Air Pollutants and Acute Respiratory Infections (ARI): A Study of Indian States

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Abstract

This study aims to examine the correlation between primary air pollutants - Sulfur Dioxide (SO_2), Nitrogen Dioxide (NO_2), and Particulate Matter (PM_{10}) - and the occurrence of Acute Respiratory Infections (ARI) in 18 Indian states from 2015 to 2022. The analysis employs panel data regression models with fixed effects for both state and time, controlling for population density and Gross State Domestic Product (GSDP). The findings indicate a substantial positive link between PM_{10} levels and ARI cases ($\beta=7{,}296$, $p<0.01$), whereas SO_2 demonstrates an unexpected negative relationship ($\beta=-55{,}886$, $p<0.05$), possibly due to underreporting in industrial regions. Moreover, increased population density is associated with a reduction in reported ARI cases ($\beta=-118.9$, $p<0.01$), indicating enhanced healthcare accessibility in urban environments. States with higher GSDP exhibit reduced ARI prevalence, highlighting the impact of economic advancement on healthcare systems and environmental stewardship. These findings underscore the pressing necessity for specific air pollution reduction strategies and equitable healthcare policies to alleviate health hazards linked to air pollution in India. Subsequent investigations should examine the prolonged health implications and the socioeconomic aspects of health outcomes associated with pollution.

Keywords: Air pollution, Respiratory diseases, Public health, Environmental epidemiology, India, Panel data analysis.

Introduction

Acute Respiratory Infections (ARI) pose a significant public health challenge in India, contributing notably to morbidity and mortality rates. The World Health Organization has identified ARI as a leading cause of death worldwide, particularly impacting vulnerable populations in developing nations. These infections, which manifest through symptoms such as cough, sore throat, and respiratory distress, can affect both the upper and lower respiratory tracts, ranging from mild to severe, potentially life-threatening conditions.

In India, the burden of ARI is exacerbated by deteriorating air quality in numerous urban and industrial centers. The rapid pace of industrialization, urbanization, increasing vehicle density, and reliance on biomass fuels have led to alarming levels of air pollution across various states. Key pollutants of concern include Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), and Particulate Matter with a diameter of 10 micrometers or less (PM_{10}), each resulting from diverse anthropogenic activities and possessing distinct physiological impacts on respiratory health.

While the correlation between air pollution and respiratory diseases has been extensively documented on a global scale, there is a pressing need for region-specific studies that consider India's unique socioeconomic, demographic, and environmental contexts. The country's large and diverse population, coupled with varying levels of economic development and significant regional disparities in pollution sources and concentrations, renders it a critical case study for understanding these dynamics.

Moreover, air pollution has escalated into a global public health emergency, with developing nations like India facing acute challenges stemming from industrial expansion, rapid urbanization, and insufficient environmental regulations. Among the myriad health issues associated with environmental degradation, ARIs have garnered considerable attention due to their profound implications for public health and the substantial socio-economic costs they impose.

This research paper aims to investigate the relationship between three major air pollutants—SO_2, NO_2, and PM_{10}—and the incidence of ARI across 18 Indian states from 2015 to 2022. Additionally, it will explore how auxiliary factors such as population density and state-level economic performance, as measured by Gross State Domestic Product (GSDP), interact with these pollutants to influence ARI outcomes.

Aim of the Study

This research aims to address this knowledge gap by examining the relationship between air pollutants and ARI across 18 Indian states from 2015 to 2022. Specifically, the study investigates three key questions:

1. Is there a significant relationship between different types of air pollutants (SO_2, NO_2, and PM_{10}) and ARI cases/deaths?
2. Does population density impact ARI cases and deaths, and how does it interact with pollution levels?
3. How are levels of Gross State Domestic Product (GSDP) related to ARI incidences?

Need of the Study

Air pollution has emerged as a significant public health crisis in India, contributing to a range of respiratory illnesses, including Acute Respiratory Infections (ARI). Despite the growing body of literature on the health impacts of air pollution, there remains a critical gap in understanding the differential effects of specific air pollutants—Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), and Particulate Matter (PM_{10})—on ARI incidence and mortality at a disaggregated, state-level scale. Given the substantial burden of ARI in India and the regional disparities in pollution exposure, a more nuanced analysis is required to inform targeted policy interventions.

This study is motivated by several key considerations. First, ARIs constitute a leading cause of morbidity and mortality, particularly among vulnerable populations such as children and the elderly. Identifying the primary pollutants that exacerbate ARI cases is crucial for designing effective public health interventions. Second, the vast geographical and economic heterogeneity among Indian states results in significant variations in air pollution levels, healthcare infrastructure, and disease burden. By conducting a state-level analysis, this study seeks to uncover region-specific dynamics that may not be evident in national-level studies.

Moreover, while existing policies such as the National Clean Air Programme (NCAP) aim to mitigate pollution, they often lack direct empirical linkages to health outcomes. By quantifying the relationship between air pollution and ARI cases, this study provides evidence-based insights that can support more effective policy formulation. Additionally, socioeconomic factors such as population density and Gross State Domestic Product (GSDP) may play a moderating role in the pollution-health nexus. Investigating these interactions can enhance the understanding of whether economic development and urbanization mitigate or exacerbate the adverse health effects of air pollution.

