

Research Paper



The impacts of air pollution on human health and well-being: a comprehensive review

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ABSTRACT

Air pollution is a pressing global environmental challenge with far-reaching consequences for human health and well-being. This review examines air pollution, its diverse sources, and its detrimental effects on individual and community health. It explores the main types of pollutants found in the atmosphere, their origins, and the mechanisms through which they affect human health, as well as the links between air pollution and climate change. It also considers the global burden of air pollution, highlighting the scale of its impact and the urgent need for effective mitigation strategies to safeguard public health and preserve the environment, and reviews the existing literature, with particular reference to Indian cities. The review identifies some of the key factors that moderate the relationship between air pollution and health, such as socio-demographic variables, perception of health risks, and coping strategies. The findings have important implications for policymakers, urban planners, and public health officials, who must consider the impact of air pollution on health when formulating policies and interventions to address this critical issue.

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1. INTRODUCTION

Air pollution is a pressing contemporary challenge, notable not only for its role in climate change but also for its serious repercussions on public and personal well-being, leading to higher rates of illness and mortality. Numerous harmful substances contribute to human illness. Particulate matter (PM), consisting of minute particles of different sizes, enters the respiratory system through inhalation, resulting in respiratory and cardiovascular disorders, disruption of the reproductive and central nervous systems, and potentially cancer. While ozone in the upper atmosphere shields the Earth against ultraviolet radiation, at ground level it is harmful in excessive amounts, damaging the respiratory and cardiovascular systems. Nitrogen oxides, sulphur dioxide, volatile organic compounds (VOCs), dioxins, and polycyclic aromatic hydrocarbons (PAHs) are also pollutants that endanger human health. Carbon monoxide can cause acute poisoning when inhaled at high concentrations, and heavy metals such as lead, once absorbed into the body, can cause either immediate poisoning or chronic intoxication, depending on the level of exposure. Addressing this issue requires public awareness and a multidisciplinary approach involving scientific experts, and national and international bodies must act on this threat and put forward sustainable solutions [1].

1.1 Types and Sources of Air Pollution

Air pollutants originate from anthropogenic activities such as industrial emissions, transportation, and agriculture, as well as from natural sources such as wildfires, windblown dust, and volcanic eruptions. The major sources of air pollution in Indian cities are summarized in Figure 1. The main pollutants are described below [2].

