ECONOMIC ANNALS, Volume LXX, No. 245 / April – June 2025
UDC: 3.33 ISSN: 0013-3264

https://doi.org/10.2298/EKA2545075C

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WHAT ARE THE PRIMARY SOURCES OF AIR POLLUTION IN INDIAN CITIES?

ABSTRACT: *India is the world's third most polluted country, with most of its cities ranking among the worst. This calls India's ambitions for sustainable urban growth into question. In this perspective, the present study investigates the sources of city air pollution in India. Due to the paucity of data, we consider 36 metropolitan cities (cities with a million-plus population) for the analysis. Eight pollutants are considered to measure air pollution at the city level. Based on several Sustainable Development Goals, indicators for infrastructure, population agglomeration, transport, waste generation, climate action, energy use, life on land are considered for the assessment. Using principal component analysis, we created pollution and infrastructure indices. The results show that Delhi is the most polluted city and Bangalore has the highest availability of infrastructure of all cities in India. The ordinary regression results show that infrastructure, waste generation, registered motor vehicles, and population size positively affect (increase) air pollution. Additionally, clean fuel usage, light-emitting diode bulb distribution, and open space negatively impact (decrease) air pollution. The study concludes with important policy interventions to address urban air pollution effectively for higher and sustainable urban growth in India.*

KEY WORDS: *Urbanisation, air pollution, infrastructure, clean energy, India*

JEL CLASSIFICATION: R11, Q53, 018

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1. INTRODUCTION

Urbanisation is one of the most influential human activities of the Anthropocene (McPhearson et al., 2021). The positive impacts of urbanisation on economic growth have been extensively studied (Northam, 1979) and are considered a vital catalyst for social advancement (Kates & Parris, 2003). Cities, the epicentres of urbanisation, have become hubs of innovation and opportunities, attracting people from diverse backgrounds and fostering a culture of inclusivity and growth. However, rampant urbanisation has caused severe air pollution, particularly in metropolitan areas with more concentrated and complicated human activities, undermining urban sustainability (Sun et al., 2023). This poses a threat to the environment and has severe implications for human health and well-being (Brook et al., 2010). According to the World Health Organisation (WHO), in 2019, 99% of the world's population was living in places where the WHO's air quality guidelines were not met, leading to an estimated 4.2 million premature deaths due to ambient air pollution, with a significant proportion of these occurring in urban areas.[1] Urbanisation and air pollution are both closely linked to sustainable development and human well-being (Chen et al., 2022). This connection is explicitly recognised in the United Nations Sustainable Development Goals (SDGs), particularly SDG 11, which aims to "make cities and human settlements inclusive, safe, resilient, and sustainable" (United Nations, 2015). Achieving this goal necessitates a comprehensive understanding of the dynamics of urbanisation and its impact on air pollution.

Most developed countries have achieved decoupling of economic growth from air pollution or emissions; this means that their emissions have decreased even as their GDP has increased (Hubacek et al., 2021). This achievement is attributed to strategic planning, sustainable infrastructure investments, and effective regulatory measures in managing urbanisation. In contrast, many developing countries, including India, are experiencing rapid and often unplanned urbanisation, exacerbating air pollution problems. The combination of increased industrial activities, transportation, and household emissions, coupled with limited infrastructure and regulatory frameworks, has resulted in severe air

[1] https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (accessed on 19 March, 2025)

quality degradation in major Indian cities (Nagdeve, 2006) with significant implications for public health (Misra et al., 2019).

Agglomeration benefits associated with higher per capita income may cause higher pollution in cities via higher production and consumption. A high per capita income leads to affordability and the demand for private vehicles, which in turn causes environmental degradation and increased energy use. Cities' expansion mostly depends on the advantages of the agglomeration economy, but after a certain point, negative externalities, such as an increase in pollution, cause cities' growth to stagnate. Indeed, these harmful externalities can be linked to policy failures and the absence of regulatory mechanisms.

Between 2001 and 2011, the percentage of private vehicles in India that are specifically designed for urban use, such as motorcycles and scooters, climbed from 24.7% to 35.2%. Moreover, the proportion of cars, jeeps, and vans rose from 5.6% in 2001 to 9.7% in 2011 (Tripathi & Kaur, 2018). Deterioration of the environment is caused by an increase in the number of vehicles. Air pollution is produced by the principal greenhouse gases carbon monoxide (CO), sulphur dioxide (SO2), carbon dioxide (CO2), and nitrogen dioxide (NO2). After the China and the United States (US), India was ranked the third largest producer of greenhouse gas emissions in 2022 (European Commission, Joint Research Centre, 2023).