Finally, with India witnessing increasing pollution levels due to industrialization, vehicular emissions, and biomass burning, the urgency to address pollution-related health risks has intensified. This study contributes to the broader discourse on environmental health by providing empirical evidence on how air pollution influences ARI cases and mortality across Indian states. The findings have significant implications for policymakers, public health officials, and environmental regulators in designing more effective air quality management and healthcare strategies.

Literature Review

The detrimental effects of air pollution on public health have been extensively documented, with a growing body of evidence linking exposure to pollutants such as particulate matter (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3) to respiratory illnesses, cardiovascular diseases, and premature mortality. Acute Respiratory Infections (ARI), in particular, have emerged as a significant consequence of air pollution, disproportionately affecting vulnerable populations, including children, the elderly, and those with pre-existing respiratory conditions. This review synthesizes global and regional evidence, with a focus on the Indian context, to highlight the health and economic burdens of air pollution and the mechanisms through which pollutants exacerbate respiratory infections.

Global Perspective on Air Pollution and Health:
Air pollution is now recognized as one of the leading environmental health risks worldwide. The Global Burden of Disease (GBD) studies have been instrumental in quantifying the health impacts of air pollution. According to the GBD 2017, air pollution was the second-largest risk factor contributing to disease burden in India, after malnutrition. The GBD 2019 study further revealed that air pollution contributed to 1.67 million deaths in India in 2019, accounting for 17.8% of total deaths. These findings underscore the severity of the crisis, particularly in regions with high levels of industrialization and urbanization.

Globally, severe air pollution episodes, such as the 1952 London smog, have demonstrated the acute health risks of pollutants like SO_2 and particulate matter. The London smog, which resulted in thousands of deaths, primarily affected vulnerable populations such as children and the elderly (Chauhan & Johnston, 2003). While legislation in developed nations has reduced traditional pollutants, emerging photochemical pollutants such as NO_2 and PM_{10} have gained prominence, particularly in urban and industrial settings. These pollutants interact synergistically with respiratory infections, amplifying inflammation and impairing immune defenses, especially in individuals with pre-existing conditions like asthma (Chauhan & Johnston, 2003; Spannhake et al., 2002).

Air Pollution in India: A State-Level Crisis:
India faces one of the highest air pollution-related disease burdens globally. The GBD 2019 study found that the highest exposure levels were observed in north Indian states, including Delhi, Uttar Pradesh, Bihar, and Haryana, where annual mean $PM_{2.5}$ concentrations exceeded 100 $\mu g/m^3$—far above the National Ambient Air Quality Standards (NAAQS) limit of 40 $\mu g/m^3$. Despite improvements in clean cooking fuel access, 56.3% of India's population continued to be exposed to household air pollution from solid fuel use.

The burden of air pollution is particularly severe in urban centers like Delhi, where PM_{10} levels exceed 160 μg/m³, more than double the national standard. A study of 11,628 Delhi children revealed a 32.1% prevalence of respiratory symptoms—nearly double that of rural controls (18.2%)—with PM_{10} strongly associated with lower respiratory tract symptoms (OR=1.48–3.12 per 50–150 μg/m³ increase) (Siddique et al., 2011). Girls exhibited higher susceptibility, likely due to prolonged indoor exposure to pollutants from cooking activities (Siddique et al., 2011; Smith et al., 2000). Seasonal variations further underscored PM_{10}'s role, with symptom prevalence peaking during winter when particulate concentrations were highest (Siddique et al., 2011).

Mechanisms Linking Air Pollution to ARI:

The link between air pollution and respiratory diseases, particularly ARI, has been well documented in epidemiological studies. Pollutants such as PM_{10}, $PM_{2.5}$, SO_2, and NO_2 can trigger inflammation of the airways, impair immune responses, and increase susceptibility to infections. According to the GBD 2019 study, lung diseases, including chronic obstructive pulmonary disease (COPD) and lower respiratory infections, accounted for 39.5% of the total disease burden attributable to air pollution. Lower respiratory infections, a subset of ARI, were responsible for approximately 15.5% of the disability-adjusted life years (DALYs) lost due to air pollution exposure.

In developing countries, indoor biomass combustion remains a critical contributor to respiratory morbidity. Studies in Gambia, Zimbabwe, and Nepal have linked biomass fuel use to elevated rates of ARI in children and chronic bronchitis in women (Chauhan & Johnston, 2003). Indoor PM_{10} levels in such settings often exceed 500 μg/m³—far above WHO guidelines—exacerbating vulnerabilities in populations with limited healthcare access (Smith et al., 2000).

Economic Impact of Air Pollution:

Beyond its health effects, air pollution imposes substantial economic costs. The GBD 2019 study estimated that lost output from premature deaths and morbidity due to air pollution resulted in an economic loss of $36.8 billion, equivalent to 1.36% of India's GDP. The study found that the economic burden varied significantly across states, with losses as a percentage of GDP ranging from 0.67% to 2.15%, with the highest losses occurring in states like Uttar Pradesh, Bihar, and Madhya Pradesh.

