Air Pollution and Health in India: A One Health Framework for Integrated Solutions

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Abstract

Air pollution represents one of the most pressing global health challenges of the 21st century, demanding an integrated One Health approach that recognizes the intricate interconnections between human health, animal welfare, and environmental integrity. This comprehensive review synthesizes recent evidence published between 2023 and 2025, examining air pollution through a One Health framework, with a particular focus on the Indian context, especially Delhi and other major metropolitan regions. The paper explores anthropogenic and natural sources of air pollution, characterizes major pollutants including particulate matter ($PM_{2.5}$, PM_{10}), gaseous pollutants (SO_2, NO_2, CO, O_3), volatile organic compounds, heavy metals, and emerging contaminants like airborne microplastics. Health consequences span respiratory disorders (asthma, COPD, bronchitis, lung cancer), cardiovascular diseases, neurological impairments, and immunological disruptions, with India experiencing over 1.6 million premature deaths annually. The review elucidates pathophysiological mechanisms including oxidative stress, systemic inflammation, and cellular senescence, while examining ecosystem impacts on crops, wildlife, and biodiversity. Delhi's air pollution crisis of 2024 exemplifies the urgent need for interdisciplinary collaboration. The One Health framework emerges as essential for developing holistic, sustainable solutions that address air pollution as a shared threat across all life domains. Future directions emphasize integrated surveillance systems, interdisciplinary research, and policy frameworks that unite environmental management with public health planning.

Keywords: *Air pollution, One health approach, Particulate matter, Respiratory health, Delhi air quality, Ecosystem impacts, COPD, Oxidative stress, National clean air programme, Environmental health.*

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Publisher: Anu Books
Book Name : Chemical Sciences at the Nexus of Sustainability: Bridging Disciplines

1. Introduction

1.1 The One Health Paradigm

The One Health approach represents a paradigm shift in understanding and addressing complex health challenges by recognizing the fundamental interconnectedness of human health, animal health, and environmental integrity [1]. This holistic framework acknowledges that the health of people is inextricably linked to the health of animals and the environment, requiring collaborative, multisectoral, and transdisciplinary approaches to achieve optimal health outcomes for all [2] .The One Health concept has gained particular prominence in addressing environmental health threats, where the boundaries between human, animal, and ecosystem health become increasingly blurred [3]. Air pollution exemplifies a quintessential One Health problem, as it simultaneously affects human populations, wildlife, domestic animals, and entire ecosystems through complex pathways and feedback mechanisms [4].The intricate links between air quality and the health of humans, biodiversity, and environmental systems demand integrated solutions that transcend traditional disciplinary boundaries [5].

1.2 Global and Indian Air Pollution Scenario

Air pollution has emerged as the seventh highest risk factor for human health globally, responsible for millions of premature deaths annually. The World Health Organization estimates that ambient air pollution alone causes approximately 4.2 million premature deaths worldwide, with 89% occurring in low- and middle-income countries [6]. This staggering mortality burden positions air pollution among the top ten risk factors for disability-adjusted life-years (DALYs) globally, with particularly severe impacts on respiratory and cardiovascular health.

India faces an especially acute air pollution crisis, with over 1.6 million premature deaths attributed to air pollution annually [7]. This mortality burden represents approximately 17% of total deaths in the country, reflecting the severity of India's air quality challenges [8] . The economic consequences are equally devastating, with air pollution-related costs; including reduced labor productivity, healthcare expenditures, and lost economic output- estimated at nearly 8.5% of India's GDP· Major metropolitan areas, particularly Delhi, consistently rank among the world's most polluted cities, with concentrations of particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxides, sulfur dioxide, ozone, and volatile organic compounds frequently exceeding hazardous levels [7]·

The air pollution crisis in India is driven by multiple anthropogenic sources, including residential and industrial activities, vehicular emissions, agricultural burning, and rapid urbanization[9]. Recent data from 2024-2025 reveal troubling increases in pollutant concentrations across major Indian cities, with post-lockdown measurements showing $PM_{2.5}$ increases of 20%, PM_{10} increases of 24%, SO_2 increases of 12%, and O_3 increases of 19% [8]. These trends underscore the urgent need for comprehensive, evidence-based interventions.

1.3 Air Pollution as a One Health Challenge

Air pollution transcends traditional environmental health boundaries, creating cascading effects across human, animal, and ecosystem health domains. The One Health implications of air pollution manifest through multiple interconnected pathways. First, air pollutants directly impact human respiratory and cardiovascular systems while simultaneously affecting wildlife populations and vegetation health. Second, air pollution contributes to climate change, which in turn alters the prevalence and distribution of vector-borne, water-borne, and food-borne diseases affecting both human and animal populations. Third, human activities that generate air pollution- such as mining, deforestation, and industrial expansion-cause habitat loss and fragmentation, bringing wildlife into closer contact with humans and livestock, thereby increasing disease transmission risks [9].

1.4 Objectives and Scope

This comprehensive review aims to synthesize recent evidence (2023-2025) on air pollution and health through a One Health lens, with particular emphasis on the Indian context. Specific objectives include:

1. Characterizing the sources, causes, and composition of air pollution, with special focus on Delhi and major Indian metropolitan areas.
2. Examining the health consequences of air pollution exposure across respiratory, cardiovascular, neurological, and immunological systems.
3. Elucidating the pathophysiological mechanisms and clinical manifestations of air pollution-induced diseases.
4. Analyzing environmental and ecosystem impacts, including effects on crops, wildlife, and biodiversity.
5. Demonstrating the application and value of the One Health approach in understanding and addressing air pollution.
6. Evaluating evidence-based prevention, mitigation, and control strategies, including India's National Clean Air Programme.
7. Identifying research gaps and future directions for integrated air quality management and public health planning.

2. Sources and Causes of Air Pollution

2.1 Anthropogenic Sources

Anthropogenic activities constitute the predominant sources of air pollution in urban and industrial regions, particularly in rapidly developing countries like India. These human-generated sources can be categorized into several major domains:

Industrial Emissions: Industrial facilities, including power plants, manufacturing units, chemical plants, and refineries, release substantial quantities of particulate matter, sulfur dioxide, nitrogen oxides, carbon monoxide, and various toxic compounds into the atmosphere[7]. In India, industrial emissions contribute significantly to the overall pollution burden, particularly in industrial corridors and manufacturing hubs.

