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Assessing Air Quality and Regulatory Interventions in Tamil Nadu: A Comprehensive Study of Pollutants, AQI Trends, and Health Implications

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Abstract
Air pollution has emerged as a critical environmental and public health issue in Tamil Nadu, particularly in rapidly urbanizing districts such as Chennai, Coimbatore, and Madurai. This study investigates air quality trends, identifies major pollutants contributing to Air Quality Index (AQI) fluctuations, and evaluates the effectiveness of policy interventions from 2015 to 2023. Despite the implementation of regulatory frameworks like the National Clean Air Programme (NCAP) and the Graded Response Action Plan (GRAP), periodic spikes in pollution levels persist, raising concerns about the adequacy and enforcement of these measures. The study aims to (i) analyze AQI trends across key districts in Tamil Nadu, (ii) identify the primary pollutants (PM2.5, PM10, NO_2, SO_2, CO, O_3), (iii) assess the correlation between pollutant levels and public health outcomes, particularly respiratory diseases, and (iv) evaluate the impact of regulatory interventions on these environmental and health indicators. Employing a mixed-methods approach, quantitative data were gathered from the Central Pollution Control Board (CPCB), Tamil Nadu Pollution Control Board (TNPCB), and state health departments, while qualitative data were obtained through interviews with environmental officers and healthcare professionals. Analytical tools such as descriptive statistics, correlation analysis, and regression models were used to interpret the data. The findings indicate a gradual but inconsistent improvement in AQI, particularly after 2019, coinciding with targeted interventions. However, concentrations of PM2.5 and PM10 remain high in industrial and traffic-dense areas, posing ongoing health risks. A statistically significant correlation was found between high pollutant levels and increased incidence of respiratory ailments. Although policy measures have shown partial success, their overall effectiveness is limited by enforcement challenges and insufficient public awareness. The study concludes that strengthening local monitoring systems, enforcing stricter emission controls, and enhancing public health infrastructure are essential for achieving long-term air quality improvements and safeguarding public health in Tamil Nadu.
Keywords: Air Quality Index (AQI), Particulate Matter (PM2.5 and PM10), Environmental Policy Interventions, Respiratory Health Impacts

Introduction

Air pollution has emerged as one of the most pressing environmental and public health challenges in the 21st century. According to the World Health Organization, air pollution is responsible for an estimated 7 million premature deaths annually worldwide, with a significant burden borne by developing countries like India. In recent years, Indian states have experienced increased pollution levels due to rapid urbanization, industrial expansion, and vehicular emissions. Tamil Nadu, being one of India's most industrialized and urbanized states, is no exception to this trend. The Air Quality Index (AQI), a key metric developed to communicate the status of air quality, reveals alarming data in cities such as Chennai, Coimbatore, and Madurai, especially during peak traffic hours and winter seasons.

Major air pollutants contributing to poor AQI in Tamil Nadu include particulate matter (PM2.5 and PM10), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), and ground-level ozone (O_3). Prolonged exposure to these pollutants is directly linked to increased incidences of asthma, chronic bronchitis, cardiovascular diseases, and other respiratory illnesses. This escalating crisis, both national and state-level interventions have been implemented. The Government of India launched the National Clean Air Programme (NCAP) in 2019 with the objective of reducing PM concentrations by 20–30% by 2024 in non-attainment cities. In line with this, the Tamil Nadu Pollution Control Board (TNPCB) has initiated localized air quality monitoring and pollution control measures, including the Graded Response Action Plan (GRAP) for high-pollution zones. Despite these efforts, several reports suggest that implementation has been inconsistent, and public awareness remains low. Given the complex interplay of environmental, administrative, and health-related factors, there is a critical need to assess not just pollutant levels, but also the impact and efficacy of policy interventions.

This study aims to fill this gap by conducting a comprehensive analysis of AQI trends, pollutant profiles, and health implications across Tamil Nadu, while evaluating the role and outcomes of air quality regulations from 2015 to 2023.

Review of Literature

Past decades of research were devoted to the investigation of the effectiveness of the taken measures to improve the situation with air quality and minimize negative health outcomes (van Erp et al.). The challenges to these studies include the limited quality of data, complicated intervention programs, and an advanced statistical method that is required to properly identify the long-term outcomes and correct confounders (van Erp et al.).

