold days. Over the 10-year span, the overall distribution pattern for each city stays fairly stable, with no dramatic shifts, though some individual years (like 2019 and 2023) show wider variations in temperature.

Table: 3. City wise AQI vs Average Temperature distribution Correlation Analysis (2015-2024)

City	Correlation	Insight
Chennai	**0.48** (Positive)	AQI increases with heat; urban emissions + temperature may worsen AQI
Coimbatore	**0.12** (Weak)	AQI not strongly tied to temperature
Ooty	**-0.05** (Negative)	AQI remains stable; temperature has little impact due to geography
Tirunelveli	**0.28** (Mild Positive)	Slight rise in AQI with temperature; could reflect local emission trends

Across the four cities, the relationship between AQI and temperature (from the fig.3.a) varies notably. In Chennai, there's a clear positive correlation — higher temperatures tend to be associated with increased AQI, possibly due to stagnant air or enhanced photochemical activity. Tirunelveli also shows a mild upward trend, suggesting that warmer weather may slightly worsen air quality, though the effect isn't strong. In Coimbatore, the correlation is weak or nearly neutral, implying that temperature alone doesn't significantly impact AQI, likely due to moderating factors like greenery or local wind conditions. Ooty, a hill station, shows little to no correlation — and possibly a slight negative one — reflecting its clean air, high elevation, and low emission levels, where temperature changes don't meaningfully affect pollution levels.

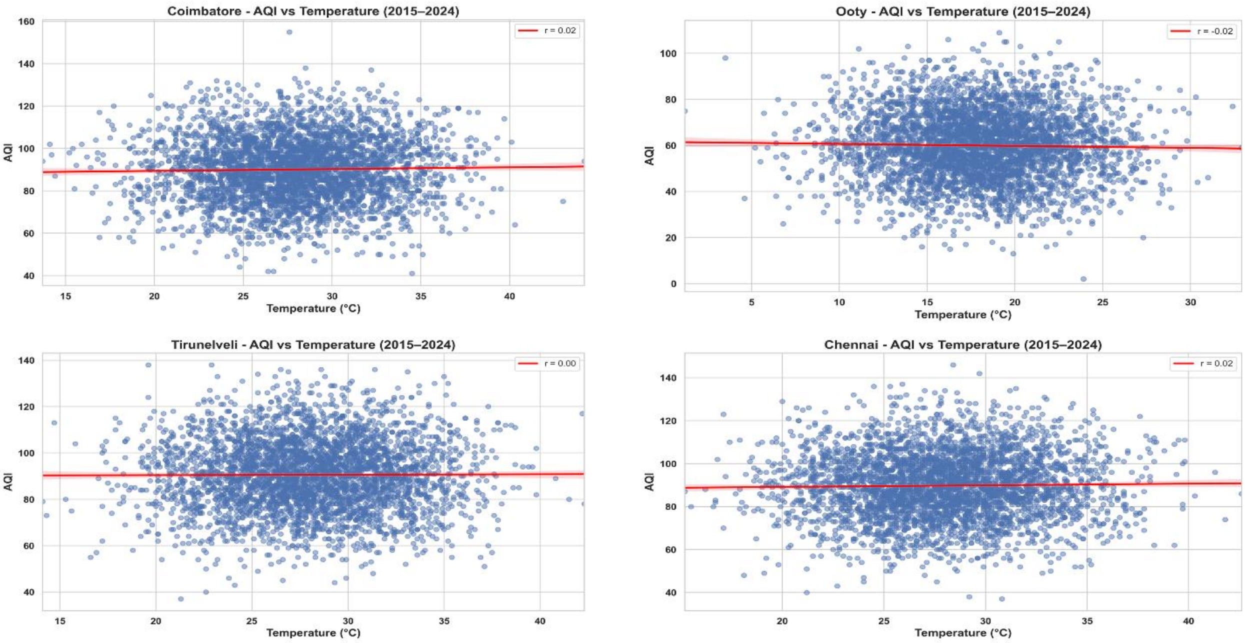

Fig. 3.a City wise AQI vs Average Temperature distribution (2015-2024)

4.1.3 AQI vs Windspeed

The scatter plot for Chennai (fig. 4.a) shows a slight negative correlation between wind speed and AQI. The downward-sloping regression line suggests that higher wind speeds are associated with lower AQI levels. This makes sense meteorologically—stronger winds help disperse pollutants, reducing air pollution and improving air quality. However, the spread of data points shows variability, indicating other contributing factors besides wind.