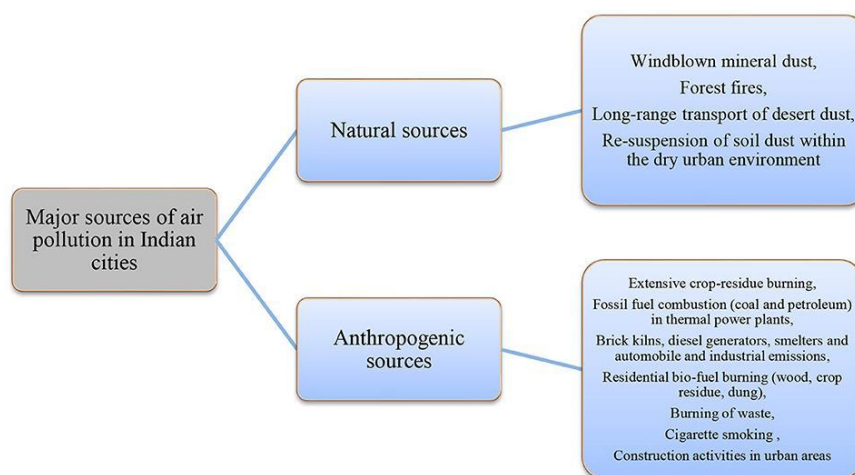


Figure 1. Major Sources of Air Pollution in Indian Cities

- **Ozone:** Surface ozone is formed by the photochemical action of solar radiation on NO_x and volatile organic compounds (VOCs). The major anthropogenic sources of these two precursors in Delhi are the transportation sector, industries, and power generation [3]. Automobile exhaust emissions contain toluene, xylenes, and ethylbenzene [4], and VOCs play a significant role in the formation of fine secondary aerosol with adverse health effects [5].
- **PM_{2.5} and PM₁₀:** Fine particulate matter (PM_{2.5}), with particles smaller than 2.5 μm, is considered the most noxious pollutant because it can be inhaled deep into the lungs and damage respiratory tissues. In urban and indoor air, cigarette smoke and asbestos fibres are among the most dangerous particles because of their carcinogenic effects [6]. Air pollutants such as PM_{2.5} are associated with depressive symptoms [7] and with decreased emotional well-being [8]. Each 5 μg/m³ increase in PM_{2.5} has been associated with an 18% increase in the risk of low birth weight at term [9]. The WHO guideline for annual mean PM_{2.5} is 5 μg/m³ [10], yet in 2022 New Delhi recorded an annual mean of

about $84 \mu\text{g}/\text{m}^3$, more than 16 times the guideline [11]. According to an emissions inventory for Delhi, the major sources of PM_{10} are the residential sector (34.5%), transport (29%), industry (26%), and the power sector (10.5%), while for $\text{PM}_{2.5}$ the contributors are transport (45%), the residential sector (27%), industry (24%), and power (4%) [12]. Transport is thus the largest contributor to $\text{PM}_{2.5}$ and the residential sector to PM_{10} ; $\text{PM}_{2.5}$ and PM_{10} are the main pollutants in Delhi.

- **NO_2 and SO_2 :** Sulphur dioxide (SO_2) causes respiratory problems and contributes to acid rain, while nitrogen dioxide (NO_2) contributes to smog and acid rain. These gases have a lasting impact on the respiratory system, with children the most susceptible group [13]. The primary source of these pollutants is vehicular emissions. According to the Central Pollution Control Board (CPCB), the concentration of SO_2 in Delhi is below $10 \mu\text{g}/\text{m}^3$, within the acceptable limit [14]. Traffic pollution poses a significant threat to both biodiversity and human health, and NO_2 from traffic has been associated with adverse mental health outcomes [7].
- **Carbon monoxide:** Even a minute concentration of 0.001% carbon monoxide in air over an extended period can be fatal [15], because CO binds strongly to haemoglobin and accumulates even with low-level exposure, reducing the oxygen-carrying capacity of the blood. CO emissions from vehicles in congested traffic can cause headaches, impaired vision, and drowsiness.
- **Ammonia:** Ammonium chloride has been shown to enhance aerosol liquid water, contributing to haze episodes in Delhi [16].
- **Lead:** Lead originates mainly from diesel and petrol emissions, paints, metal mining and smelting, waste incineration, battery recycling, and wood and coal burning.
- **Carbon dioxide:** Carbon dioxide is the most important anthropogenic greenhouse gas, even though it is a naturally occurring component of the atmosphere essential to respiration and plant growth [17].

In November 2016, New Delhi experienced an intense air pollution episode with an Air Quality Index (AQI) exceeding 500, affecting the entire National Capital Region (NCR) because of stagnant air and biomass-burning aerosols transported from the plains of Punjab and Haryana. The $\text{PM}_{2.5}$ concentration rose from $142 \mu\text{g}/\text{m}^3$ before this severe air pollution episode to $563 \mu\text{g}/\text{m}^3$ during it, and subsequently decreased to $240 \mu\text{g}/\text{m}^3$ [18].

Airborne pollutants can harm human health, wildlife, and ecosystems. Exposure to air pollution has been associated with respiratory conditions such as asthma and lung cancer, as well as heart disease, stroke, and other health problems; air pollution also reduces visibility, damages crops and other vegetation, and contributes to climate change. The depth to which particles of different sizes penetrate the human respiratory system is shown in Figure 2.