The economic losses stem from reduced productivity due to illness, healthcare expenditures, and loss of working-age individuals due to premature mortality. Given the high disease burden from ARI, especially among children and the elderly, the indirect costs associated with caregiving and hospitalizations further exacerbate the economic impact. Policymakers need to consider these economic implications while designing interventions to curb air pollution and its associated health risks.

Policy Responses and Gaps:
Despite numerous policy interventions, including the National Clean Air Programme (NCAP) and increased adoption of clean cooking fuels, air pollution remains a persistent challenge in India. While policies have focused on reducing household air pollution, ambient air pollution—especially from industrial emissions, vehicular traffic, and agricultural burning—continues to rise. There is a critical need for state-specific strategies that account for regional pollution sources and economic constraints. The findings from the GBD studies emphasize that policy responses must be multi-sectoral, involving stricter emissions regulations, improved urban planning, and better healthcare access to mitigate the impacts of pollution-induced respiratory diseases.

Conclusion

In summary, past literature suggests that air pollution likely plays a role in acute respiratory infections, but the magnitude and direction of effect can vary by pollutant and context. Particularly in India, with its diverse states and pollution sources, the net impact on ARI could depend on a combination of factors including baseline healthcare, population demographics, and dominant pollution sources (e.g., vehicular vs. industrial). The existing literature underscores the severe public health and economic burden imposed by air pollution in India. The disproportionate impact on states with lower socio-economic development highlights the need for targeted interventions to reduce pollution levels and mitigate health risks. Acute Respiratory Infections, a major component of this burden, are strongly linked to exposure to PM_{10} and other pollutants, necessitating urgent action. This study builds on the literature by using recent data across multiple Indian states to statistically assess how three major pollutants – SO2, NO2, and PM10 – correlate with ARI cases and deaths, while controlling for confounders like population density and economic development.

Data and Methodology

Data Sources and Description:

This study utilized a panel dataset covering 18 Indian states from 2015 to 2022. The states included in the analysis were Andhra Pradesh, Bihar, Chandigarh, Chhattisgarh, Delhi, Gujarat, Jammu & Kashmir, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, Tamil Nadu, Telangana, Uttar Pradesh, and West Bengal.

The data was compiled from multiple authoritative sources:

1. Acute Respiratory Infections (ARI) data: Cases and deaths due to ARI were obtained from the Ministry of Health and Family Welfare (MoH&FW), Government of India. This includes gender-disaggregated data on both cases and mortality.
2. Air Pollutant measurements: Data on three key air pollutants—Sulphur Dioxide (SO_2), Nitrogen Dioxide (NO_2), and Particulate Matter (PM_{10})—were collected from the Central Pollution Control Board (CPCB). These measurements represent annual average concentrations for each state.
3. Population data: State-wise projected total population figures were sourced from the Ministry of Health and Family Welfare, Government of India (ON3074).
4. Geographical area data: Information on the geographical area of each state was obtained from the Office of the Registrar General and Census Commissioner, India.
5. Economic indicators: Gross State Domestic Product (GSDP) at constant prices was collected from the Reserve Bank of India's Handbook of Statistics on Indian States.

From these primary data sources, additional variables were derived:

1. Population density: Calculated as the ratio of total population to geographical area, expressed as persons per square kilometre.
2. Interaction terms: To examine the combined effects of pollution and population density, interaction terms were created between population density and each pollutant (PopDensity_SO2, PopDensity_NO2, PopDensity_PM10).

It is important to note that while the WHO Global Air Quality Guidelines (2021) recommend 24-hour average limits of 40 $\mu g/m^3$ for SO_2, annual average limits of 10 $\mu g/m^3$ for NO_2, and annual average limits of 15 $\mu g/m^3$ for PM_{10}, India's National Ambient Air Quality Standards (NAAQS) from 2009 set less stringent limits: 80

μg/m³ for SO_2 (24-hour average), 40 μg/m³ for NO_2 (annual average), and 60 μg/m³ for PM_{10} (annual average).

Pollutant	**WHO Global Air Quality Guidelines (2021)**	**National Ambient Air Quality Standards (NAAQS) in India (2009)**
SO2 (Sulfur Dioxide)	24-hour average: 40 μg/m³	24-hour average: 80 μg/m³
NO2 (Nitrogen Dioxide)	Annual average: 10 μg/m³	Annual average: 40 μg/m³
PM10 (Particulate Matter with a diameter of 10 micrometers or less)	Annual average: 15 μg/m³	Annual average: 60 μg/m³

Analytical Framework

This study employed panel regression models to examine the relationship between air pollutants and ARI outcomes while controlling for socioeconomic factors. The panel structure allowed for controlling both state-specific time-invariant characteristics and time trends common across all states.