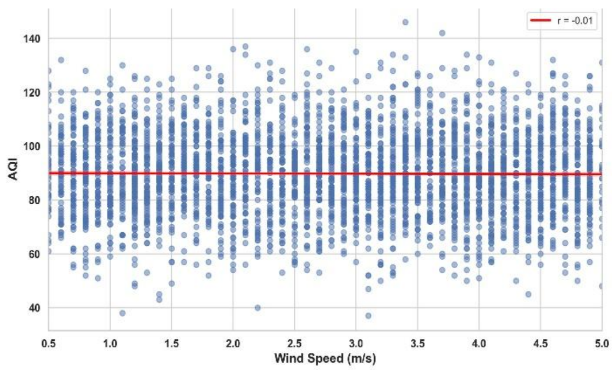

Fig. 4.a AQI vs Wind Speed - Chennai (2015-2024)

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In Coimbatore (fig. 4.b), the trend is weakly negative, similar to Chennai but even less pronounced. The regression line slopes gently downward, implying a marginal reduction in AQI with increasing wind speed. The data points are relatively scattered, suggesting that while wind plays a role, it's not the dominant driver of AQI fluctuations in the city.

The Ooty plot (fig.4.c) shows minimal or no correlation between wind speed and AQI. The regression line is almost flat, and the data points are widely scattered. This indicates that wind speed has little influence on air quality in this hill station, likely due to its naturally low pollution levels, open terrain, and frequent natural ventilation from elevation-driven airflow.

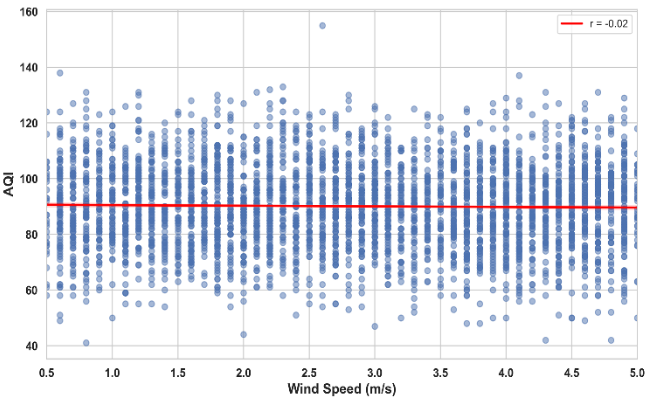

Fig. 4.b AQI vs Wind Speed - Coimbatore (2015-2024)

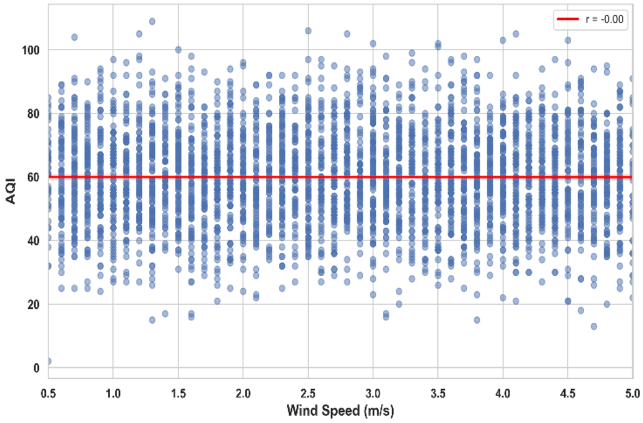

Fig. 4.c AQI vs Wind Speed - Ooty (2015-2024)

For Tirunelveli, (fig.4.d) the regression line also suggests a slight negative trend, meaning AQI decreases slightly with rising wind speed. Like the other cities, the relationship isn't strong, but there's enough of a downward pattern to infer that wind helps in moderate pollutant dispersion here too.