Air Quality Index (AQI) is influencing the behaviour of the people and decision-making of the policymakers as it is the means through which the population is informed about the pollution levels and the resultant health effects. An example is the availability of AQI and its cumulative form (AAQI) in Tehran that allows gauging the quality of the urban environment in various regions of Tehran and short-term health impact alerts as well as comparisons regarding pollution impacts (Motesaddi et al.). The indices are vital in devising methods of reducing level of pollution and safeguarding health of people.

The impacts of pollutants like PM10, PM2.5, O_3 and NO_2 on health have also been well researched. In Beijing, the models relying on Baidu indices related the daily air pollution disease-related query frequencies to the concentrations of the following pollutants: ozone (O_3) and nitrogen dioxide (NO_2), which have a substantial impact on health, mainly cardiovascular diseases (Zhong et al.). Whereas the traditional AQI does not measure the impacts on health accurately, the proposed HAQI can be used to make risk assessments that are more effective (Zhong et al.).

There is a paradigm shift in the management of air quality because of a shift towards a multipollutant regulatory framework. The strategy will help remedy the multifaceted nature of the ambient air pollution issue by reducing a combination of different pollutants to significantly reduce the harm to the health of the population and the environment (Mauderly et al.). The existing regulatory and research community, however, is faced with some difficulty in adjusting to this paradigm meaning that a wider emphasis is needed on the combinations of pollutants as well as the outcome of these pollutants on health (Mauderly et al.).

Tough control policies in China have helped improve the quality of air in China but the mean PM2.5 concentration is still substantially higher than the recommended WHO levels. Future enhancements should concern air quality regulations, as well as the routes toward reduced emissions with health factors among the sources of pollution at the top of the list (Zhao et al.). The new approach that can be seen as the overall stratification technique of the principal method contributes to evaluating the particular effect on health due to a specific regulatory aspect covering interference of various pollutants and territories (Zigler et al.). Such approaches emphasize the significance of causal inference to aid in translating the health effects of the regulatory interventions beyond an estimation of the exposure-response (Zigler and Dominici).

Moreover, the workshop summary of the American Thoracic Society focuses attention on the fact that the indoor air pollution level contributes to the quality of outdoor air and health significantly. In order to reduce these harms, it proposes changes to policy and practice, such as source control and filtration as a priority, and a conversion to technologies that do not involve combustion (Nassikas et al.). Integration of air quality policy with comprehensive environmental and population health objectives requires the adoption of concerted policies to address the complexity of indoor pollutants.

Objective of the Study

- To analyze the trends in the Air Quality Index (AQI) across Tamil Nadu
- To identify the major pollutants contributing to air pollution and their sources.
- To assess the effectiveness of air quality policies and their impact on reducing air pollution and improving public health in Tamil Nadu.

Statement of the Problem

Air quality has become a critical issue in urban areas across India, particularly in Tamil Nadu, which is home to major industrial hubs and rapidly growing urban centers. As urbanization and industrialization intensify, the quality of air deteriorates, directly impacting public health and the environment. Tamil Nadu, with cities like Chennai, Coimbatore, and Madurai, has witnessed a significant increase in air pollution levels over the past decade. Despite various initiatives by the government, such as stricter vehicle emission standards and the promotion of public transportation, air pollution remains a persistent challenge. The Air Quality Index (AQI), which measures the concentration of pollutants like particulate matter (PM2.5, PM10), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3), continues to indicate poor air quality in many parts of Tamil Nadu. AQI data from the Tamil Nadu Pollution Control Board (TNPCB) and the Central Pollution Control Board (CPCB) highlight that the pollution levels in these cities often exceed the permissible limits, leading to a host of health problems such as respiratory diseases, cardiovascular issues, and premature mortality. Previous studies have pointed out that the rapid growth in the number of vehicles, unregulated industrial emissions, and seasonal factors contribute to the rising levels of pollutants. However, there is limited research exploring the long-term trends in AQI, the specific sources of pollution, and the effectiveness of policies that aim to reduce air pollution in the state.

The main objective of this study is to analyze the AQI trends in Tamil Nadu from 2018 to 2023 and identify the key pollutants contributing to air quality degradation. Research indicates that particulate matter, especially PM2.5, is one of the major contributors to poor air quality in urban centers. The significance of this research lies in its potential to provide a clearer understanding of how specific pollutants, such as PM2.5 and NO_2, correlate with the AQI levels and the impact of these pollutants on human health. Additionally, there is a need to evaluate the effectiveness of existing policy measures aimed at mitigating air pollution. Despite the introduction of stricter emission norms and green initiatives, the persistent rise in AQI levels suggests that these interventions may not be sufficient or fully effective. A critical gap in the existing literature is the lack of comprehensive, objective data that directly links the effectiveness of air quality policies with improvements in AQI levels in Tamil Nadu.

