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Air Pollution and Health in a Changing Climate: A Comprehensive Review of Exposure, Disease Burden, and Policy Response

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Abstract

Airborne contaminants and global warming are both of the leading severe and interrelated environmental issues impacting people worldwide in the 21st century. Together, these factors have a significant effect on healthy ecosystems, ecological sustainability, human well-being, and especially impact on vulnerable communities in developed as well as developing nations. Human-caused processes such as burning of fossil fuels, industrial development, urbanization, transport and agricultural methods have resulted in a substantial rise in atmospheric levels of particulate matter (PM2.5 and PM10), nitrogen dioxide (NO2), sulphur dioxide (SO2), ozone (O3), carbon monoxide (CO), volatile organic compounds (VOCs) and black carbon. Around a comparable time, climate change influences weather trends due to higher temperatures, different patterns of rainfall, enhanced atmospheric equilibrium, burning forests, and severe thunderstorms, all of which affect the production, transportation and scattering of harmful substances, and the human inhalation of these substances. This article critically examines the connections among air pollution, global warming, human contact, health effects, and government policies. It covers the main sources of atmospheric pollutants, routes of exposure, biological systems, and the effects of air pollutants on pulmonary, cardiovascular, nervous system, metabolism, reproduction, and psychological health, cancer, and premature death. It also assesses the effect of airborne pollutants on DALYs, YLL and shortfalls in life cycle, along with health disparities in various regions and socioeconomic categories. This article also discusses how global warming can worsen airborne pollutants episodes due to enhanced photochemical ozone synthesis, wildfire emission levels, urban heat island phenomenon, and changes in airflow.The success rate, difficulties with implementation, and potential outcomes of various national and international policy proposals, such as the World Health Organization's (WHO) air quality standards, the UN Sustainable Development Goals (SDGs), Paris Agreement, as well as India’s National Clean Air Program (NCAP) were assessed critically. Technological advances including satellite-based remote sensing; cost-effective network sensors, AI, machine learning, and high-level precision health care are introduced as revolutionary instruments for risk assessment and ecological governance. Strengthening multidisciplinary studies, expanding long-term exposure observation, improving surveillance frameworks, and implementing scientifically supported environmental regulations are critical to reducing disease burdens and building adaptability to global warming. A coordinated worldwide approach of

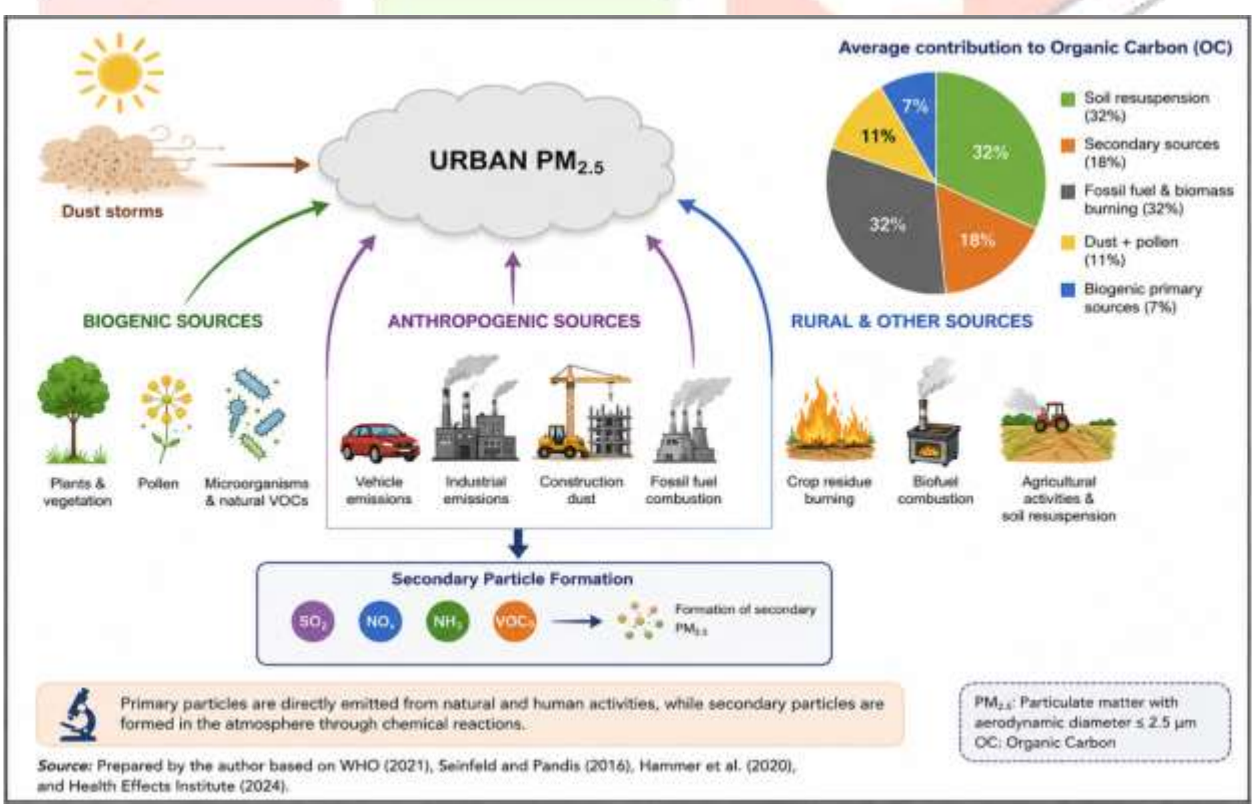
atmospheric science, epidemiological research, public health and environmental policies will be required to achieve sustainable progress and protect subsequent generations.