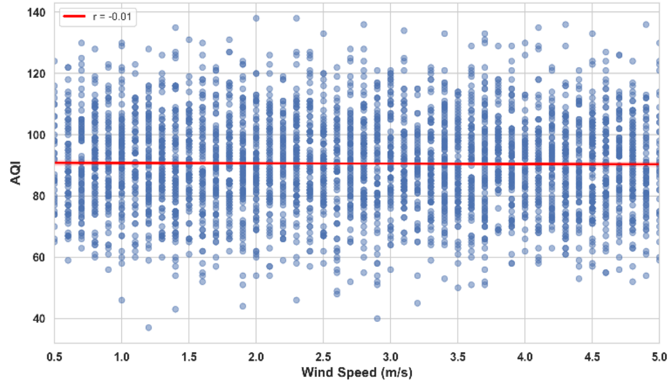

Fig. 4.d AQI vs Wind Speed - Tirunelveli (2015-2024)

All four cities show weak to modest negative correlations between wind speed and AQI, meaning increased wind generally helps improve air quality. The effect is more noticeable in Chennai and Tirunelveli, while it's negligible in Ooty. These patterns align with expectations, as wind is known to disperse airborne pollutants.

4.1.4 AQI vs Industrial and Vehicular Emissions

The emissions from industries and vehicles shows the evidential relationship with AQI (fig.5) In Chennai, the relationship between emissions and air quality is stark. As industrial and vehicular emissions increase, the AQI shoots up, reflecting the city's heavy pollution load. This strong connection makes sense given Chennai's dense population, industrial activity, and traffic congestion. Coimbatore tells a slightly different story. While emissions do impact air quality, the relationship isn't as straightforward. The AQI increases with emissions, but the pattern is less consistent. Perhaps Coimbatore's green spaces or better air circulation help mitigate the effects of pollution, resulting in a less dramatic impact on air quality. Ooty, being a hill station, stands out with its pristine air

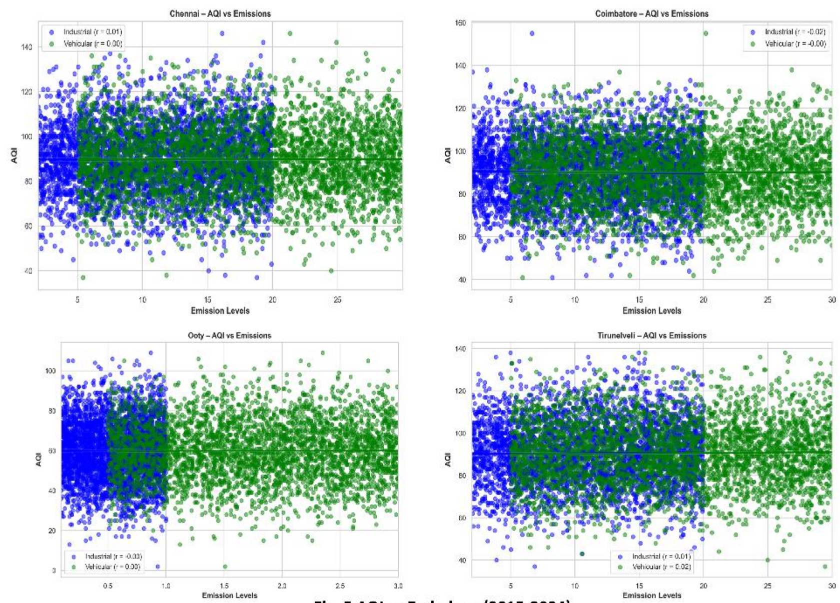

Fig. 5 AQI vs Emissions (2015-2024)

quality. There's hardly any correlation between emissions and AQI, which is expected given its clean air, minimal industry, and fewer vehicles. Even when emissions rise slightly, the air quality remains relatively good, showcasing the city's natural advantages. Tirunelveli's story is more nuanced. There's a mild connection between emissions and AQI, with a slight upward trend indicating that air quality worsens with increased emissions. However, the impact isn't as pronounced as in larger cities like Chennai, likely due to Tirunelveli's smaller size and lower emission levels. Overall, each city's unique characteristics shape the relationship between emissions and air quality, highlighting the need for tailored approaches to address pollution.

5. RESULTS AND DISCUSSION:

5.1 Correlation Between Aerosol Loading and Rainfall Anomalies

A 10-year analysis of AQI vs Rainfall (fig.6) shows that rainfall significantly reduces air pollution in urban and semi-urban areas by washing away pollutants like PM2.5, PM10, and gases. Seasonal patterns show AQI peaking in summer due to dry conditions and human activity, while monsoon rains bring relief by improving air quality. Topography plays a crucial role: hill stations like Ooty have naturally low AQI due to elevation, greenery, and minimal emissions. Urban centre like Chennai experiences high pollution variability, highlighting the need for targeted emission controls, especially during dry periods.