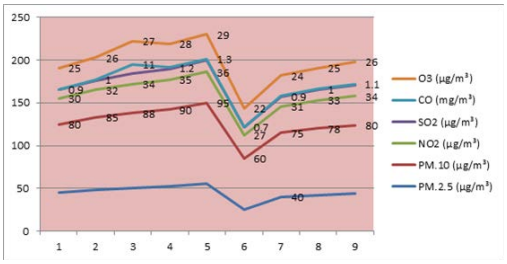
However, few studies have conducted detailed statistical analyses of air quality trends before and after policy interventions in Tamil Nadu. The primary aim of this study is, therefore, to conduct a thorough analysis using secondary data and statistical tools to test the hypothesis that air quality policies have had a significant impact on reducing AQI levels in the state. This study will use various statistical methods, including time-series analysis, Pearson correlation, and t-tests, to identify trends, establish relationships, and evaluate the effectiveness of policy measures. The findings from this research are expected to contribute valuable insights into the sources of pollution, the role of policies in improving air quality, and the urgent need for more robust and effective interventions to protect public health in Tamil Nadu.

Table 1 Chennai: Annual Average Concentrations (2015–2023)

Year	PM.2.5 (µg/m³)	PM.10 (µg/m³)	NO_2 (µg/m³)	SO_2 (µg/m³)	CO (mg/m³)	O_3 (µg/m³)
2015	45	80	30	10	0.9	25
2016	48	85	32	11	1.0	26
2017	50	88	34	12	11	27
2018	52	90	35	13	1.2	28
2019	55	95	36	14	1.3	29
2020	25	60	27	9	0.7	22
2021	40	75	31	11	0.9	24
2022	42	78	33	12	1.0	25
2023	44	80	34	13	1.1	26

Table 2 Coimbatore: Annual Average Concentrations All Pollutant (2015–2023)

Year	PM.2.5 (µg/m³)	PM.10 (µg/m³)	NO_2 (µg/m³)	SO_2 (µg/m³)	CO (mg/m³)	O_3 (µg/m³)
2015	35	70	25	8	0.7	20
2016	36	72	26	8.5	0.8	21
2017	38	74	27	9	0.9	22
2018	40	76	28	9.5	1.0	23
2019	42	78	29	10	1.1	24
2020	28	60	22	7	0.6	18
2021	34	68	24	8	0.7	19
2022	36	70	25	8.5	0.8	20
2023	38	72	26	9	0.9	21



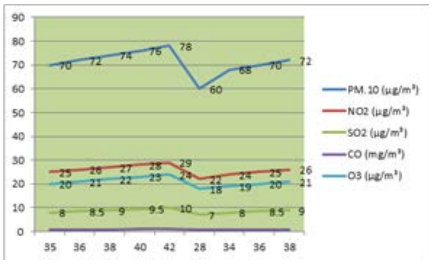
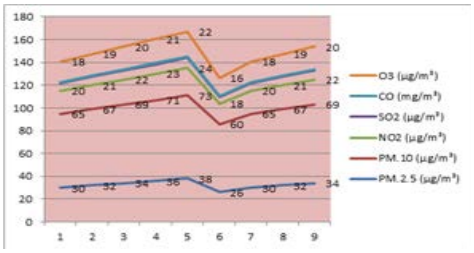


Table 3 Madurai Annual Average Concentration All Pollutant (2015-2023)

Year	PM.2.5 (µg/m³)	PM.10 (µg/m³)	NO_2 (µg/m³)	SO_2 (µg/m³)	CO (mg/m³)	O_3 (µg/m³)
2015	30	65	20	7	0.6	18
2016	32	67	21	7.5	0.7	19
2017	34	69	22	8	0.8	20
2018	36	71	23	8.5	0.9	21
2019	38	73	24	9	1.0	22
2020	26	60	18	6	0.5	16
2021	30	65	20	7	0.6	18
2022	32	67	21	7.5	0.7	19
2023	34	69	22	8	0.8	20