Vehicular Pollution: The exponential growth in vehicle ownership, particularly in urban areas, has made transportation one of the leading contributors to air pollution. Vehicular emissions release nitrogen oxides, carbon monoxide, particulate matter, volatile organic compounds, and other pollutants. Traffic-related air pollution (TRAP) has been specifically linked to acute respiratory symptoms, reduced lung function, and biomarkers of airway injury in controlled exposure studies [10]. The implementation of Bharat Stage VI vehicular emission norms represents India's effort to address this source, though enforcement and fleet modernization remain ongoing challenges.

Fossil Fuel Combustion: The burning of coal, petroleum, and natural gas for energy generation, heating, and industrial processes releases massive quantities of pollutants, including particulate matter, sulfur dioxide, nitrogen oxides, and carbon dioxide.

Biomass Burning and Agricultural Activities: Agricultural residue burning, particularly prevalent in northern India during harvest seasons, contributes substantially to seasonal air pollution spikes [9]. The practice of burning crop stubble releases large quantities of particulate matter, carbon monoxide, and other pollutants. Additionally, agricultural activities including livestock operations, fertilizer application, and pesticide use contribute to air pollution through ammonia emissions and volatile organic compounds [10].

2.2 Natural Sources

Natural sources also contribute to air pollution, especially in specific regions and seasons. Dust storms, wildfires, and volcanic eruptions release large amounts of particulate matter and gases into the atmosphere. Additionally, pollen and biological aerosols from plants increase air pollution and can cause allergic reactions.

2.3 Indoor versus Outdoor Air Pollution

The distinction between indoor and outdoor air pollution is critical for comprehensive health risk assessment, particularly in developing countries where indoor air pollution from traditional cooking fuels remains prevalent.

Indoor Air Pollution: Indoor air pollution sources include combustion of solid fuels (biomass, coal, dung) for cooking and heating, tobacco smoke, building materials, household products, and inadequate ventilation [11]**.** Research reveals a 2.8-fold increase in indoor air research publications over the past decade, reflecting growing recognition of this health threat**.** Indoor air pollution causes respiratory diseases, cardiovascular conditions, cancer, and premature deaths, with children and elderly populations particularly vulnerable. In developing countries, traditional cooking sources predominate, while non-conventional sources are more significant in developed nations**[11]**. India's clean household energy initiatives aim to address this burden through promotion of liquefied petroleum gas (LPG) and other cleaner cooking fuels.

Outdoor Air Pollution: Ambient or outdoor air pollution arises from the sources described in sections 2.1 and 2.2, affecting entire populations within affected regions. The health impacts of outdoor air pollution are well-documented, with ambient $PM_{2.5}$ exposure alone causing 0.98 million deaths in India in 2020 [8].

2.4 Climate Change and Air Pollution Synergies

Air pollution and climate change exhibit complex bidirectional relationships, with each phenomenon exacerbating the other through multiple mechanisms [9]. Air pollutants, particularly carbon dioxide and black carbon, contribute to global warming and climate change.

2.5 Delhi Air Pollution: A Case Study

Delhi exemplifies the severe air pollution challenges facing rapidly developing megacities. The 2024 air pollution crisis in Delhi highlighted the multifaceted nature of the city's air quality problems [12]**.** Recent assessments of Delhi's Air Quality Index (AQI) reveal consistently hazardous pollution levels, with $PM_{2.5}$ and PM_{10} concentrations far exceeding prescribed safety standards.

Delhi's air pollution mainly comes from vehicles, industries, construction dust, waste burning, and domestic fuel use, with crop residue burning causing severe seasonal spikes. Pollution becomes worst during winter months due to temperature inversion and low wind speed, which trap pollutants near the ground.

Health and Nationwide Impact: The 2024 Delhi air pollution crisis demonstrated significant health risks, with exposure linked to cardiovascular and respiratory outcomes. The crisis had nationwide implications, affecting not only

Delhi's 20+ million residents but also neighboring regions and highlighting the need for coordinated regional air quality management strategies.

3. Major Air Pollutants

3.1 Particulate Matter ($PM_{2.5}$ and PM_{10})

Particulate matter represents the most extensively studied and health-relevant category of air pollutants. PM is classified by aerodynamic diameter: PM_{10} (particles <10 micrometers) and $PM_{2.5}$ (particles < 2.5 micrometers, also called fine particulate matter). The size distinction is critical because it determines deposition patterns in the respiratory system and subsequent health effects.

Mechanisms of Health Effects: $PM_{2.5}$ due to its small size, can penetrate deep into the alveolar regions of the lungs and even translocate into the systemic circulation [13].

Inhalation of particulate matter leads to multiple pathophysiological consequences:

1. **Lung Parenchymal Destruction:** Chronic PM exposure causes structural damage to lung tissue, contributing to emphysema and reduced lung function.
2. **Cellular Senescence:** PM-induced chronic pulmonary inflammation triggers cellular senescence, accelerating lung aging and disease progression.
3. **Oxidative Stress:** PM generates reactive oxygen species, overwhelming antioxidant defenses and causing oxidative damage to cellular components.
4. **Inflammatory Cascades:** PM activates the nuclear factor kappa B pathway, leading to significant increases in pro-inflammatory cytokines.
5. **Airway Remodeling:** Chronic PM exposure causes airway remodeling with increased pro-fibrotic cytokines and collagen deposition.

Health Outcomes: $PM_{2.5}$ exposure is strongly associated with respiratory diseases (asthma, COPD, bronchitis, lung cancer), cardiovascular diseases, and premature mortality. In the UK Biobank cohort study of 451,566 participants, ambient air pollution ($PM_{2.5}$, $PM_{2.5}$ absorbance, NOx, NO_2) correlated with reduced lung function (FEV_1, FVC, FEV_1:FVC ratio, PEF) and elevated COPD risk, with hazard ratios ranging from 1.08 to 1.15 [14]. $PM_{2.5}$ was identified as the dominant predictor of respiratory morbidity in Indian cities, explaining up to 72% of variance in Delhi and approximately 60% in other major cities [15].

Indian Context: $PM_{2.5}$ concentrations in Indian cities frequently exceed WHO guidelines by several-fold. The 2024 Delhi crisis saw $PM_{2.5}$ levels reaching hazardous categories, with similar patterns observed in other major metropolitan areas.