Particle size	Penetration degree in human respiratory system
$>11 \mu\text{m}$	Passage into nostrils and upper respiratory tract
$7-11 \mu\text{m}$	Passage into nasal cavity
$4.7-7 \mu\text{m}$	Passage into larynx
$3.3-4.7 \mu\text{m}$	Passage into trachea-bronchial area
$2.1-3.3 \mu\text{m}$	Secondary bronchial area passage
$1.1-2.1 \mu\text{m}$	Terminal bronchial area passage
$0.65-1.1 \mu\text{m}$	Bronchioles penetrability
$0.43-0.65 \mu\text{m}$	Alveolar penetrability

Figure 2. Particle Size and Degree of Penetration into the Human Respiratory

In less developed nations, the problem is exacerbated by high population densities, unregulated urban expansion, and industrialization, resulting in poor air quality, particularly in regions marked by

social inequalities and limited knowledge of sustainable environmental management. Reliance on low-cost fuels such as wood or other solid fuels for household needs exposes people to polluted indoor air; globally, about three billion people rely on these fuels for heating and cooking [19]. In less developed nations, women appear to be the most susceptible to disease because of their prolonged exposure to indoor air pollution. China, with rapid industrialization and a dense population, faces severe air pollution, and lung cancer mortality in China has been linked to fine particles [20]. Extended exposure is also associated with harmful effects on the cardiovascular system [21]. However, cardiovascular diseases are predominantly observed in affluent, developed nations rather than in low-income developing countries with high levels of air pollution [22].

India faces severe air pollution, with hazardous air quality in cities such as New Delhi, where flights are frequently cancelled because of reduced visibility. Both urban and rural areas are affected, driven by rapid industrialization, urban expansion, and increased use of motorized transport, while a significant source of household air pollution in India and Nepal is biomass combustion for heating and cooking. Indoor air quality varies geographically across India with climate, population, and education; North Indian states show higher household PM_{2.5} levels (557–601 µg/m³) than southern states (183–214 µg/m³), possibly because the colder climate requires more time indoors and more heating. Household air pollution in India has substantial health impacts, particularly for women and young children who spend long periods indoors: chronic obstructive respiratory disease and lung cancer are predominantly observed in women, while children under 5 years are susceptible to acute lower respiratory infection [23]. This review examines the sources of air pollution in relation to public health and puts forward potential remedies and measures relevant to environmental policymakers and decision-makers.

1.2 Impact of Air Pollution on Micro- and Macro-Climate

Climate and pollution are closely entwined, with pollution exerting a substantial influence on the Earth's climate system through diverse feedback loops and mechanisms:

- **Greenhouse Gas Emissions:** Burning fossil fuels, industrial processes, and deforestation release large amounts of carbon dioxide (CO₂), methane (CH₄), and other greenhouse gases, which trap heat and lead to global warming and altered climate patterns.
- **Airborne Particulates and Aerosols:** Aerosols affect the Earth's energy balance by reflecting sunlight back into space, cooling the planet, while particles deposited on ice and snow reduce surface reflectivity, causing more sunlight to be absorbed and accelerating melting.
- **Feedback Loops:** Warming can release methane previously trapped in frozen ground and ice; because methane is a potent greenhouse gas, its release intensifies warming, leading to further melting and methane release.
- **Ocean Pollution and Acidification:** The oceans absorb a significant portion of atmospheric CO₂, leading to ocean acidification that harms marine ecosystems and organisms that build calcium carbonate shells and skeletons, which may in turn affect the oceans' capacity to absorb CO₂.
- **Air Quality and Health Co-Benefits:** Pollutants harmful to health, such as smog and fine particulate matter, are often emitted together with greenhouse gases, so policies that reduce them can also help mitigate climate change.
- **Urban Heat Island Effect:** Polluted urban areas experience higher local temperatures, which can exacerbate heatwaves and increase energy demand.
- **Deforestation:** Burning forests releases the carbon stored in trees and reduces the planet's capacity to absorb CO₂, accelerating climate change.