The basic model specification was:

$$Y_{it} = \beta_0 + \beta_1 SO2_{it} + \beta_2 NO2_{it} + \beta_3 PM10_{it} + \alpha_i + \gamma_t + \varepsilon_{it}$$

where,

Yit represents the dependent variable (either Total ARI Cases or Total ARI Deaths) in state *i* at time *t*

- $SO2it$, $NO2it$, and $PM10it$ are the annual average concentrations of the respective pollutants
- αi captures state fixed effects
- γt captures time fixed effects
- εit is the error term

To account for socioeconomic factors, extended models were developed incorporating population density and GSDP:

$$Yit = \beta 0 + \beta 1SO2it + \beta 2NO2it + \beta 3PM10it + \beta 4PopDensityit + \beta 5GSDPit + \alpha i + \varepsilon it$$

Further, to examine the potential modifying effect of population density on pollution impacts, models with interaction terms were specified:

$$\mathrm{Yit} = \beta 0 + \beta 1\mathrm{SO2it} + \beta 2\mathrm{NO2it} + \beta 3\mathrm{PM10it} + \beta 4\mathrm{PopDensityit} + \beta 5\mathrm{PopDensity\_SO2it} + \beta 6\mathrm{PopDensity\_NO2it} + \beta 7\mathrm{PopDensity\_PM10it} + \alpha i + \varepsilon it$$

All models were estimated using fixed effects regression to control for unobserved state-specific heterogeneity. The fixed effects approach was preferred over random effects based on the assumption that state-specific factors influencing ARI outcomes are likely correlated with the observed variables included in the model. Additionally, on running the Hausman Test, it preferred fixed effects over random effects.

The estimation strategy involves:

1. Univariate Regressions: Estimating the impact of each pollutant separately on ARI cases and deaths.
2. Multivariate Regressions**:** Including all three pollutants simultaneously in the model.
3. Interaction Models: Introducing interaction terms between population density and each pollutant.
4. Robustness Checks: Assessing the stability of coefficients when controlling for economic output (GSDP) and when using logarithmic transformations of GSDP.

Statistical significance is assessed at conventional levels (1%, 5%, and 10%), and the R-squared values are reported to indicate the proportion of variance explained by the models.

Descriptive Statistics

Table 1 presents summary statistics for the key variables used in the analysis. The data reveals substantial variation in both pollution levels and ARI outcomes across the states and time periods studied.

Table 1: Descriptive Statistics

summary table

Variable	Obs	Mean	Std. Dev.	Min	Max
SO2	133	9.718	5.004	2	23.33
NO2	134	28.62	12.4	8.66	73
PM10	136	121.068	53.067	38.11	298.5
TotalCases	142	1524333	1464304.9	15263	5887367
TotalDeaths	142	216.887	567.15	0	4494

The average SO_2 concentration across all observations was 9.72 μg/m^3, with values ranging from 2.00 to 23.33 μg/m^3. The mean NO_2 concentration was 28.62 μg/m^3, varying from 8.66 to 73.00 μg/m^3. PM_{10} displayed the highest average concentration at 121.07 μg/m^3, with a considerable range from 38.11 to 298.50 μg/m^3. Notably, the average PM_{10} concentration exceeds both the WHO guideline (15 μg/m^3) and India's NAAQS (60 μg/m^3) by substantial margins. Notably, all the pollutants registered a steep decline in concentration in the COVID years. (Graphs 1, 2 and 3)

ARI cases showed considerable variation, with a mean of 1,524,333 cases per state-year observation, ranging from 15,263 to 5,887,367. ARI deaths averaged 216.89 per state-year, with a range from 0 to 4,494, indicating significant disparities in mortality outcomes across states.

Results

In the ARI Cases model (a), a significant negative association was found between SO_2 levels and acute respiratory infections (ARI), with a coefficient of approximately -55,886 ($p < 0.05$), suggesting that increased SO_2 correlates with fewer ARI cases, a counterintuitive result warranting further exploration. Conversely, PM_{10} exhibited a positive and significant relationship with ARI cases (≈ 6,919, $p < 0.05$), indicating that a 10 μg/m3 rise in PM_{10} is linked to about 69,000 additional ARI cases. NO_2 showed no significant effect on ARI incidence. The model's R^2 of 0.131 indicates that these pollutants explain a modest portion of the variance in ARI cases.

In contrast, the ARI Deaths model (b) revealed no significant impact of pollutants on ARI mortality, with coefficients for SO_2 and NO_2 being negative yet insignificant, and PM_{10} showing a negligible negative coefficient. The R^2 for this model was only 0.028, suggesting that ARI mortality is influenced more by factors such as healthcare access and comorbidities than by pollution levels.

The consistent negative association of SO_2 with ARI cases, confirmed through single-pollutant models, indicates a robust finding that merits further investigation into potential underlying factors, such as the health dynamics in industrial versus rural regions.