3.2 Gaseous Pollutants

Sulfur Dioxide (SO_2): SO_2 primarily originates from fossil fuel combustion, particularly coal burning in power plants and industrial facilities. SO_2 exposure causes respiratory irritation, exacerbates asthma, and contributes to acid rain formation. In the Indian context, post-lockdown SO_2 concentrations increased by 12%, with each 10 μg/m³ increment associated with a 7.7% increase in COVID-19 cases and 4.5% increase in deaths [8].

Nitrogen Dioxide (NO_2): NO_2 is generated primarily from vehicular emissions and industrial combustion processes. NO_2 exposure is associated with respiratory symptoms, reduced lung function, and increased susceptibility to respiratory infections. The UK Biobank study demonstrated that NO_2 and NOx exposure correlated with reduced lung function and elevated COPD risk [14]. Monitoring studies comparing satellite and ground-based measurements confirm NO, as a critical pollutant requiring accurate assessment for health hazard evaluation [15].

Carbon Monoxide (CO): CO results from incomplete combustion of carbon-containing fuels, with vehicular emissions as a major source**.** CO binds to hemoglobin with much greater affinity than oxygen, reducing oxygen delivery to tissues and causing hypoxia. Acute high-level exposure can be fatal, while chronic low-level exposure contributes to cardiovascular stress.

Ozone (O_3): Ground-level ozone forms through photochemical reactions involving nitrogen oxides and volatile organic compounds in the presence of sunlight**.** Unlike other pollutants that are directly emitted, ozone is a secondary pollutant. O_3 exposure causes breathing difficulties, coughing, throat irritation, and exacerbates asthma and COPD. Post-lockdown O_3 concentrations in Indian cities increased by 19%, with each 10 μg/m³ increment associated with a 10% increase in COVID-19 cases and 7.2% increase in deaths [16]. Ozone also causes significant agricultural damage, with ozone-induced crop yield losses documented in India**.**

3.3 Volatile Organic Compounds

Volatile organic compounds (VOCs) comprise a diverse group of carbon-containing chemicals that readily evaporate at room temperature. Sources include vehicular emissions, industrial processes, solvent use, and biogenic emissions from vegetation. VOCs contribute to ozone formation and can have direct health effects. Exposure to VOCs is associated with respiratory disorders, cardiovascular diseases, and cancer [16]**.** Some VOCs, such as benzene, are known carcinogens. Indoor sources of VOCs include building materials, household products, and combustion processes, contributing to indoor air quality problems**.**

3.4 Heavy Metals and Toxic Aerosols

Air pollution includes various heavy metals and toxic compounds that pose serious health risks. Lead, historically a major concern from leaded gasoline, remains present in some industrial emissions**.** Other heavy metals in airborne particulate matter include cadmium, arsenic, chromium, and mercury. These metals can cause neurological damage, developmental impairments, cardiovascular effects, and cancer [Figure 1].

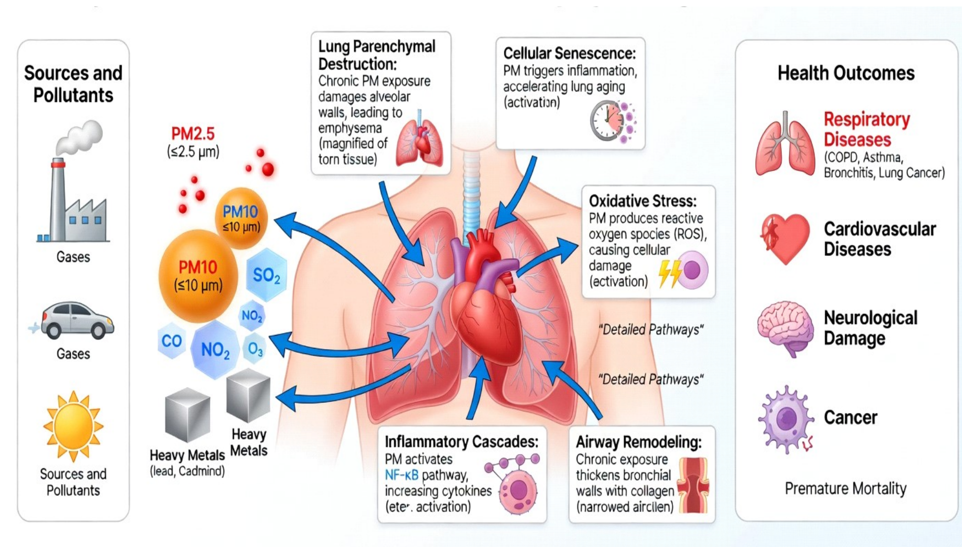

Figure 1: Major Air Pollutants and Their Pathophysiological Mechanisms

3.5 Emerging Contaminants: Airborne Microplastics

Airborne microplastics are tiny plastic particles formed from breakdown of plastics, tire wear, and synthetic materials, which can travel in air and be inhaled. They may cause respiratory irritation, carry pollutants or pathogens, and add to the complexity of air pollution impacts on health.

3.6 India's Most Polluted Cities

India hosts multiple cities with severe air pollution challenges. Based on recent data from 2024–2025, the following information provides a comparative analysis of the top five most polluted cities in India. Delhi ranks highest with $PM_{2.5}$ levels of 110–130 μg/m³, mainly from vehicular emissions, crop burning, industries, construction, and domestic fuels, causing severe respiratory diseases like asthma, COPD, and strong morbidity correlation. Ghaziabad follows with 105–120 μg/m³ due to industrial emissions, traffic, and proximity to Delhi, leading to respiratory and cardiovascular problems with increased hospital admissions. Noida records 100–115 µg/m³ from industrial zones, vehicles, and regional pollution, showing similar health impacts as Delhi with high respiratory and cardiac issues. Faridabad has 95–110 µg/m³ mainly from industries, vehicles, and construction, causing respiratory disorders especially in children, elderly, and industrial workers. Lucknow shows 90–105 µg/m³ from vehicles, biomass burning, and construction, leading to respiratory problems and seasonal pollution spikes. Overall, these cities demonstrate that high $PM_{2.5}$ levels are strongly linked to serious respiratory and cardiovascular health burdens.

4. Health Consequences: Human Health Perspective

4.1 Respiratory Disorders

Respiratory diseases represent the most direct and extensively documented health consequences of air pollution exposure. The respiratory system serves as the primary interface between inhaled pollutants and the human body, making it particularly vulnerable to air pollution-induced damage [Figure 2].