Building upon the existing literature on urbanisation and air pollution, this study aims to provide a comprehensive assessment of the impact of various urbanisation indicators on air pollution in 36 metropolitan cities across India. While previous research has often focused on specific pollutants or employed broad geographical scales, this study addresses these limitations by utilising city-level data encompassing a wide range of air quality indicators, urban infrastructure, transportation, waste generation, and population dynamics. By adopting this approach, the study offers a more nuanced understanding of the intricate relationship between urbanisation and air pollution, particularly within India's rapidly growing urban centres. Through granular analysis, the study seeks to identify key drivers of air pollution in Indian metropolitan cities and inform targeted policy interventions to mitigate its adverse effects. This study contributes

to the broader discourse on sustainable urban development and human well-being by bridging the gap between research and policy.

The study adopts the following structure. In the next section, a brief review of the literature is presented. Section 3 explains the main conceptual framework of the study. Section 4 provides the data and methods and Section 5 the empirical results. Sections 6 and 7 present the discussion and conclusions, respectively. Finally, Section 8 highlights the main limitations of the study.

2. REVIEW OF LITERATURE

Early studies of the relationship between urbanisation and environmental pollution focused on the relationships between population growth, resources, economic growth, and the environment. Grossman and Krueger (1991) integrated the Kuznets curve concept into exploring how economic development impacts environmental pollution, proposing the environmental Kuznets curve (EKC). They discovered an inverted U-shaped correlation between economic growth and environmental pollution (Grossman & Krueger, 1995). Dinda (2004) confirmed that the dynamic between economic growth and environmental pollution in developed nations adheres to the EKC hypothesis. Population increase has also been identified as a significant contributor to environmental pollution (Jorgensen and Clark, 2010).

Nonetheless, urbanisation encompasses more than just demographic shifts; it involves population, economy, society, and spatial organisation transformations. The impact of urbanisation on environmental pollution varies across countries and regions, depending on their level of development (Grimm et al., 2008). In their examination of 99 countries, Poumanyvong and Kaneko (2010) investigated how urbanisation affects energy consumption and carbon emissions, considering population size, GDP per capita, the urbanisation rate, and industrial composition. They observed that in low-income nations, urbanisation leads to reduced energy consumption. In contrast, it increases energy use in middle-income and high-income countries and consistently contributes to higher carbon emissions. Martínez-Zarzoso and Maruotti (2011) demonstrated that the relationship between urbanisation and carbon emissions in developing countries also follows an inverted U-shaped curve.

In the context of developing countries, the relationship between urbanisation and air pollution becomes even more complex. Rapid urbanisation in these regions often outpaces infrastructure development and regulatory frameworks, increasing pollution (Cohen, 2006). For instance, in many African cities, rapid urban growth has led to increased vehicle emissions, industrial pollution, and waste burning, contributing to poor air quality (Songsore, 2003). Similarly, in Latin America, urbanisation has been linked to increased deforestation and land degradation, leading to increased carbon emissions (Perz & Skole 2003). The situation is particularly concerning in India, a country experiencing rapid urbanisation. Indian cities are among the most polluted in the world, with high levels of PM2.5 and PM10 (Balakrishnan et al., 2019). The rapid growth of cities and a lack of effective pollution control measures have led to severe air quality issues. Studies have shown that in India, urbanisation has a significant positive relationship with CO_2 emissions (Paul and Bhattacharyya, 2004).

Table 1 summarises the empirical studies on the impact of urbanisation on air pollution. The existing research on air pollution often focuses on a limited set of pollutants or employs broad geographical scales. In contrast to existing studies in India that often focus on a restricted range of emissions and indicators of urbanisation, this study tries to fill that gap by utilising a comprehensive set of city-level data.

Table 1: A selected review of empirical studies

Author	Objective	Variable	Methodology	Source of Data	Conclusion
International context					
Wang et al. (2021)	Analyse impacts of urbanisation on carbon emissions in OECD countries	Independent variables: economic growth, energy efficiency, final energy consumption of industry, transport, residential sectors, urban population ratio. Dependent variables: CO2 emissions per capita, total CO2 emissions, CO2 emission intensity	Dynamic panel autoregressive distributed lag (ARDL) model	Carbon Dioxide Information Analysis Center (CDIAC), World Banks's World Development Indicators (WDI), International Energy Agency (IEA) World Energy Balances	Urbanisation negatively impacts carbon emissions in OECD countries. Decoupling between urbanisation and emissions is observed, indicating potential for sustainable urban development.
Khoshnevis Yazdi and Dariani (2019)	Explore urbanisation's impact on CO2 emissions in Asian countries	Dependent variable: CO2 emissions Independent variable: GDP/capita, energy consumption, urban population (in %), trade (export + import)/GDP) (1980–2014)	Stochastic impacts by regression population; affluence and technology (STIRPAT) model and panel data analysis	World Bank's World Development Indicators (2015)	Found a positive link between urbanisation and CO2 emissions in Asia, driven by economic growth and increased energy use. Urges policies blending urban development with environmental goals for sustainable growth.
Bereitschaft and Debbage (2014)	To explore the relationships between urban form and air pollution among 86 large US metropolitan areas.	Dependent variables: O3, NOx, VOCs, PM2.5, CO2 Independent variables: sprawl index, population density, land use mix, and urban continuity/urban shape complexity. Control variables: temperature, moisture, metropolitan population, and metropolitan land area.	Ordinary least squares (OLS)	US Census Bureau and the National Land Cover Database, US Environmental Protection Agency's Air Quality System (AQS).	Metropolitan areas with higher levels of urban sprawl generally exhibited higher concentrations and emissions of air pollution and CO2. Metropolitan areas with higher population density and more mixed land use patterns generally exhibited lower concentrations and emissions of air pollution and CO2.
Borck, R., & Schrauth (2021)	Analyse the impact of population density on urban air quality in Germany.	NO2, PM10, PM2.5, O3, Aggregate AQI	Panel data analysis for German districts. Instrumental variables and long difference regressions.	Administrative panel data from Germany for 2002–2015. Emission data from the German Environmental Agency for 2002–2015.	Denser cities increase NO2 and PM10 by 0.25% and 0.07%, respectively. PM2.5 results are less precise but similar to PM10. O3 concentrations decrease with denser cities, while aggregate AQI decreases with population density.