Table 2. Fixed-Effects Panel Regression of ARI Outcomes on Air Pollutants

Variables	**(a) ARI Cases**	**(b) ARI Deaths**
SO_2 (μg/m³)	-55,886** (21,805)	-8.637 (15.830)
NO_2 (μg/m³)	8,318 (10,579)	-8.010 (7.679)
PM_{10} (μg/m³)	6,919** (2,935)	-0.824 (2.131)
Constant	996,225*** (347,083)	646.8** (251.9)
State Fixed Effects	Yes	Yes
Year Fixed Effects	Yes	Yes
Observations	131	131
R-squared	0.131	0.028

Notes:
1. Dependent variables: Total ARI Cases and Total ARI Deaths.
2. Coefficients for ARI Cases are in absolute numbers (not millions), and for ARI Deaths, they are in the number of deaths.
3. Robust standard errors are reported in parentheses.
4. Significance levels: **$p < 0.05$, ***$p < 0.01$.

Role of Population Density and Economic Development:

This study investigates the relationship between pollution, population density, and Gross State Domestic Product (GSDP) in relation to Acute Respiratory Infections (ARI). Interestingly, population density shows a significant negative relationship with both NO_2 and PM_{10} levels, suggesting that more densely populated states have lower concentrations of these pollutants. In contrast, population density has a small but significant positive association with SO_2 levels, indicating that more densely populated states tend to have slightly higher SO_2 concentrations. (Table 3).
Figure 1 illustrates a simple correlation: plotting average ARI cases per capita against population density shows an inverse relationship – more densely populated states (generally urbanized states) tend to have fewer ARI cases per 1,000 people. This is somewhat surprising, as high density is often thought to facilitate contagion. Our regression analysis confirms this counter-intuitive finding (Table 4).
When we include population density (per km^2) in the panel regression alongside the pollutants, the coefficient on density is negative and statistically significant. The analysis reveals a counter-intuitive inverse correlation between population density and ARI incidence, where more densely populated states, typically urbanized, report fewer ARI cases per capita. This finding is substantiated by regression analyses indicating that an increase in population density correlates with a significant reduction in ARI cases, potentially attributable to enhanced healthcare access and immunization coverage in urban areas, as well as differing exposure patterns to indoor air pollution. Population density shows a significant negative relationship with ARI cases, with an increase of 1 person per square kilometer associated with approximately 119 fewer ARI cases. This relationship persists even when controlling for pollutant levels, suggesting that more densely populated areas consistently report fewer ARI cases.

The interaction terms reveal that the relationship between pollutants and ARI cases varies with population density. The significant positive coefficient for PopDensity_SO_2 suggests that the negative association between SO_2 and ARI cases becomes less pronounced in more densely populated areas. Conversely, the negative coefficient for PopDensity_PM_{10} indicates that the positive association between PM_{10} and ARI cases becomes weaker in more densely populated areas. (Table 5)

The incorporation of Gross State Domestic Product (GSDP) into the analytical models yielded significant insights regarding the incidence of Acute Respiratory Infections (ARI). The analysis revealed a negative correlation between GSDP and ARI cases, with a coefficient of approximately -0.0190 ($p < 0.01$), indicating that an increase of ₹100,000 lakh in a state's GSDP—serving as a proxy for economic advancement—correlates with an average reduction of approximately 1.9 million ARI cases. This relationship persists even when controlling for pollution levels, suggesting that wealthier states experience fewer ARI cases.

Further exploration of the logarithmic transformation of GSDP to assess potential non-linear effects maintained a negative association, with a 10% increase in GSDP correlating with roughly 110,000 fewer ARI cases ($p < 0.10$). However, the impact of GSDP on ARI mortality was not statistically significant, indicating that while higher state income is associated with lower ARI incidence, it does not necessarily translate into reduced mortality rates. This discrepancy may arise from the fact that once an infection occurs, survival is more contingent upon the quality of healthcare rather than overall economic prosperity. (Table 6)

The finding that wealth correlates with lower ARI prevalence supports the notion that socio-economic development – through improved nutrition, cleaner cooking fuels, better sanitation, and stronger health systems – plays a key role in reducing infectious disease burden . It also aligns with the idea that some of the worst ARI burdens in India are concentrated in poorer, rural, and backward regions despite those often having lower measured outdoor pollution; thus, pollution is only part of the puzzle.

Discussion

This research paper explores the intricate relationship between air pollutants and Acute Respiratory Infections (ARIs) across 18 Indian states from 2015 to 2022, revealing significant insights into the environmental health landscape in India. The study primarily focuses on sulfur dioxide (SO2) and particulate matter (PM10), highlighting their respective impacts on ARI incidence.

The analysis indicates a negative correlation between SO2 levels and ARI cases, which may lead to erroneous interpretations suggesting that SO2 serves as a protective factor against infections. This correlation is likely influenced by indirect factors, including the underreporting of ARI cases in regions with high SO2 emissions, typically linked to industrial activities. These areas often have lower population densities and inadequate public health reporting systems, resulting in an underdiagnosis of ARIs. In contrast, states with robust public health initiatives may report higher ARI cases despite lower SO2 levels, contributing to the observed inverse relationship.