Asthma: Air pollution is a well-established trigger for asthma exacerbations and may contribute to asthma development. Systematic reviews of long-term outdoor air pollution effects in low- and middle-income countries (LMICs) confirm significant associations between air pollution exposure and asthma symptoms among adults [17]**.** Particulate matter, ozone, nitrogen dioxide, and sulfur dioxide can all trigger asthma attacks, increase medication requirements, and lead to emergency department visits and hospitalizations. In Indian cities, the correlation between $PM_{2.5}$ and respiratory morbidity including asthma is particularly strong ($r \sim 0.58–0.75$, $p < 0.01$)**.**

Chronic Obstructive Pulmonary Disease (COPD): COPD represents one of the most serious long-term consequences of air pollution exposure. The UK Biobank cohort study of 451,566 participants demonstrated that ambient air pollution ($PM_{2.5}$, $PM_{2.5}$ absorbance, NOx, NO,) correlated with reduced lung function and elevated COPD risk, with hazard ratios ranging from 1.08 to 1.15 [14]. Race-stratified analyses revealed that White populations had greater COPD susceptibility, suggesting potential genetic or environmental modifiers. COPD is a leading cause of global mortality and morbidity, with particulate matter inhalation causing lung parenchymal destruction, cellular senescence, chronic pulmonary inflammation, and oxidative stress[13]. In Indian cities, COPD represents a significant component of the respiratory morbidity burden associated with $PM_{2.5}$ exposure [15].

Bronchitis: Both acute and chronic bronchitis are associated with air pollution exposure. Particulate matter and gaseous pollutants irritate the bronchial airways, causing inflammation, mucus hypersecretion, and impaired mucociliary clearance. Children and elderly individuals are particularly susceptible to pollution-induced bronchitis.

Lung Cancer: Long-term exposure to air pollution, particularly $PM_{2.5}$ and certain toxic components like polycyclic aromatic hydrocarbons and heavy metals, increases lung cancer risk. The carcinogenic mechanisms involve oxidative DNA damage, chronic inflammation, and impaired DNA repair mechanisms.

Acute Respiratory Infections: Air pollution increases susceptibility to respiratory infections by impairing immune defenses and damaging respiratory epithelium. The Global Burden of Disease Study 2019 systematic analysis demonstrated that $PM_{2.5}$ air pollution contributes significantly to the global burden of lower respiratory infections (LRIs) [17]. In Indian cities, surveillance data show strong correlations between $PM_{2.5}$ and acute respiratory infections (ARI), influenza-like illness (ILI), and severe acute respiratory illness (SARI) [15].

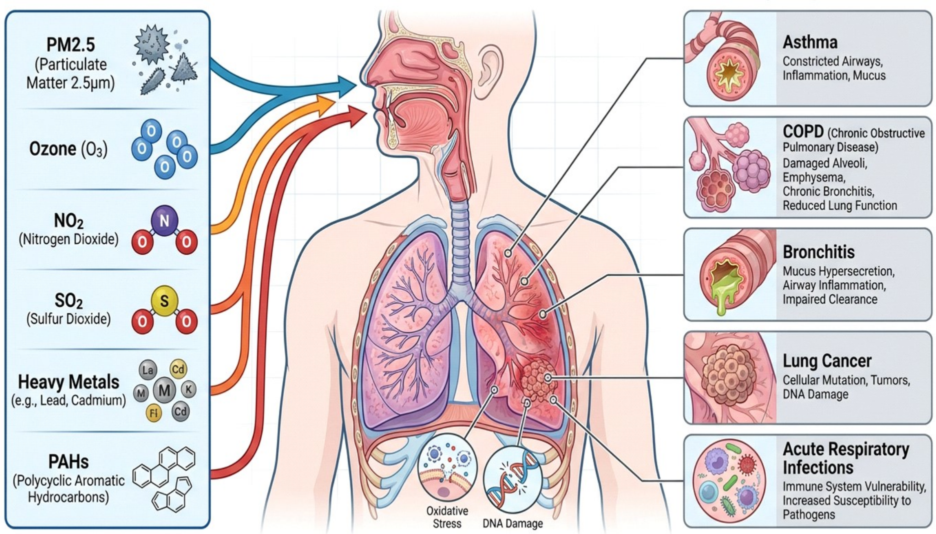

Figure 2: Impact of Air Pollution on Human Respiratory System

Indian Epidemiological Data: India experiences a substantial respiratory disease burden attributable to air pollution. Over 1.6 million premature deaths annually are linked to air pollution, with respiratory conditions representing a major component [7]. In 2020, air pollution caused 1.6 million deaths in India, with 0.98 million specifically attributed to $PM_{2.5}$ exposure, contributing 17% of total deaths [8].Ecological analysis of major Indian cities revealed that $PM_{2.5}$ explains up to 72% of respiratory morbidity variance in Delhi and approximately 60% in other metropolitan areas [15].

4.2 Cardiovascular Diseases

Air pollution's cardiovascular effects are increasingly recognized as equally important as respiratory impacts. Particulate matter and gaseous pollutants can trigger acute cardiovascular events and contribute to chronic cardiovascular disease development through multiple mechanisms.

Mechanisms: $PM_{2.5}$ is linked to enhanced atherosclerosis, increased blood coagulability, systemic inflammation, and oxidative stress. These mechanisms contribute to various cardiovascular outcomes including heart failure, ischemia, arrhythmias, and thrombosis [6, 16].

Indian Context: The 2024 Delhi air pollution crisis demonstrated significant cardiovascular risks, with exposure linked to cardiovascular outcomes. Inhaling contaminated air can lead to cardiovascular issues through direct effects on the cardiovascular system and indirect effects mediated by pulmonary inflammation. Air pollution contributes to chronic heart disorders globally, with particularly severe impacts in heavily polluted Indian cities [8, 12].

4.3 Neurological and Developmental Effects

Emerging evidence reveals that air pollution affects the nervous system and neurodevelopment, with potentially profound implications for cognitive function, mental health, and neurodegenerative diseases.

Neurological Impacts: Air pollution exposure is associated with neurodegeneration, dementia, and cognitive decline. Ultrafine particles can potentially translocate from the lungs to the brain via the bloodstream or through olfactory pathways. Mechanisms include neuroinflammation, oxidative stress, and direct neurotoxic effects of pollutants like heavy metals.