Indian context					
Misra et al. (2019)	Estimate the impact of urban growth on air quality in Indian cities using a hierarchical Bayesian approach	PM 2.5, urban land-use, brick kiln, vehicle kilometers travelled, emission intensity, seasonal emission activity, meteorological data	Hierarchical Bayesian framework, land-use regression model incorporating remote sensing and meteorological data	Moderate resolution imaging spectroradiometer (MODIS), Google Earth imagery, Ministry of Road Transport and Highways, World Resource Institute	Successful prediction of rising PM2.5 levels due to urban growth, identification of primary contributors to PM2.5 emissions, seasonal emission activity effects, and importance of considering socioeconomic factors in policy formulation.
Sridhar (2018)	Aims to analyse the determinants of carbon emissions in India and China, with a focus on the relationship between urban land use regulations and emissions in Indian cities.	Dependent variable: CO2 emissions Independent variables: exports & imports, urban population, electric power consumption, industry, value added, electricity production from coal sources, GDP per capita (1971–2011)	Cross-national regression analysis	World Bank's World Development Indicators	Analysis of carbon emissions data in India and China suggests a positive correlation with electricity consumption and GDP per capita. Surprisingly, urbanisation shows no significant impact on emissions per capita or per unit area.
Ahmad et al. (2015)	Discuss carbon dioxide emissions from direct energy use of urban households in India and their determinants across 60 major Indian cities.	Household income, household size, urban density, access to urban amenities, energy consumption for cooking, water heating, lighting, air conditioning	Panel regression analysis	National Sample Survey (NSS) "Household Consumer Expenditure" (July 2009–June 2010)	The conclusion of the study is that income and household size are the most important determinants of household emissions. Urban density is negatively correlated with emissions except for cooking fuel emissions. Access to urban amenities increases overall emissions.

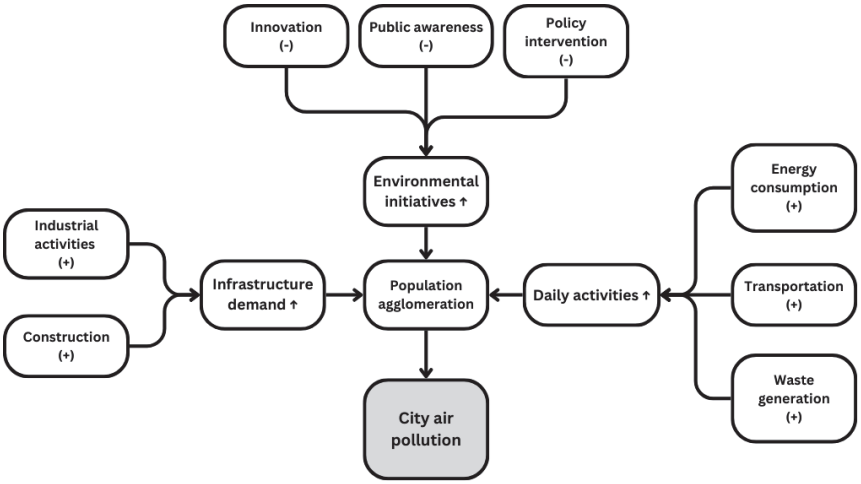
Source: Authors' compilation

3. CONCEPTUAL FRAMEWORK IN THE CONTEXT OF INDIA

Urban agglomeration has both positive and negative effects on the environment. Krugman's (1992) core-periphery model considered increasing returns to scale and transport costs and explained that centrifugal and centripetal forces form the urban system (Fujita et al., 2001). Agglomeration drivers include diversity preference, the home market effect, and increasing returns; centrifugal forces include crowding impacts, the rising cost of living, and pollution. A common belief is that environmental pollution slows down agglomeration (Wang & Wei, 2019). Agglomeration does not always result in more pollution, though, as the management of pollutant emission abatement may benefit from economies of scale. The spatial concentration of possible polluters may help with processing or limiting pollutant emissions (Kyriakopoulou & Xepapadeas, 2013; Verhoef & Nijkamp, 2002; Wei & Ewing, 2018; Wei, 2016; Lu & Feng, 2014).