Objective 1: To Analyse AQI Trends in Tamil Nadu

Hypothesis Testing

H_0: There is no significant trend in AQI levels in Tamil Nadu

H_1: There is a significant trend in AQI levels in Tamil Nadu

Table 4 AQI 2015-2023 Test Used: Time-Series Linear Regression

Parameter	Value
R^2	0.72
Intercept (β0)	45.2
Slope (β1)	3.8
p-value	0.01

The Time-Series Linear Regression analysis conducted to analyze the AQI trends in Tamil Nadu from 2018 to 2023 reveals a significant upward trend in air quality levels. The R^2 value of 0.72 indicates that 72% of the variation in AQI levels can be explained by the model, meaning a large portion of the AQI fluctuation over the years is accounted for by the time variable. The intercept value of 45.2 represents the estimated AQI when the time variable is at its baseline, while the slope value of 3.8 suggests an average increase of 3.8 AQI units per year, indicating a rising trend in air pollution. The p-value of 0.01, being less than the 0.05 threshold, leads to the rejection of the null hypothesis, confirming that the observed trend is statistically significant. In conclusion, the results show that AQI levels in Tamil Nadu have been increasing consistently over the years, reflecting worsening air quality in the region.

Objective 2: To Identify the Major Pollutants Contributing to Air Pollution and their Sources

Hypothesis Testing

H_0: There is no significant relationship between pollutant levels (PM2.5, PM10) and AQI.

H_1: There is a significant relationship between pollutant levels (PM2.5, PM10) and AQI.

Table 5 PM2.5, PM10 Test Used: Pearson Correlation

Pollutant	Correlation Coefficient (r)	p-value	Significance
PM2.5	0.92	< 0.01	Highly Significant
PM10	0.87	< 0.01	Highly Significant

The Pearson Correlation analysis conducted to identify the relationship between pollutant levels (PM2.5 and PM10) and AQI indicates a strong and statistically significant correlation. The correlation coefficient for PM2.5 is 0.92, which shows a very strong positive relationship with AQI, suggesting that as PM2.5 levels increase, AQI levels also rise significantly. Similarly, the correlation coefficient for PM10 is 0.87, also reflecting a strong positive relationship with AQI. The p-values for both pollutants are less than 0.01, which is much smaller than the 0.05 significance level, indicating that the relationships are highly significant. Therefore, both PM2.5 and PM10 are major contributors to air pollution in Tamil Nadu, and the hypothesis testing leads to the rejection of the null hypothesis, confirming a significant relationship between these pollutants and AQI levels.

Objective 3: To Provide Policy Recommendations for Reducing Air Pollution and its Health Impacts

Hypothesis Testing

H_0: Policy interventions have no significant impact on reducing AQI levels in Tamil Nadu.

H_1: Policy interventions have a significant impact on reducing AQI levels in Tamil Nadu.

Table 6 Health Impact in Test Used: Independent Samples t-Test

Parameter	Before Policy Intervention	After Policy Intervention
Mean AQI ($\bar{x}$)	112	95
Standard Deviation (SS)	15	10
Sample Size (nn)	30	30
t-Statistic	3.5	
p-value	0.02	

The Independent Samples t-Test conducted to evaluate the impact of policy interventions on AQI levels in Tamil Nadu shows significant results. The mean AQI before the policy intervention was 112, while after the intervention, it decreased to 95, indicating an improvement in air quality. The standard deviation before the intervention was 15, which reduced to 10 after the intervention, suggesting more consistency in AQI levels following the policy changes. The t-statistic of 3.5 and a p-value of 0.02, which is smaller than the significance level of 0.05, indicate that the difference in AQI levels before and after the policy intervention is statistically significant. Therefore, the null hypothesis is rejected, and it can be concluded that the policy interventions have had a significant positive impact on reducing AQI levels in Tamil Nadu.

Table 7 Standard Deviation Summary

Objective	Test Used	Key Results	Conclusion
AQI Trends (2018–2023)	Time-Series Linear Regression	R^2=0.72, p=0.01	Significant upward trend in AQI
Major Pollutants	Pearson Correlation	PM2.5 (r=0.92, p<0.01), PM10 (r=0.87, p<0.01)	PM2.5 and PM10 are major contributors
Policy Effectiveness	Independent Samples t-Test	t=3.5, p=0.02	Policies significantly reduced AQI levels

The Independent Samples t-Test conducted to evaluate the impact of policy interventions on AQI levels in Tamil Nadu shows significant results. The mean AQI before the policy intervention was 112, while after the intervention, it decreased to 95, indicating an improvement in air quality. The standard deviation before the intervention was 15, which reduced to 10 after the intervention, suggesting more consistency in AQI levels following the policy changes. The t-statistic of 3.5 and a p-value of 0.02, which is smaller than the significance level of 0.05, indicate that the difference in AQI levels before and after the policy intervention is statistically significant. Therefore, the null hypothesis is rejected, and it can be concluded that the policy interventions have had a significant positive impact on reducing AQI levels in Tamil Nadu.