Moreover, the study posits that the primary causative agents of ARIs are viral or bacterial pathogens, whose transmission is affected by environmental factors such as crowding and indoor air quality. SO2, primarily an outdoor pollutant, may not directly influence ARI incidence; rather, chronic respiratory conditions associated with SO2 exposure could manifest as chronic illnesses rather than acute infections. Additionally, indoor air pollution from biomass burning in rural areas significantly contributes to ARIs, yet is not captured by ambient SO2 measurements.

The research also highlights the potential for ecological fallacy in state-level analyses, where the aggregated data may obscure the relationship between SO2 levels and ARI rates. The inclusion of Gross State Domestic Product (GSDP) in regression analyses revealed a reduction in the negative coefficient for SO2, suggesting that economic development may confound its effects. Despite this adjustment, a residual negative effect of SO2 on ARI rates persisted, indicating the influence of unobserved factors such as healthcare infrastructure quality or climatic conditions.

In contrast, the study identifies a significant positive correlation between PM10 levels and ARI incidence, suggesting that elevated particulate pollution exacerbates respiratory conditions. The findings advocate for public health initiatives aimed at mitigating PM10 sources, including construction activities and industrial emissions, to reduce respiratory infections.

Interestingly, the analysis reveals a lack of significant correlation between nitrogen dioxide (NO2) levels and ARI cases, potentially due to the relatively stable NO2 concentrations across states. This suggests that targeting PM10 may yield more immediate benefits for ARI reduction compared to NO2.

Additionally, the research uncovers a counterintuitive trend where states with higher population densities report fewer ARIs per capita than rural areas. This phenomenon can be attributed to better healthcare access, vaccination coverage, and living conditions in urban settings, despite the absolute number of ARI cases remaining high in megacities. The inverse relationship between GSDP and ARI cases further underscores the protective effect of economic development on public health, as wealthier states demonstrate improved sanitation, literacy, and healthcare resources.

In conclusion, this study emphasizes the need for a nuanced interpretation of the relationship between air pollution and health outcomes in India, considering the interplay of diverse environmental and socioeconomic factors. Future research is essential to disentangle these complex interactions and inform targeted public health interventions.

Policy Implications

The findings of this study present significant policy implications for public health practitioners and policymakers in India, particularly concerning the relationship between particulate matter (PM10) and acute respiratory infections (ARI). The established correlation underscores the necessity for stringent air quality regulations aimed at reducing particulate pollution. Implementing measures such as dust control at construction sites, mechanized road sweeping, and incentivizing farmers to refrain from crop burning could not only improve air quality but also reduce ARI incidence, particularly among vulnerable populations such as children. This highlights the public health rationale for environmental regulations, especially in the context of initiatives like the National Clean Air Programme (NCAP), which aims to mitigate particulate pollution in urban areas. Health impact assessments of these programs should encompass potential reductions in ARI alongside traditional metrics such as asthma and cardiac events.

Furthermore, the study emphasizes the importance of enhancing healthcare and socio-economic conditions, as pollution control alone may not suffice in decreasing ARI mortality rates. The absence of a significant pollutant effect on mortality suggests that interventions aimed at strengthening primary healthcare systems, expanding immunization coverage for influenza and pneumococcal diseases, and ensuring the availability of antibiotics are essential for reducing ARI-related fatalities. The negative correlation observed with sulfur dioxide (SO2) indicates that certain states may effectively manage ARI rates despite high pollution levels, potentially due to superior healthcare practices or other unmeasured factors. Identifying and replicating these best practices in regions with high ARI burdens could be beneficial.

Additionally, the study highlights the critical role of indoor air pollution, particularly in households reliant on solid fuels, which contribute to elevated levels of particulate matter and respiratory irritants. Government initiatives such as the UJALA scheme, which promotes the use of liquefied petroleum gas (LPG) for cooking, are vital in addressing this issue. The findings suggest that the primary drivers of ARI may stem from indoor environments or factors not captured by outdoor air quality monitors. Therefore, promoting clean cooking fuels, enhancing ventilation, and educating the public about smoke inhalation risks could significantly mitigate ARI prevalence in rural settings.

Lastly, the study identifies a pressing need for improved surveillance and data collection mechanisms. The inconsistencies and gaps in data, such as missing ARI cases in West Bengal and pollution data for certain Union Territories, highlight the necessity for a robust monitoring system that integrates environmental data with health outcomes at more granular spatial

Conclusion

This research paper investigates the correlation between ambient air pollution and acute respiratory infections (ARIs) across various Indian states over an eight-year timeframe. Utilizing fixed-effects panel regressions, the study reveals a positive association between particulate matter (PM10) and increased ARI case counts, while sulfur dioxide (SO_2) exhibited an unexpected negative correlation with ARI incidence. Nitrogen dioxide (NO_2) did not demonstrate a significant effect. The findings indicate that more urbanized and economically developed states report fewer ARI cases, emphasizing the role of socio-economic factors in disease prevalence. Notably, none of the pollutants analyzed were significantly linked to ARI mortality, suggesting that determinants such as healthcare accessibility and timely treatment play a more crucial role in mortality outcomes from respiratory infections.