Agglomeration, however, has the potential to degrade the environment by increasing pollutant emissions (Mao & He, 2017). Based on the *pollution haven hypothesis*, district-level abatement policies may encourage polluting companies to relocate to less developed areas (Shen at al., 2017; Copeland & Taylor, 2004; Wang & Wei, 2019).

Figure 1: Diagrammatical representation of the relationship between urbanisation and city air pollution



Source: Authors' compilation

Rapid urbanisation in India presents a complex challenge. While cities fuel economic growth, they also concentrate multiple activities within a confined space, leading to several environmental issues, with air pollution at the forefront. Figure 1 presents a conceptual framework that examines the impacts of urbanisation on air quality in urban India. According to Carozzi and Roth (2023), dense urban living limits emission dispersion among polluters due to reduced average distance between individuals. However, poor urban planning makes things worse. As the urban agglomerations expand, energy demands increase to meet the needs of the burgeoning population. This increases industrial activity and daily life emissions (Yang et al., 2021). The relentless demand for housing and transportation infrastructure leads to congested roads and longer commutes, further intensifying reliance on vehicles and their associated emissions (Yang et al., 2021).

In nearly every Indian city, transportation is the primary source of air pollutants, largely due to the escalating number of vehicles, which is outpacing existing infrastructure, such as roads and fuel stations (Gurjar et al., 2004). Gurjar et al. (2016) found that from 1951 to 2012, the number of motorised vehicles in India surged from 0.3 million to 159.5 million. They also argued that urban areas such as Delhi, Mumbai, Bengaluru, and Kolkata bear a significant burden of vehicular emissions, with road traffic being a major contributor to air pollution. Road dust notably contributes to particulate matter (PM) emissions in major cities like Delhi, Mumbai, and Kolkata (Gurjar, 2021). Moreover, inadequate municipal solid waste (MSW) management practices add to air pollution issues. Approximately 80% of MSW is disposed of in open dumping yards and landfills, leading to various greenhouse gas emissions and environmental concerns (Gurjar, 2021). In Delhi alone, burning garbage and MSW generates substantial PM10 and PM2.5 annually (Nagpure et al., 2016). India's energy usage is central to air pollution and climate change challenges, with implications for the growing urban population (International Energy Agency [IEA], 2021). The rapid industrialisation witnessed in recent decades has further deteriorated air quality, particularly in urban areas. Certain industries, categorised by the Central Pollution Control Board, contribute significantly to pollution, emitting pollutants such as SPM, SOX, NOX, and CO2 (Gurjar et al., 2016).

Construction activities also contribute to air pollution through dust and emissions from machinery (Tomar & Tyagi, 2022). Even after completion, construction waste adds to pollution and potential greenhouse gas emissions (Guttikunda & Goel, 2013). Integrating green building technologies and materials could mitigate these issues and maintain cleaner air quality (Tomar & Tyagi, 2022).

Despite the challenges, it is important to acknowledge the potential mitigating factors that can emerge from urbanisation. Densely populated urban areas can incentivise a shift from polluting industries to cleaner, more sustainable ones. Furthermore, urbanisation can foster technological innovation for emission reduction and pollution control. As cities grow, environmental awareness among residents can also rise, potentially leading to increased demand for cleaner air and prompting stricter environmental regulations (Yang et al., 2021).

The conceptual framework suggests that as the concentration of population increases within urban areas, there is an anticipated rise in the demand for infrastructure and daily activities, subsequently contributing to elevated levels of city air pollution. However, environmental efforts implemented within these densely populated regions can potentially mitigate this pollution.

4. DATA AND METHODS

4.1 Data

The study includes the following 36 Indian metropolitan cities: Agra, Ahmadabad, Allahabad, Amritsar, Aurangabad, Bangalore, Bhopal, Chennai, Coimbatore, Delhi, Dhanbad, Mumbai, Gwalior, Hyderabad, Indore, Jaipur, Jodhpur, Kanpur, Kolkata, Kota, Lucknow, Ludhiana, Madurai, Nagpur, Nashik, Patna, Pune, Raipur, Rajkot, Ranchi, Srinagar, Surat, Vadodara, Varanasi, Vijayawada, and Visakhapatnam.