Developmental Effects: Children are particularly vulnerable to air pollution's neurodevelopmental effects. Prenatal and early childhood exposure may affect brain development, cognitive function, and behavioral outcomes. The mother-child birth cohort study in Central India investigating early life exposure to ambient fine particulate matter and its heavy metal composition recognizes these developmental vulnerabilities [18].

Mental Health: Recent research suggests associations between air pollution exposure and mental health outcomes, including depression and anxiety, though mechanisms remain under investigation.

4.4 Immunological and Endocrine Disruption

Air pollution affects immune system function and endocrine regulation through multiple pathways [Figure 3].

Immunological Effects: Air pollution causes immune dysregulation and may trigger allergic reactions. Chronic exposure can impair immune responses, increasing susceptibility to infections. Paradoxically, pollution can also promote inappropriate immune activation, contributing to allergic and autoimmune conditions. The potential contribution of air pollution to antimicrobial resistance represents an emerging One Health concern linking environmental contamination, immune function, and infectious disease management [4].

Endocrine Disruption: Air pollutants can interfere with endocrine function, affecting hormone production, metabolism, and signaling. Metabolic disorders have been linked to air pollution exposure. Endocrine disruption may contribute to diabetes, obesity, and reproductive health problems.

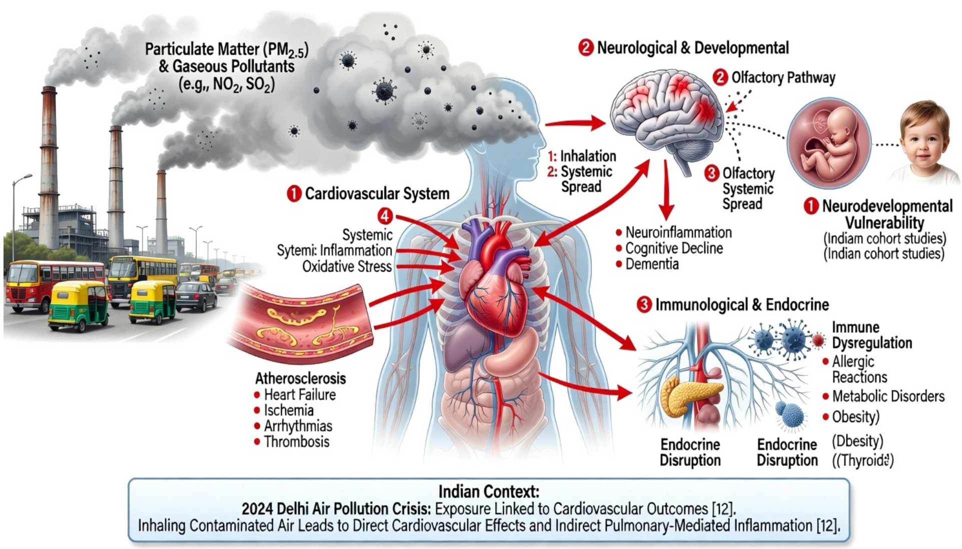

Figure 3: Systemic Health Impacts of Air Pollution: Cardiovascular, Neurological, and Immunological Pathways

4.5 Vulnerable Populations

Certain population groups face disproportionate risks from air pollution exposure due to physiological, socioeconomic, or occupational factors.

Children: Children are particularly vulnerable due to higher breathing rates relative to body size, developing respiratory and immune systems, and longer remaining lifespans for chronic disease development. Air pollution causes 600,000 deaths annually in children under 15 globally. Indoor air pollution impacts vary across age groups, with children identified as more vulnerable [11].

Elderly: Older adults face elevated risks due to pre-existing health conditions, reduced physiological reserves, and cumulative lifetime exposures. Elderly populations show greater vulnerability to indoor air pollution. In Pakistan, average lifespan is reduced by 3.9 years due to air pollution, with Lahore experiencing a seven-year reduction.

Pregnant Women: Pregnancy represents a critical window of vulnerability, with air pollution exposure potentially affecting both maternal health and fetal development. The Central India mother-child cohort study specifically addresses health burdens from early life exposure [18].

Occupational Groups: Workers in certain industries (construction, transportation, outdoor labor) face higher exposure levels. Occupational exposures in industrial workers contribute to respiratory disorders in cities like Faridabad with significant industrial clusters.

Socioeconomic Disparities: Indoor air pollution impacts vary across economic strata and genders[11]. Lower socioeconomic groups often face higher exposure due to proximity to pollution sources, reliance on polluting fuels, and limited access to healthcare.

4.6 Mortality and Morbidity Statistics for India

India bears a staggering burden of air pollution-related mortality and morbidity:

Mortality Statistics:

- Over 1.6 million premature deaths annually attributed to air pollution [7].
- Air pollution contributes to approximately 17% of total deaths in India [8].
- In 2020, air pollution caused 1.6 million deaths, with 0.98 million specifically due to $PM_{2.5}$ exposure.
- Respiratory, cardiovascular, neurological, and maternal-child health conditions contribute to this mortality burden.

Morbidity Statistics:

- Strong positive correlations between $PM_{2.5}$ and respiratory morbidity counts ($r \sim 0.58–0.75$, $p < 0.01$) across five major Indian cities.
- $PM_{2.5}$ explains up to 72% of respiratory morbidity variance in Delhi and approximately 60% in other cities.
- Dose-response relationship: approximately 0.03 cases per $\mu g/m^3$ increase in $PM_{2.5}$ ($p < 0.001$).
- Lag analysis shows delayed morbidity spikes 2-3 weeks post-pollution exposure [15].

- For every 10 μg/m³ increment in pollutants, COVID-19 cases increased: $PM_{2.5}$ (3%), PM_{10} (1%), SO_2 (7.7%), O_3 (10%); deaths increased: $PM_{2.5}$ (2.8%), PM_{10} (1%), SO_2 (4.5%), O_3 (7.2%) [8].

Economic Burden:

- Air pollution-related costs amount to nearly 8.5% of India's GDP.
- Costs include reduced labor productivity, healthcare expenditures, and lost economic output

These statistics underscore the urgent public health crisis posed by air pollution in India and the critical need for comprehensive interventions.

5. Pulmonological and Clinical Insights

5.1 Pathophysiology of Air Pollution-Induced Lung Injury

Air pollution-induced lung injury involves complex pathophysiological processes that begin with pollutant deposition in the respiratory tract and cascade through multiple cellular and molecular pathways. Understanding these mechanisms is essential for developing targeted preventive and therapeutic strategies.