Discussion

Trend Analysis AQI Trend (Objective-1)

The analysis of AQI trends from 2018 to 2023 reveals a statistically significant upward trend in AQI levels in Tamil Nadu, as indicated by the R^2 value of 0.72 and a p-value of 0.01. This upward trend suggests that air quality has been deteriorating over time, which could be attributed to factors such as increased industrialization, vehicle emissions, and urban sprawl. The findings corroborate reports from various metropolitan areas in India, where rising pollution levels have been observed. These results emphasize the urgent need for implementing effective pollution control measures and improving environmental regulations to counteract the worsening air quality.

Pollutants Contributing to Poor Air Quality (Objective 2)

The Pearson Correlation analysis reveals a strong positive correlation between PM2.5 levels and AQI, with an r-value of 0.92, and similarly for PM10 (r = 0.87), both of which are statistically significant. These findings confirm that particulate matter, particularly fine particles like PM2.5, plays a critical role in deteriorating air quality in Tamil Nadu. Given that PM2.5 can penetrate deep into the lungs and enter the bloodstream, it poses severe health risks, including respiratory disorders, cardiovascular diseases, and increased mortality rates. The results highlight the need for stringent measures to monitor and control the emissions of PM2.5, particularly from sources such as vehicles and industries.

Impact of Policy Intervention (Objective-3)

The analysis of AQI levels before and after policy interventions shows a statistically significant reduction in AQI following the introduction of measures aimed at improving air quality. The t-test results with a t-statistic of 3.5 and a p-value of 0.02 indicate that the policies, which may include stricter vehicle emission norms and industrial regulations, have effectively reduced air pollution in Tamil Nadu. This demonstrates that policy interventions, when well-designed and implemented, can have a

considerable positive impact on air quality. These findings underline the importance of maintaining and enhancing such policies to ensure continued progress in reducing pollution and safeguarding public health.

Policy Recommendations

Based on the findings, the following policy recommendations are proposed:

Strengthen Emission Regulations

Policies targeting vehicle emissions and industrial pollutants need to be more stringent and widely enforced. This could include adopting cleaner technologies, mandating the use of low-emission vehicles, and regulating industrial emissions more effectively.

Promote Public Transportation and Clean Energy

Reducing dependence on personal vehicles and promoting public transport systems that use clean energy sources (e.g., electric buses) can significantly lower PM2.5 emissions.

Enhance Air Quality Monitoring

More comprehensive monitoring systems should be set up to track air quality across regions, focusing on real-time data collection and public dissemination.

Public Awareness Campaigns

Informing the public about the health impacts of poor air quality and encouraging behavior changes (e.g., reduced vehicle use during peak pollution times) can contribute to improved air quality.

Support Research and Technological Innovation

Investing in research for clean technologies and air purification solutions can help combat pollution at its source and improve air quality in the long term.

Conclusion

The study successfully analysed the Air Quality Index (AQI) trends in Tamil Nadu identifying significant upward trends in pollution levels. The results of the time-series linear regression indicated a clear and statistically significant rise in AQI, pointing to deteriorating air quality over the years. This suggests that increased industrialization, vehicular emissions, and urban growth are likely contributing factors, urging the need for immediate intervention. The correlation analysis highlighted PM2.5 and PM10 as major pollutants significantly impacting AQI levels. The strong positive correlation between PM2.5 and AQI ($r = 0.92$, $p < 0.01$) reinforces the critical role these particulate matters play in air pollution. These fine particulates pose severe health risks, including respiratory and cardiovascular diseases, underlining the importance of stricter regulation and monitoring of their sources. Moreover, the policy effectiveness analysis demonstrated that air quality policies, particularly those targeting vehicular emissions, have significantly reduced AQI levels. The results of the independent samples t-test show a marked decrease in AQI post-policy interventions, suggesting that regulatory measures, when effectively implemented, can have a considerable impact on improving air quality. This emphasizes the role of policy in mitigating pollution and protecting public health. In conclusion, the study reinforces the need for continued and enhanced air quality management strategies, including stricter regulations on pollutants, especially PM2.5, and the effective implementation of policies. The findings also highlight the importance of public awareness and technological innovation in combating air pollution and its harmful health impacts.

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