Table 2 outlines the study's variables and their respective sources. The emissions data for Chennai, Pune, Jaipur, Kanpur, Nagpur, Indore, Bhopal, Patna, Ludhiana, Agra, Varanasi, Amritsar, Coimbatore, Raipur, Bangalore, and Ranchi are sourced from 2015. For Mumbai, Hyderabad, Ahmedabad, Kolkata, Allahabad (Prayagraj), Gwalior, Surat, Lucknow, Vishakhapatnam, Vadodara,

Nashik, Rajkot, Srinagar, Aurangabad, Dhanbad, Vijayawada-Guntur, Jodhpur, Madurai, and Kota, the data pertain to 2018. Lastly, the emissions data for Delhi-NCR are from 2020. Furthermore, the data on waste generation (tonnes per day) correspond to 2015–16.

Table 2: Variables used and their sources

Variable	Source
Air pollution indicators:	urbanemissions.info and Sahu et al. (2023) for Delhi-NCR
Particulate matter 2.5 (PM 2.5)	
Particulate matter 10 (PM 10)	
Black carbon (BC)	
Organic carbon (OC)	
Nitogen oxides (NOx)	
Carbon monoxide (CO)	
Volatile organic compounds (VOC)	
Sulphur dioxide (SO2)	
Infrastructure indicators:	2011 Census data, GOI. (https://censusindia.gov.in/census.website/)
Pucca road length (km) (road)	
Total number of latrines (latrines)	
Total number of electricity connections (electricity)	
Total number of hospitals (hospitals)	
Total number of schools (schools)	
Total number of colleges (colleges)	
Total number of working women's hostels (women hostels)	
Total number of banks (banks)	
Total number of credit societies (credit soc)	
Population agglomeration factors:	
Growth rate (growth)	
Density (density)	
Total population (pop)	
Transport indicators:	Road Transport Yearbook (2019-20) by Ministry of Road Transport and Highways (https://morth.nic.in/road-transport-year-books)
Total registered motor vehicles (vehicles)	
Waste generation:	Central Pollution Control Board (CPCB) (https://cpcb.nic.in/)
Waste generation (tonnes per day) (waste)	

SDG 13 (Climate Action) indicators:	SDG Urban Index 2021-22 by NITI Aayog (https://sdgindiaindex.niti.gov.in/urban/#/)
LED bulbs distributed under UJALA per 1,000 population (bulbs)	
SDG 7 (Affordable and Clean Energy) indicators:	
Percentage of households using clean fuel for cooking (clean fuel)	
SDG 15 (Life on Land) indicators:	
Area under green cover as a percentage of total area (green cover)	
Open space for public use as a share of total area (percentage) (open space)	

Source: Authors' compilation

4.2 Methodology

This study employed the following OLS regression model:

$$Air\ pollution = \alpha_0 + \sum_{i=1}^{7} \alpha_i X_i + \epsilon, \quad (1)$$

where air pollution is a dependent variable and is measured by a total of eight pollutants, X_i are independent variables including infrastructure, population agglomeration, transport, waste generation, climate action, energy use, and *life on land* indicators, and ϵ is a well-behaved error term.

Based on previous research, this study identifies the following as significant determinants of air pollution: urban population (Wang et al., 2021; Khoshnevis Yazdi & Dariani, 2019; Sridhar, 2018), density (Bereitschaft & Debbage, 2014; Ahmad et al., 2015), transport (Wang et al., 2021), and energy consumption (Wang et al., 2021; Sridhar, 2018; Ahmad et al., 2015).

We employ principal component analysis (PCA), a powerful statistical tool for condensing complex datasets by extracting essential information into more manageable summary indices. Reducing dimensionality helps uncover patterns and highlights the most critical parameters within a dataset. Unlike subjective weighting methods, PCA objectively assigns weights to variables based on their variability, offering a robust data analysis and interpretation approach. On the basis of PCA, we calculated pollution and infrastructure indices.

5. EMPIRICAL RESULTS

5.1 PCA analysis

We estimated the eigenvalues displayed in Table 3 using the PCA technique. Kaiser (1960) suggests retaining principal components with eigenvalues greater than 1; we analysed the eigenvalues for both the emission and infrastructure indices. In the emission index, only the first principal component (comp1) has an eigenvalue greater than 1, while in the infrastructure index, the first three principal components (comp1, comp2, and comp3) meet this criterion. Hence, we focus on these components for further analysis.

Table 4 displays the weights derived from a rotated orthogonal varimax. For the emission index, PM 2.5, PM 10, and BC stand out with the highest weight among the indicators, although the difference between the weights of all indicators is minimal. As for the infrastructure index, pucca (i.e. metalled) road length ranks first in component 1.[2] The total number of hospitals holds the highest weight in component 2, while the total number of credit societies ranks first in component 3.