Pollutant Deposition Patterns: The site of pollutant deposition in the respiratory system depends on particle size. Coarse particles (PM_{10}) deposit primarily in the upper airways and conducting zones, while fine particles ($PM_{2.5}$) penetrate to the alveolar regions. Ultrafine particles can translocate across the alveolar-capillary barrier into the systemic circulation.

Cellular Responses: Upon deposition, particulate matter triggers immediate cellular responses in respiratory epithelial cells, alveolar macrophages, and other immune cells.

Tissue-Level Changes: Chronic exposure leads to structural and functional alterations [13]:

- **Lung Parenchymal Destruction:** Progressive damage to alveolar walls and loss of functional lung tissue.
- **Airway Remodeling:** Structural changes in airway walls including smooth muscle hypertrophy, subepithelial fibrosis, and mucous gland hyperplasia.
- **Vascular Changes:** Alterations in pulmonary vasculature contributing to pulmonary hypertension.
- **Impaired Gas Exchange:** Reduced surface area and thickened alveolar-capillary membrane impairing oxygen and carbon dioxide exchange.

5.2 Molecular Mechanisms: Oxidative Stress and Inflammation

Oxidative stress and inflammation represent the central molecular mechanisms underlying air pollution-induced health effects [Figure 4].

Oxidative stress pathways are implicated in $PM_{2.5}$ -induced lower respiratory infections. and represent a key mechanism in pollution-induced lung injury. Studies of adults with airway diseases demonstrate significant oxidative stress responses to air pollution exposure [17, 19, 20].

Inflammatory Cascades: Air pollution triggers robust inflammatory responses [13]:

- **Nuclear Factor Kappa B (NF-$_K$B) Pathway:** PM inhalation activates the NF-$_K$B pathway, leading to significant increases in pro-inflammatory cytokines.
- **Cytokine Production:** Elevated levels of tumor necrosis factor-alpha (TNF-α), interleukins (IL-1β, IL-6, IL-8), and other inflammatory mediators
- **Chronic Inflammation:** Persistent low-grade inflammation contributes to cellular senescence and tissue damage.
- **Systemic Inflammation:** Inflammatory mediators can enter the circulation, contributing to systemic effects including cardiovascular disease.

Pro-Fibrotic Responses: Chronic inflammation and injury trigger pro-fibrotic responses [13]:

- Increased production of transforming growth factor-beta (TGFβ) and other pro-fibrotic cytokines
- Collagen deposition in airways and lung parenchyma.
- Progressive fibrosis contributing to restrictive lung disease

Cellular Senescence: Chronic pulmonary inflammation induced by PM exposure leads to cellular senescence, a state of irreversible growth arrest .Senescent cells accumulate in the lungs, secreting inflammatory mediators and contributing to tissue dysfunction and accelerated aging.

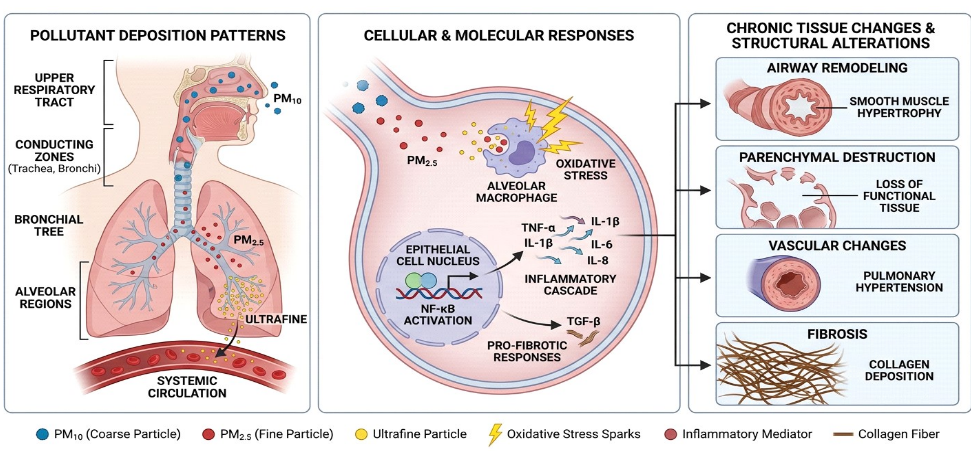

Figure 4: Pathophysiology of Air Pollution-Induced Lung Injury

5.3 Long-term Disease Burden and Mortality

The long-term health consequences of air pollution exposure manifest as chronic disease burden and premature mortality.

COPD Burden: COPD represents a leading cause of global mortality and morbidity, with air pollution as a major contributing factor. The UK Biobank cohort demonstrated hazard ratios for COPD incidence ranging from 1.08 to 1.15 for various air pollutants. Meta-analysis confirmed air pollution-COPD links across multiple populations [14].

Cumulative Effects: Long-term exposure to outdoor air pollution in LMICs shows significant associations with asthma and respiratory symptoms among adults [21]. The effects are cumulative, with longer exposure durations and higher concentrations associated with greater disease burden.

Mortality Impacts: Air pollution causes 7 million premature deaths annually globally, including 600,000 children under 15. Ambient air pollution alone causes 4.2 million premature deaths worldwide, with 89% in low- and middle-income countries. In India, over 1.6 million premature deaths annually are attributed to air pollution.

Life Expectancy Reduction: Air pollution significantly reduces life expectancy. Pakistan's average lifespan is reduced by 3.9 years due to air pollution, with Lahore experiencing a seven-year reduction. Similar impacts are likely in heavily polluted Indian cities.

Delayed Health Effects: Lag analysis in Indian cities shows delayed morbidity spikes occurring 2-3 weeks post-pollution exposure, indicating both acute and subacute health effects that contribute to long-term disease burden.

5.4 Case Presentations from Indian Clinical Settings

Clinical observations from Indian settings provide real-world evidence of air pollution's health impacts.

Northern India Acute Exposure Study: A pilot study in Northern India investigated acute effects of ambient air pollutants on pulmonary variables and inflammatory markers in healthy adults. The study focused on smog conditions containing PM_{10} and $PM_{2.5}$ examining how air quality index (AQI) impacts respiratory physiology and inflammation. The research linked PM exposure to acute pulmonary and inflammatory changes in healthy Indian adults, demonstrating that even individuals without pre-existing conditions experience measurable physiological impacts from pollution exposure [19].