Air pollution and climate change are two sides of the same coin that diminishes the quality of our planet [24]. Substances such as black carbon, methane, tropospheric ozone, and aerosols affect the amount of incoming sunlight, raising the Earth's temperature and melting ice and glaciers. Land use and land cover change also plays an important role in urban climate change in Indian cities, where built-up areas have expanded rapidly over the past three decades. Climate change has also facilitated the spread of vector-borne disease, as illustrated by chikungunya outbreaks in Italy [25] and autochthonous cases in France [26]. The relationship between climate and pollution is therefore bidirectional: pollution contributes to

climate change by releasing greenhouse gases and altering the energy balance and feedback mechanisms, while climate change influences pollution patterns through shifts in weather, precipitation, and atmospheric circulation.

2. EFFECTS OF AIR POLLUTION ON HEALTH

Air pollution comes in two main forms: outdoor (ambient) pollution and indoor pollution arising mainly from the combustion of household fuels. People exposed to high levels of air pollutants can experience health problems ranging from mild to severe, which can be divided into short-term and long-term effects. Extensive research has documented the adverse effects of climate change on human health, which are expected to worsen as climate conditions continue to change; climate change compromises health mainly by increasing the frequency and intensity of extreme weather events such as heatwaves, heavy rainfall, floods, droughts, strong winds, and landslides, and contributes to the spread of waterborne and airborne infections, vector-borne diseases, malnutrition, diarrhoeal diseases, and heat-related illness and mortality [2].

The relative strengths of the short-term and long-term effects of air pollution are still not fully understood because of differences in epidemiological approaches and errors in exposure measurement, and novel methods have been proposed to assess human exposure over short and extended periods [27]. Short-term effects are transient and include irritation of the eyes, nose, skin, and throat, wheezing, coughing, chest tightness, and breathing difficulties, which can escalate to asthma, pneumonia, bronchitis, and lung and heart complications; headaches, nausea, and dizziness may also occur. With long-term exposure, these problems can worsen: prolonged contact with pollutants can damage the neurological, reproductive, and respiratory systems and contribute to cancer and, in some cases, death [28]. Respiratory diseases are strongly linked to inhaled pollutants, which enter the airways and accumulate in cells; the harm depends on the pollutant, its source, and its dose, as well as on the country, locality, season, and duration of exposure. Particulate matter, dust, benzene, and ozone can cause significant harm to the respiratory system, and there is a heightened risk of asthma, the most prevalent concern in this regard [29].

2.1 Heat, Extreme Events, and Health in India

Extreme weather conditions have negative implications for public health, and the health effects of rising temperatures are of particular concern. Heatwaves and recurring extreme weather events are evidence of the impact of climate change in eastern India; the heatwaves of 1998 and 2015 each killed more than 2,000 people in India, about 1,625 people died in heatwaves between 1978 and 1999, mainly in Rajasthan, followed by Bihar, Uttar Pradesh, and Odisha, and the toll rose to 3,442 heat-related deaths during 1999–2003 [2]. More than 600 people died in heatwaves in India in 2013, about 1,400 deaths were attributed to high ambient temperatures (reaching 50 °C) in Andhra Pradesh in 2002, a temperature of 46.8 °C in Ahmedabad caused many deaths in 2010, and heatwaves significantly affected Rajasthan and Uttarakhand in 2009 [2]. Given the increasing frequency of hot days and nights between 1951 and 2016, a fourfold increase has been projected by 2050 and a twelvefold increase by 2100, which would amplify heat-related mortality [2].

Climate change also triggers droughts, floods, and cyclones with adverse implications for health. Floods cause drowning, hypothermia, and trauma; severe droughts leading to food scarcity have caused deaths from starvation in India; and heavy rainfall and floods that destroy crops lead to food shortages, malnutrition, and public health problems. Malnutrition is a pressing issue in India, affecting about 47% of children, and anaemia affects around 70% of children, 55% of women, and 25% of men [2].