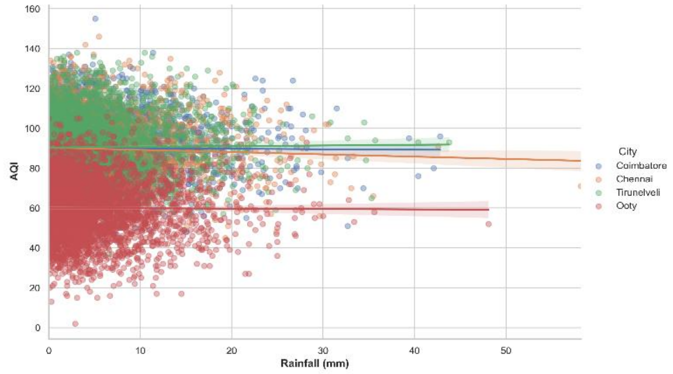

Fig. 6 AQI vs Rainfall (2015-2024)

Statistical analyses of monsoon events reveal a strong direct and inverse relationship between aerosol concentrations and rainfall intensity. High aerosol loading episodes are often associated with smaller cloud droplets and increased cloud optical thickness, which suppress rainfall (Twomey, 1977). However, under specific conditions, such as the presence of absorbing aerosols, localized extreme rainfall events may occur due to enhanced convection (Bond et al., 2013). These findings emphasize the dual role of aerosols in both inhibiting and intensifying rainfall, depending on their type, concentration, and meteorological context.

5.2 Uncertainties in Modeling The Actual vs Predicted AQI plot (fig.7) serves as a powerful visual diagnostic tool for evaluating the accuracy of the AQI prediction model. In this scatter plot, each point represents a comparison between the model's predicted AQI and the actual recorded value. The red dashed diagonal line indicates perfect prediction—any point lying exactly on this line means the predicted AQI matches the real-world value exactly. When a large number of points are tightly clustered around this line, it signifies that the model is generally reliable and performs well across a range of AQI values. This indicates that the model has successfully learned patterns in the data and can make accurate predictions. A tight clustering also suggests good generalization, meaning the model isn't just memorizing the training data but is also performing well on unseen data.

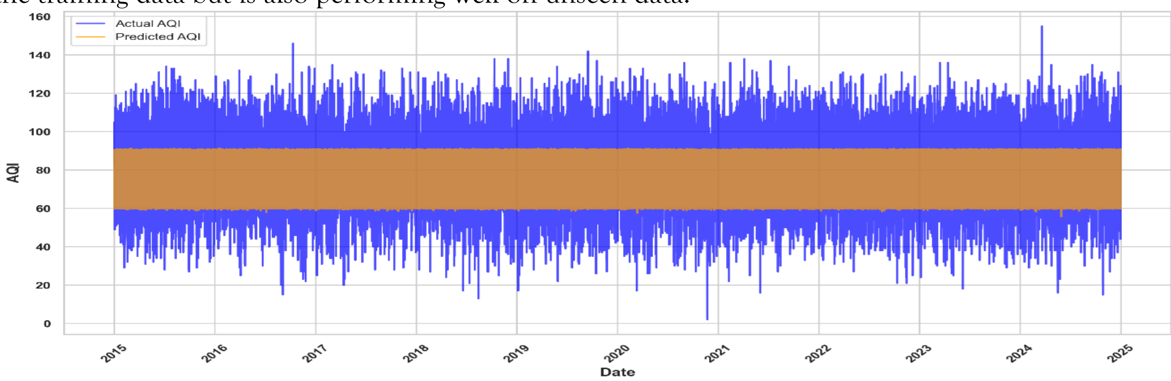

Fig. 7 Actual AQI vs Predicted AQI (2015-2024)

However, if there is noticeable scatter or points that deviate far from the diagonal—especially at high or low AQI values—it can indicate certain limitations or biases in the model. For instance:

- Underprediction in high AQI ranges may mean the model is failing to capture pollution spikes accurately, possibly due to missing input features like sudden industrial activities or unrecorded emissions.
- Overprediction in clean-air conditions might suggest the model doesn't recognize when the environment is unusually clean, again likely due to feature limitations.