Delhi 2024 Crisis Clinical Observations: The 2024 Delhi air pollution crisis resulted in increased clinical presentations for respiratory and cardiovascular complaints[12]. Healthcare facilities reported surges in patients with:

- Acute exacerbations of asthma and COPD
- Respiratory infections
- Cardiovascular events
- Eye and throat irritation

Multi-City Surveillance Data: Ecological analysis using public health surveillance data from major Indian cities (Delhi, Mumbai, Kolkata, Bengaluru, Chennai) revealed strong correlations between $PM_{2.5}$ and respiratory morbidity including ARI, ILI, SARI, asthma, and COPD. Delhi exhibited the highest pollutant load and morbidity burden, with $PM_{2.5}$ explaining 72% of respiratory morbidity variance [15].

COVID-19 and Air Pollution Interactions: Analysis of 20 major metropolitan cities across India from April 2020 to November 2021 demonstrated significant associations between short-term air pollution exposure and COVID-19 cases and deaths. Clinical observations suggested that pulmonary infection and alveolar damage were directly associated with $PM_{2.5}$ indicating a high chance of mortality from air pollutant exposure in COVID-19 patients [8].

These clinical observations from Indian settings underscore the real-world health impacts of air pollution and the urgent need for clinical preparedness, public health interventions, and pollution control measures.

6. Environmental and Ecosystem Impacts

6.1 Effects on Plants, Crops, and Forest Health

Air pollution's impacts extend beyond human health to affect vegetation, agricultural productivity, and forest ecosystems, creating cascading effects throughout the One Health continuum [Figure 5].

Crop Yield Losses: Ozone represents a particularly damaging pollutant for vegetation. In India, ozone-induced crop yield losses have been documented, affecting food security and agricultural livelihoods. Ground-level ozone damages plant tissues, reduces photosynthetic efficiency, and impairs growth and reproduction. Major crops including wheat, rice, pulses, and vegetables show yield reductions under elevated ozone exposure.

Forest Productivity: Air pollution reduces forest productivity by causing leaf damage, soil acidification, nutrient imbalance, and increased susceptibility to pests and diseases. It also alters plant physiology by damaging stomata, reducing photosynthesis through chlorophyll loss, and causing oxidative stress. These effects ultimately impair growth, nutrient uptake, and reproductive success in plants [7].

6.2 Impact on Wildlife and Biodiversity

Air pollution causes direct health effects in wildlife, including respiratory diseases, reproductive problems, developmental abnormalities, and reduced survival. It also degrades habitats by damaging vegetation, contaminating soil and water, and altering ecosystem structure. As a result, biodiversity declines, ecological relationships are disrupted, and ecosystem balance is affected.

Air pollutants deposit on soil and water through dry and wet processes like acid rain, leading to contamination. This causes soil acidification, heavy metal accumulation, reduced fertility, and impacts on soil organisms, while in water it leads to acidification, eutrophication, and harm to aquatic life. These pollutants can enter the food chain through crops and aquatic organisms, ultimately affecting human health.

6.3 Feedback Loops Between Ecosystem Degradation and Human Health

Air pollution creates feedback loops between ecosystem degradation and human health by reducing crop yields, leading to food shortages, nutritional deficiencies, and economic hardship. Degraded ecosystems provide fewer essential services like air purification, water filtration, and medicinal resources, negatively affecting human well-being. Air pollution also contributes to climate change, increasing disease spread, extreme weather events, and food and water insecurity. Additionally, habitat loss due to pollution-related activities increases human-wildlife contact, raising the risk of disease transmission and zoonotic outbreaks.

6.4 Indian Agricultural and Ecosystem Examples

In India, regions like the Indo-Gangetic Plain face severe air pollution that reduces crop yields of wheat and rice, threatening food security. Forest ecosystems in the Western Ghats and Eastern Himalayas show reduced growth, altered species composition, and increased pest vulnerability due to pollution. Urban green spaces are also affected, as high pollution levels reduce plant health and limit their role in air purification and climate regulation [6]. Additionally, crop burning and atmospheric deposition pollute both land and water, creating a cycle that harms agriculture, ecosystems, and human health.

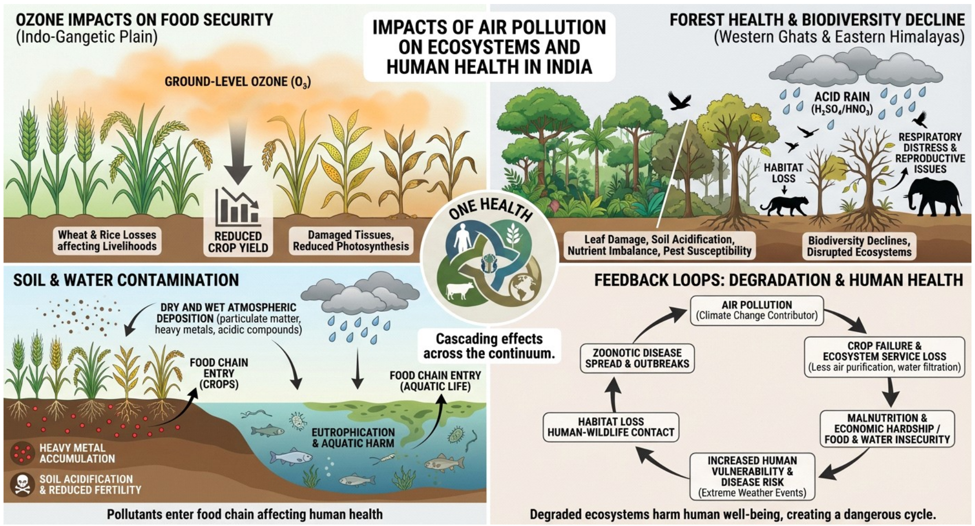

Figure 5: Impact of Air Pollution on Ecosystems and Human Health in India

7. One Health Integration

7.1 Interconnections: Air Pollution, Ecosystems, and Health

The One Health approach provides a comprehensive framework for understanding air pollution as a shared threat across human, animal, and environmental health domains. Air pollution exemplifies the intricate connections between these domains, with impacts cascading through multiple pathways.

Human-Environment Linkages: Air pollution directly affects human health through respiratory, cardiovascular, neurological, and other pathways while simultaneously degrading environmental quality. Environmental degradation, in turn, compromises ecosystem services essential for human health and well-being. This bidirectional relationship creates feedback loops that amplify both environmental and health impacts [1].