2.2 Relation between Air Pollution, Health, and Environment

Studying the interplay between urban climate, air pollution, and human well-being is a crucial undertaking, as developing nations such as India face significant challenges from both air pollution and climate change, and their combined health effects have received limited attention [2]. Climate governs how air pollutants disperse in space and time: changes in climate can influence pollutant levels and the

formation of secondary pollutants, and climatic factors together with atmospheric conditions, terrain, and urban form determine how pollutants spread, accumulate, and transform, leading to respiratory conditions such as asthma, emphysema, allergies, and chronic bronchitis [2]. According to WHO estimates, warming and precipitation trends driven by human-induced climate change over the past three decades have claimed about 150,000 lives annually [2]. Moreover, atmospheric aerosols can amplify climate change through direct and indirect effects: they deteriorate air quality and also warm the lower and middle troposphere, altering land-sea temperature contrasts, monsoon patterns, rainfall distribution, solar radiation, and cloud properties, thereby changing the frequency of heatwaves, the intensity of storms, and precipitation patterns [2].

3. GLOBAL BURDEN OF AIR POLLUTION AND POLICY RESPONSES

Air pollution causes premature deaths, loss of healthy life years, and substantial health-care costs worldwide, with some regions experiencing much higher pollution and worse effects. In 2018, WHO Director-General Dr Tedros Adhanom Ghebreyesus described air pollution as a silent public health emergency comparable to tobacco [30]. Despite the challenge of tackling human-caused pollution, a solution may arise through collaboration among authorities, organizations, and medical professionals; governments should disseminate information, educate the public, and engage experts. Source-based technologies to reduce air pollution should be widely adopted in industries and power plants. The Kyoto Protocol of 1997, which aimed for a reduction of more than 5% in greenhouse gas emissions by 2012 [31], was a significant milestone, followed by the 2009 Copenhagen summit [32] and the 2011 Durban summit. A more recent and pivotal international accord is the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), which received widespread ratification and calls on parties to strengthen education, training, public awareness, and engagement to achieve its climate objectives [33]. A comprehensive global preventive policy against anthropogenic air pollution is therefore needed, together with sustainable development practices informed by research, international cooperation in research, development, administration, monitoring, and policy, and harmonized and updated air pollution legislation.

4. CONCLUSION

This review underscores the elevated levels of air pollution in many major Indian cities, which exceed acceptable thresholds. Persistent emissions from human activities and natural sources lead to high concentrations of particulate matter with detrimental effects on human health, highlighting the need for continuous monitoring of air pollutants across the Indian subcontinent using both ground-based measurements and satellite remote sensing. Information on air quality in Indian megacities can guide mitigation strategies by identifying vulnerable areas within each city and supports air quality modelling and prediction, preparedness, and adaptation. The considerable disease burden and mortality associated with air pollution in Indian cities call for comprehensive nationwide measures to control pollutant levels, and the reductions in pollution observed during the COVID-19 lockdown suggest that short-term restrictions can improve air quality and public health. As a developing nation, India also faces adverse health effects of climate change, with its cities increasingly exposed to extreme events such as heavy rainfall, floods, droughts, and heatwaves; strengthening health surveillance for heatwaves, floods, and vector-borne diseases, and adopting mitigation and adaptation strategies, are therefore essential. Advanced technologies such as satellite data integrated with geospatial techniques can monitor and map the spatio-temporal distribution of air pollution and climate change and their health implications, and prudent urban planning and sustainable practices are imperative to build resilient cities that minimize adverse health consequences.

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Authors Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Hiba Gul	✓	✓	✓		✓	✓		✓	✓		✓		✓	
Bijay Kumar Das	✓	✓		✓	✓		✓	✓		✓		✓		✓

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

Conflict of Interest Statement

No conflict of interest.

Informed Consent

Not Applicable.

Ethical Approval

Not Applicable.

Data Availability

This study draws on publicly available data. No new datasets were created.

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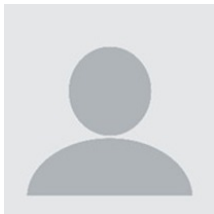
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