Study Limitations

The unexpected relationship with SO_2 suggests that observed correlations may reflect underlying state-level differences—such as industrialization and data reporting discrepancies—rather than a genuine protective effect. The study acknowledges limitations, including potential underreporting and the challenges of state-aggregate data, advocating for further research at the individual level through longitudinal cohort studies or localized time-series analyses.

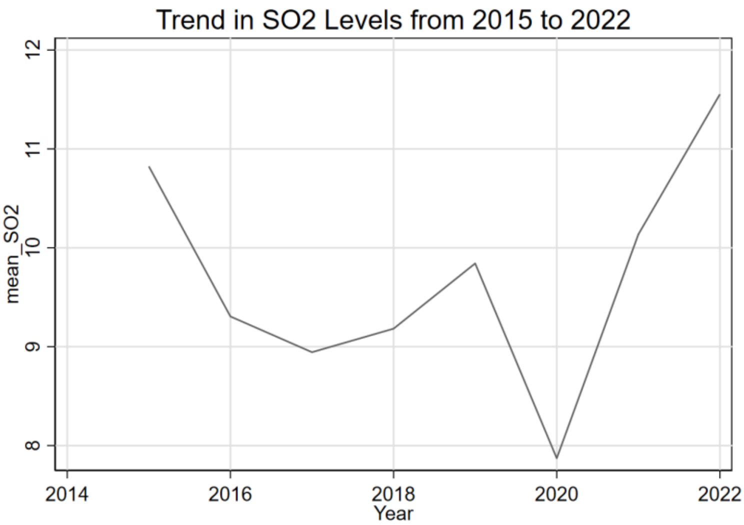
From a policy perspective, the findings advocate for dual strategies: enhancing environmental controls, particularly for particulate pollution, and strengthening public health infrastructure. Mitigating ambient particulate levels could potentially reduce ARI incidence, thereby alleviating healthcare system burdens during peak infection periods. Concurrently, improving healthcare access, economic conditions, and indoor air quality—especially through initiatives promoting clean cooking fuels—may yield more substantial reductions in ARI rates, given the strong association of socio-economic factors with health outcomes.

Scope for Future Work

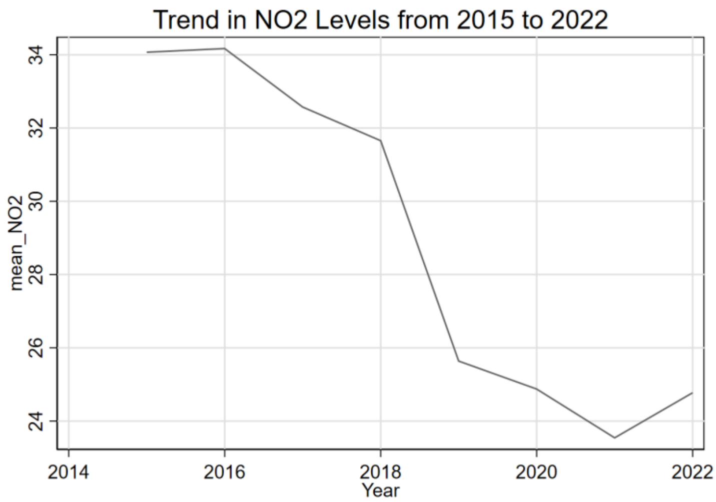
Future research avenues include the utilization of more granular data, such as district-level analyses and satellite-derived pollution metrics, to address areas lacking ground monitoring. Investigating the lagged effects of pollution on ARI outbreaks and differentiating between upper and lower respiratory infections are also recommended. Additionally, exploring the interaction between pollution and vaccination rates could provide insights into the resilience of well-vaccinated populations against infection rates. With climate change exacerbating extreme weather conditions that influence air quality and disease transmission, ongoing research in these domains remains critical for public health safeguarding.

In summary, this study enhances the understanding of the interplay between environmental quality and public health in India. Addressing ARIs, a significant health challenge, necessitates a comprehensive approach that encompasses air quality improvement, enhanced living conditions, and robust healthcare systems. By tackling these interconnected issues, India can mitigate the impact of ARIs and promote healthier lives for its citizens amidst environmental changes.

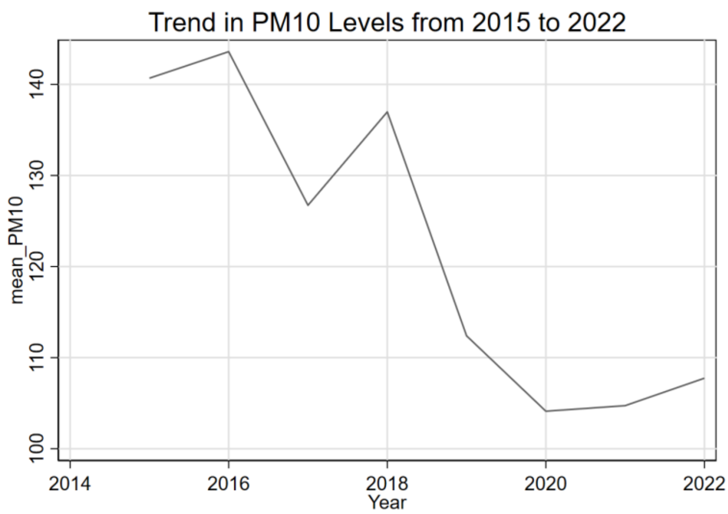
Appendix



Trend in SO2 Levels from 2015 to 2022
mean_SO2
8
9
10
11
12
2014
2016
2018
2020
2022
Year