Table 3: Principal components estimates for emission and infrastructure indicators

Emission					Infrastructure				
Component	Eigenvalue	Difference	Proportion	Cumulative	Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	**6.70062**	6.14995	0.8376	0.8376	Comp1	**5.34982**	4.2478	0.5944	0.5944
Comp2	0.55067	0.245241	0.0688	0.9064	Comp2	**1.10202**	0.053915	0.1224	0.7169
Comp3	0.30543	0.045742	0.0382	0.9446	Comp3	**1.0481**	0.410729	0.1165	0.8333
Comp4	0.259688	0.14226	0.0325	0.9771	Comp4	0.637376	0.303911	0.0708	0.9041
Comp5	0.117428	0.086139	0.0147	0.9917	Comp5	0.333465	0.131707	0.0371	0.9412
Comp6	0.031289	0.00429	0.0039	0.9956	Comp6	0.201758	0.024474	0.0224	0.9636
Comp7	0.026999	0.019129	0.0034	0.999	Comp7	0.177284	0.046678	0.0197	0.9833
Comp8	0.007871	.	0.001	1	Comp8	0.130606	0.11104	0.0145	0.9978
					Comp9	0.019566	.	0.0022	1

[2] Pucca roads are paved roads that are typically found in towns and cities and are made of materials like concrete or tar.

Table 4: Varimax rotated component loadings (pattern matrix)

Emission			**Infrastructure**				
Variable	Comp1	Unexplained	Variable	Comp1	Comp2	Comp3	Unexplained
PM 2.5	0.3571	0.1455	road	**0.463**	-0.1145	0.0268	0.1373
PM 10	0.3752	0.05694	latrines	0.292	**0.3397**	-0.0553	0.09336
BC	0.3764	0.05074	electricity	0.3072	**0.3124**	0.0244	0.08373
OC	0.3601	0.131	hospitals	-0.1194	**0.7389**	-0.0271	0.2371
NOx	0.3583	0.1396	schools	**0.4075**	0.0354	0.0178	0.1756
CO	0.3393	0.2287	colleges	**0.4167**	-0.139	0.1633	0.2875
VOC	0.3401	0.225	women hostels	**0.4624**	-0.1962	-0.199	0.2008
SO2	0.3181	0.3219	banks	0.1955	**0.4108**	0.063	0.2602
			credit soc	-0.0026	-0.0089	**0.9614**	0.0246

Source: Authors' calculation

Table 5 presents the ranking of cities on the basis of emission and infrastructure indices according to the PCA. The ranking indicates that Delhi stands out with the highest level of emissions among the listed cities. On the other hand, Bangalore takes the lead in infrastructure, signifying the most developed infrastructure. Other notable cities with high emission rankings include Kolkata, Chennai, and Greater Mumbai. Cities such as Surat, Ahmadabad, and Hyderabad also have relatively high emission rankings. In terms of infrastructure, Pune, Chennai, and Greater Mumbai show strong rankings. At the lower end of the emission ranking spectrum, Coimbatore, Aurangabad, and Madurai have lower emission levels. As for infrastructure, Varanasi, Delhi, and Kanpur, and are among the cities with lower-ranking infrastructure.

Table 5: Emission rank and Infrastructure rank of the cities

City	Emission rank	Infrastructure rank
Agra	34	22
Ahmadabad	7	8
Allahabad	17	20
Amritsar	28	15
Aurangabad	31	23
Bangalore	11	1
Bhopal	36	12
Chennai	3	3
Coimbatore	30	30
Delhi	1	35
Dhanbad	5	32
Greater Mumbai	4	4
Gwalior	33	24
Hyderabad	8	10
Indore	32	13
Jaipur	21	7
Jodhpur	25	19
Kanpur	16	34
Kolkata	2	2
Kota	22	28
Lucknow	13	5
Ludhiana	24	14
Madurai	35	26
Nagpur	9	9
Nashik	20	16
Patna	19	25
Pune	18	6
Raipur	12	29
Rajkot	26	21
Ranchi	27	33
Srinagar	23	31
Surat	6	11
Vadodara	15	17
Varanasi	29	36
Vijayawada	14	27
Visakhapatnam	10	18

Source: Authors' calculation

5.2 Regression analysis

Table 6 displays the descriptive statistics and diagnosis of the multicollinearity test. The variance inflation factor (VIF) values range from 1.28 to 15.02, with cities' population having the highest VIF. While the mean VIF remains within acceptable limits (<10), some variables exhibit higher multicollinearity with higher VIFs. Therefore, we use parsimonious regression models to avoid the multicollinearity problem.