Animal Health Connections: Wildlife and domestic animals experience health effects from air pollution similar to humans, including respiratory disease, cardiovascular impacts, and reproductive impairments. Air pollution may contribute to antimicrobial resistance, affecting both human and animal health and complicating infectious disease management. The increased global movement of people, animals, and products accelerates disease spread, as demonstrated by COVID-19, with air pollution potentially exacerbating disease transmission and severity [9].

Ecosystem Health: Air pollution affects ecosystem structure and function through impacts on vegetation, soil, water, and biodiversity. Ecosystem degradation reduces the provision of services essential for human and animal health, including air and water purification, climate regulation, food production, and disease regulation. Healthy ecosystems provide resilience against environmental stressors, while degraded ecosystems amplify vulnerability.

Climate Change as a Unifying Threat: Air pollution and climate change are inextricably linked, with air pollutants contributing to global warming and climate change influencing air pollution patterns. Climate change affects human, animal, and ecosystem health through multiple pathways, including altered disease patterns, extreme weather events, food and water insecurity, and habitat loss. Addressing air pollution and climate change requires integrated One Health approaches that recognize these interconnections.

7.2 Case Studies: One Health Failures and Successes

One Health Failure: Delhi Air Pollution Crisis 2024

The 2024 Delhi air pollution crisis exemplifies a One Health failure, where fragmented approaches failed to address the interconnected nature of the problem. Multiple factors contributed to this failure:

- **Sectoral Silos:** Air quality management, public health, agriculture, transportation, and industrial regulation operated in separate silos without adequate coordination
- **Regional Coordination Gaps:** Crop burning in neighboring states (Punjab, Haryana) contributed substantially to Delhi's pollution, but lack of effective regional coordination prevented comprehensive solutions
- **Human Health Focus:** Responses focused primarily on human health impacts without adequately addressing ecosystem and agricultural dimensions
- **Short-term Measures:** Emergency measures during crisis periods (school closures, construction bans) provided temporary relief without addressing root causes
- **Limited Interdisciplinary Collaboration:** Insufficient collaboration among environmental scientists, healthcare professionals, policymakers, agricultural experts, and urban planners

The crisis resulted in severe health impacts, ecosystem damage, economic losses, and social disruption, demonstrating the consequences of failing to apply One Health principles.

One Health Success: Integrated Air Quality and Health Surveillance

Ecological analysis of air pollution and respiratory morbidity using public health surveillance data in major Indian cities represents a step toward One Health integration [15].

This approach:

- **Integrated Data Systems:** Combined air quality monitoring data with public health surveillance data
- **Multi-City Analysis:** Examined patterns across five major metropolitan centers (Delhi, Mumbai, Kolkata, Bengaluru, Chennai)
- **Evidence Generation:** Demonstrated strong correlations between PM, ... and respiratory morbidity, providing evidence for policy action
- **Lag Analysis:** Identified delayed health effects, informing clinical preparedness and public health planning
- **Interdisciplinary Collaboration:** Required collaboration among environmental scientists, epidemiologists, clinicians, and public health officials

This integrated surveillance approach provides a model for One Health implementation in air quality management.

Global One Health Success: COVID-19 and Air Pollution Research

Research examining the interplay between air pollution and COVID-19 in India demonstrates One Health principles in action [22].

- **Integrated Environmental and Health Data:** Combined air quality data with COVID-19 case and mortality data
- **Spatio-temporal Analysis:** Examined patterns across 20 metropolitan cities over time
- **Mechanistic Understanding:** Explored pathophysiological mechanisms linking pollution exposure to COVID-19 outcomes
- **Policy Relevance:** Provided evidence for region-specific mitigation strategies
- **Interdisciplinary Collaboration:** Required expertise from environmental science, epidemiology, pulmonology, and public health

This research informed public health responses and highlighted the importance of environmental factors in infectious disease outcomes.

7.3 Role of Interdisciplinary Collaboration

Effective One Health approaches to air pollution require strong interdisciplinary collaboration among fields such as environmental science, public health, clinical and veterinary medicine, ecology, agriculture, engineering, urban planning, social sciences, and economics. These disciplines work together through integrated research teams and shared data systems to address air pollution from multiple perspectives. The One Health conceptual framework includes key components such as pollution sources, environmental pathways, exposure assessment, health effects, interconnections, interventions, and monitoring systems. It explains how pollutants move through air, soil, and water, affect humans, animals, and ecosystems, and create feedback loops like climate change and disease emergence. The framework supports problem analysis, intervention design, research prioritization, policy development, stakeholder engagement, and evaluation. Overall, it emphasizes that air pollution must be managed through integrated, multi-sectoral strategies rather than isolated approaches.

8. Prevention, Mitigation, and Control Strategies

Effective air pollution control requires coordinated efforts in policy, technology, urban planning, and public health. In India, major initiatives like the National Clean Air Programme (NCAP), Bharat Stage VI standards, clean energy programs, and crop burning control aim to reduce pollution, though challenges in enforcement and coordination remain. Technological solutions such as renewable energy, electric vehicles, pollution control systems, and advanced monitoring can significantly lower emissions. Urban planning and public health measures, including sustainable transport, green infrastructure, air quality alerts, and protection of vulnerable groups, help reduce exposure and health risks. Global examples show that strong enforcement, innovation, and long-term commitment are essential, and India must adapt these strategies to its conditions with focus on equity and sustainability.

9. Future Directions and Recommendations

Significant research gaps remain in understanding air pollution, especially its molecular effects, pollutant mixtures, and long-term health impacts. Emerging pollutants like microplastics and ultrafine particles, along with risks to vulnerable populations, need focused study. A One Health approach requires research on ecosystem impacts, wildlife health, and links between environmental degradation and human diseases. Effective management depends on integrated surveillance systems, policy evaluation, and combining air quality strategies with public health planning. In India, priorities include stronger policy implementation, regional cooperation, clean technologies, public awareness, and international collaboration.

10. Conclusion

Air pollution is a major One Health challenge, affecting human, animal, and environmental health simultaneously. It causes around 7 million deaths globally each year, with India facing severe health, economic, and environmental impacts. Pollutants lead to diseases like asthma and cardiovascular disorders, while also damaging crops, ecosystems, and biodiversity. A One Health approach with strong policies, clean technologies, sustainable planning, and public health measures is essential for control. Global examples show that strict standards and enforcement can improve air quality significantly. Effective action requires political commitment, resources, collaboration, equity, and long-term integrated efforts.

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