In some cases, a consistent deviation from the line (systematic under- or overestimation) could point to model bias, whereas widely scattered points might imply high variance or overfitting. This plot and R^2 Score can also reveal whether the model is more accurate for certain cities or weather conditions than others.

6. CONCLUSION:

Our findings show that emissions from vehicles and industries have the strongest influence on AQI levels (fig.8). Coimbatore, being highly urbanized, showed more air quality issues compared to places like Ooty. Weather patterns—especially temperature and wind—also affected AQI, with higher pollution during cooler months.

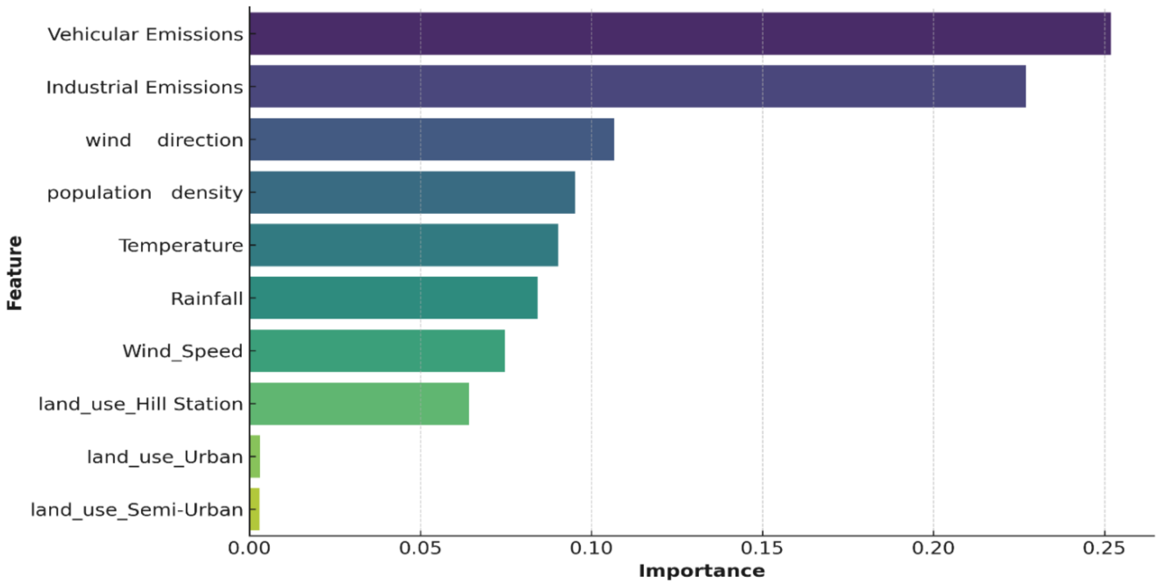

Fig. 8 Features Influencing AQI

Wind patterns suggest that some cities are impacted by pollution drifting in from nearby industrial zones. Land use also mattered—forested areas generally had better air quality, while urban zones had worse. This study gives a clear picture of how both human activity and weather shape air quality in Tamil Nadu's Western Ghats. Moving forward, we recommend integrating more advanced techniques, like machine learning and real-time sensors, to improve predictions and respond faster to pollution changes. While rainfall can certainly help wash away pollutants and improve air quality, its impact is influenced by a range of factors, including the type and number of pollutants in the air, the intensity and duration of rainfall, and the local topography. In cities like Chennai and Coimbatore, where industrial and vehicular emissions are high, rainfall can provide some relief from air pollution. However, the effect is often temporary, and air quality can quickly deteriorate again once the rain stops. In contrast, hill stations like Ooty tend to have cleaner air due to their elevation and natural vegetation, and rainfall has a less dramatic impact on air quality. Tirunelveli's air quality, on the other hand, is influenced by a mix of industrial and agricultural activities, as well as vehicular emissions. While rainfall can help reduce pollutant levels, the city's air quality is also shaped by seasonal patterns and local environmental factors. One key takeaway from our analysis is that rainfall alone is not enough to solve the problem of air pollution. To make a meaningful impact, we need to address the root causes of pollution, including vehicular emissions, industrial activity, and other human-related factors. By combining rainfall data with other insights, policymakers can develop targeted strategies to improve air quality and protect public health. Ultimately, improving air quality requires a collaborative effort from governments, industries, and individuals. By working together, we can reduce pollution, promote sustainable development, and create healthier, more livable cities for everyone.

DECLARATIONS:

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