Table 6: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max	VIF
emission index	36	0.0	2.6	-2.3	11.6	
infra index	35	0.0	2.2	-2.1	10.3	7.55
growth	33	26.2	21.8	-11.7	97.0	4.23
density	36	11,298.7	7,081.7	1,901.0	3,5420.0	2.08
pop	36	2,301,756.0	2,076,912.0	108,534.0	9,356,962.0	15.02
bulbs	36	841.1	611.1	38.9	2,559.0	1.69
clean fuel	36	88.0	12.8	27.6	98.8	1.75
vehicles	34	2,540.4	2,450.8	337.0	1,1893.0	7.51
green cover	30	21.6	21.8	0.1	92.5	1.37
open space	34	10.9	13.9	0.1	43.9	1.28
waste	33	1,737.3	2,446.1	150.0	11,000.0	13.47
Mean VIF						5.60

Source: Authors' calculation

Table 7 displays the correlation coefficient matrix. Strong positive correlations exist between population size and infrastructure (0.78), as well as between waste generation and emissions (0.76). Moderate positive correlations are observed between infrastructure and population growth (0.58), population and population growth rate (0.38), and clean fuel usage and total number of vehicles (0.38). Conversely, a moderate negative correlation is found between emission index and open space (-0.38).

Table 7: Correlation coefficient

	growth	infra index	emission index	density	pop	bulbs	clean fuel	vehicles	green cover	open space	waste
growth	1.00										
infra index	0.58	1.00									
emission index	-0.22	0.00	1.00								
density	-0.08	0.35	0.03	1.00							
pop	0.38	0.78	0.15	0.49	1.00						
bulbs	0.17	-0.16	-0.31	-0.27	-0.36	1.00					
clean fuel	0.04	0.35	0.34	0.12	0.48	-0.51	1.00				
vehicles	0.04	0.51	0.78	0.18	0.41	-0.26	0.38	1.00			
green cover	-0.07	-0.22	-0.19	-0.21	-0.09	0.15	-0.12	-0.35	1.00		
open space	-0.12	-0.11	-0.38	0.09	-0.20	0.16	-0.21	-0.32	-0.01	1.00	
waste	-0.29	0.27	0.76	0.28	0.58	-0.49	0.46	0.70	-0.06	-0.29	1.00

Source: Authors' calculation

Table 8 presents the results of size models of the pollution index employing the OLS method. Regression models 1–4 present the findings for a parsimonious model that addresses the issue of multicollinearity. Due to the lack of data, the regression models show the best-fit models in terms of predicted signs, significance level of variables, and goodness of fit of regressions based on the different number of variable observations available. All the regression models report OLS results with robust standard errors in parentheses to correct heteroscedasticity.

The results reveal that infrastructure, waste generation, and registered motor vehicles exhibit a statistically significant positive impact on air pollution at the 5% significance level. Moreover, the cities' population demonstrates a positive correlation with air pollution, reaching statistical significance at the 1% level. Conversely, variables related to the SDG Urban Index, such as households using clean fuel for cooking (significant at 1%), LED bulbs per 1,000 population distributed under Unnat Jyoti by Affordable LEDs for All (UJALA) (significant at 5%), and open space for public use as a share of total area (significant at 5%), display statistically significant negative relationships with air pollution. In particular, the area under green cover as a percentage of total area shows a negative relationship with air pollution, but does not achieve statistical significance.

Additionally, it is observed that population growth and density variables do not significantly impact air pollution across the models. While the link is weak, density shows a negative relationship with air pollution, which indicates that higher density decreases air pollution due to low mobility. These findings contribute to a comprehensive understanding of the factors influencing air pollution, highlighting the crucial role of infrastructure, adoption of clean energy, population density, and management of vehicular emissions.

Table 8: OLS regression results

			Dependent variable: air pollution (emission index)	
Independent variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
Infrastructure				
infra index	0.334**			
	(0.134)			
Population agglomeration				
pop				6.38e-07***
				(2.29e-07)
density				-0.000108
				(0.000159)
growth	-0.0394			-0.0497
	(0.0348)			(0.0459)
Transport				
vehicles		0.000843**		
		(0.000311)		
Waste generation				
waste			0.000702**	
			(0.000334)	
SDG 13: Climate action				
bulbs		-0.00108**		
		(0.000465)		
SDG 7: Affordable and clean energy				
clean fuel		-0.0630***		
		(0.0218)		
SDG 15: Life on land				
open space			-0.0382**	
			(0.0164)	
green cover		0.0129	-0.0121	
		(0.0171)	(0.0122)	
Constant	1.007	4.097**	-0.428	0.874
	(1.223)	(1.825)	(0.749)	(2.723)
Observations	32	28	27	33
R-squared	0.096	0.643	0.562	0.193

Note: robust standard errors in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

6. DISCUSSION

The empirical analysis underscores key factors exacerbating urban air pollution in Indian cities, including infrastructure, waste generation, transportation, and population agglomerations. While the government of India has initiated several measures to combat air pollution, such as revising standards, promoting renewable energy, and implementing the National Clean Air Programme (NCAP), further policy interventions are imperative to address the root causes effectively.