Trend in NO2 Levels from 2015 to 2022
mean_NO2
24
26
28
30
32
34
2014
2016
2018
2020
2022
Year



Trend in PM10 Levels from 2015 to 2022
mean_PM10
100
110
120
130
140
2014
2016
2018
2020
2022
Year

Table 3: Relationship between Population Density and Pollution Levels

VARIABLES	NO_2	PM_{10}	SO_2
PopDensity	-0.0145***	-0.0323**	0.00273*
	(0.00389)	(0.0143)	(0.00159)
Constant	53.69***	176.0***	5.002*
	(6.731)	(24.43)	(2.754)
Observations	134	136	133
R-squared	0.108	0.042	0.025

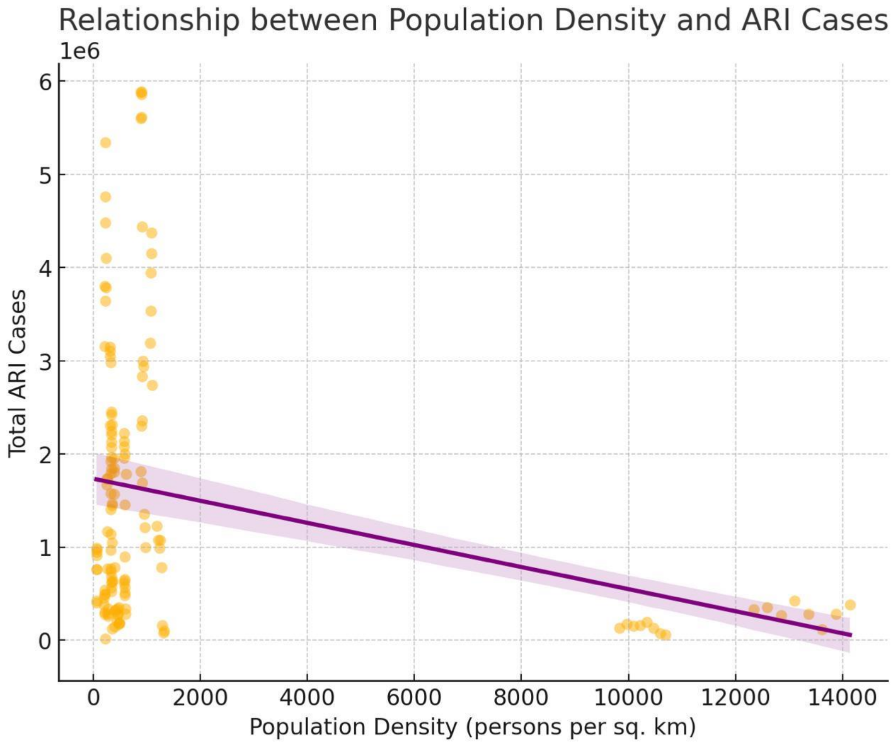


Figure 1

Table 4: Relationship between Population Density and ARI Cases

VARIABLES	(a)ARI Cases	(b)ARI Cases
PopDensity	-118.9***	-155.8*
	(32.68)	(84.46)
SO_2	-	-59,054***
		(21,015)
NO_2	-	7,979
		(10,265)
PM_{10}	-	5,768**
		(2,804)
Constant	1,736,000***	1,449,000***
	(131,396)	(467,492)
Observations	142	131
R-squared	0.086	-

Table 5: Interaction between Population Density and Pollutants on ARI Cases

	(1)
VARIABLES	TotalCases
SO2	-116,847***
	(24,970)
NO2	12,464
	(16,340)
PM10	2,220
	(3,421)
PopDensity	-186.2***
	(51.11)
PopDensity_SO2	18.87***
	(5.223)
PopDensity_NO2	1.969
	(1.856)
PopDensity_PM10	-1.136*
	(0.677)
Constant	2.315e+06***
	(478,228)
Observations	131
R-squared	0.205

Table 6 : Relationship between GSDP and ARI Cases

Variables	(a) Model 1(GSDP)	(b) Model 2(log_GSDP)
SO_2 (μg/m³)	-41,439* (23,120)	-46,010* (23,910)
NO_2 (μg/m³)	5,977 (11,419)	9,094 (11,586)
PM_{10} (μg/m³)	4,563 (3,044)	4,317 (3,322)
PopDensity	329.3 (419.8)	380.1 (428.7)
GSDPConstantPrices	-0.0190*** (0.00660)	-
log_GSDPConstantPrices		-1,100,000* (593,322)
Constant	2,192,000** (934,023)	20,420,000* (10,790,000)
State Fixed Effects	Yes	Yes
Year Fixed Effects	Yes	Yes
Observations	125	125
R-squared	0.202	0.166

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