The policy implications of green infrastructure are profound and multifaceted, as highlighted by the strategic positioning of vegetation within urban areas. By leveraging green infrastructure, cities can effectively mitigate downwind pollution exposure, safeguarding public health. Additionally, urban trees offer indirect yet significant benefits for air quality improvement (Kumar et al., 2019). Moreover, incentivising the integration of green infrastructure into urban planning and development projects is paramount (Kumar et al., 2019). By offering incentives such as tax breaks, grants, or expedited permitting processes, policymakers can encourage developers and stakeholders to prioritise the incorporation of green roofs, walls, and vegetated swales. Trees play a crucial role in reducing air conditioning needs during hot weather, thereby mitigating energy demand, particularly in regions heavily reliant on coal for energy production (Akbari et al., 1997). Their shading properties and cooling effects collectively alleviate the strain on energy resources, consequently curbing emissions associated with energy production. Thus, integrating green infrastructure into urban planning and development enhances air quality and contributes to broader sustainability objectives, promoting healthier and more resilient urban environments.

The digitalisation of waste management in India has the potential to significantly improve the efficiency and effectiveness of waste collection and recycling (Manuja & Sodhi, 2024). By implementing digital tools such as the Sansadhan Portal, cities can track waste trends, monitor material recovery facilities (MRFs), and make data-driven decisions to improve waste management practices. This can lead to increased recycling rates, reduced waste disposal, and a more sustainable waste management system. Additionally, digitalisation can promote transparency and accountability within the waste management sector, ensuring

all stakeholders are involved and benefiting from improved waste management practices.

According to the Institute for Transportation and Development Policy (ITDP, 2020), low-emission zones (LEZs) create zones where only cleaner vehicles can enter, either by charging fees for high-polluting cars or entirely banning them. This incentivises people to switch to cleaner vehicles, for instance electric cars, which reduces overall traffic and harmful emissions, such as particulate matter and nitrogen oxide. Congestion pricing tackles the problem from a different angle. Charging drivers a fee to enter busy zones during peak hours discourages unnecessary trips, frees up road space, and encourages people to consider public transport, cycling, or walking. Electrifying public transportation, especially buses, also offers a significant opportunity to cut emissions. Since buses make frequent trips compared to private vehicles, replacing them with electric alternatives drastically reduces tailpipe emissions and improves air quality. Finally, people-centred solutions such as Barcelona's superblocks demonstrate that car restrictions do not have to be explicit bans. These superblocks are designated areas where car traffic is discouraged through one-way streets and lower speed limits, prioritising pedestrians and cyclists. This creates a car-unfriendly environment that encourages residents to explore alternative ways of getting around within the zone, leading to a shift towards cleaner transportation options.

However, it is essential to acknowledge the limitations of existing studies, particularly in terms of data availability and temporal analysis, underscoring the need for continued research and monitoring to inform evidence-based policymaking for long-term air quality improvement and urban sustainability.

7. CONCLUSIONS

In conclusion, this study offers a comprehensive analysis of the sources of urban air pollution in Indian metropolitan cities, shedding light on the intricate relationship between various socioeconomic, environmental, and infrastructural factors. Using principal component analysis and regression modelling, we have identified key drivers of air pollution and evaluated the effectiveness of policy interventions to mitigate its adverse effects.

Our findings underscore the pressing need for concerted efforts to address the root causes of air pollution, particularly in rapidly urbanising regions of India. The empirical evidence presented in this paper emphasises the importance of infrastructure development, waste management, transportation policies, and the adoption of clean energy technologies in combating urban air pollution. Furthermore, incorporating indicators for the Sustainable Development Goals (SDGs) into policy frameworks highlights the interconnected nature of environmental sustainability, public health, and socioeconomic development.

Policy implications from this study offer actionable insights for policymakers, urban planners, and stakeholders to design and implement targeted interventions to improve air quality and promote sustainable urban development. By prioritising investments in green infrastructure, digitalising waste management systems, implementing innovative transportation solutions, and fostering community engagement, Indian cities can transition towards cleaner, healthier, and more liveable urban environments.

In essence, this paper contributes to the growing body of research on urban air pollution in India, offering evidence-based policy formulation and implementation recommendations. By embracing a holistic approach to urban planning and governance, India can mitigate air pollution, enhance public health, and foster sustainable development, ultimately creating vibrant, resilient, and environmentally sustainable cities for present and future generations.

8. LIMITATIONS OF THE STUDY

The main limitation of the study is the sample size. The data availability at the city level is minimal. We could only access data for 36 metropolitan cities in India. Therefore, the sample size used to apply multiple linear regression models is very small. Furthermore, the limiting factor is the emission data for some cities. For example, emission data for some cities is from 2015, some cities from 2018, and one from 2020. Therefore, the recommendation is that conclusions should be taken with a measure of caution. Once data are available, estimations of panel data regression models will be necessary for robust conclusions.

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Received: October, 21, 2024
Accepted: February, 11, 2025