Keywords: *Air pollution, Climate change, Human health burden, particulate matter, Air quality management, Sustainable development, Human health policies*

1. Introduction

Airborne pollution is one of the predominant environmental risk factors over the worldwide burden of illness and premature deaths, and a significant risk for public wellness and sustainable growth. The WHO (World Health Organization) has reported that nearly 99% of the world's population lives in regions where ambient air quality is higher than the suggested thresholds (WHO, 2021). At the same time global warming impacts atmospheric mechanisms by raising temperatures, altering precipitation trends and extreme weather conditions. Both issues are mainly driven by humans via the use of fossil fuels, industrialization, urbanization, public transit, and biomass combustion (IPCC, 2023).

Environmental pollution and climatic change are connected and both affect the creation, transportation, and diffusion of contaminants. Increased temperatures create more ground-level ozone, and drought, natural calamities, and stable atmospheres produce higher levels of PM2.5 and different pollutants. It cumulative environmental contact, therefore, contributes to the human illness threat.Continuous getting exposed to $PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, CO and volatile organic compounds, or VOCs, has been linked with a higher probability of respiratory and cardiovascular illnesses, neurological illnesses, endocrine disorders, complications during pregnancy, cancer and early death. Current investigations also link airborne contaminants to neurodegenerative conditions, psychological disorders, autoimmune conditions, and the seriousness of lung infections such as COVID-19.



Outdoor and indoor air pollutants constitute one of the top reversible risk factors for several million premature deaths and also several million of disability-adjusted life years (DALYs) averaged annually, as stated by the Global Burden of Disease (GBD) study. The healthcare effect of air pollution: Air pollution's healthcare impact is not equally distributed. Increasing urbanization, industrialization, poor pollution management, and insufficient health services have disproportionately impacted low- and middle-income countries (LMICs). “Urban populations, children, senior citizens, pregnant women and persons with pre-existing illnesses are thought to be more vulnerable.”

2. Research Gaps

- Geographically research gap: Most of the studies are from high-income countries, but there is a shortage of proof from middle- and low-income nations (LMICs), especially in South Asia and Africa. (HEI, 2024; WHO, 2021).
- Risk assessment restrictions: Conventional observation stations do not sufficiently measure personal behaviors’, household air pollution and regular transportation habits (Hammer, et al., 2023).
- Limited knowledge of biological mechanism: The biological mechanisms of mental health, microbial, autoimmune and genital disorders due to persistent pollutants inhalation are yet to be recognized thoroughly (Landrigan, et al., 2022).
- Insufficient studies on cumulative impact: Continuous, multidisciplinary studies looking into the cumulative health consequences of global warming and air pollution remains insufficient (IPCC, 2023).

3. Air Pollution in the Context of Climate Change

3.1 Definition and Classification of Air Pollutants

Airborne pollution is the accumulation of physical, chemical or biological contaminants in the environment that are damaging to human health, natural environments, and the climate. There are two kinds of air pollutants: primary and secondary. Primary pollutants are directly produced, while secondary pollutants result from chemical processes in the atmosphere (WHO,, 2021; Seinfeld, & Pandis, 2016).

The main primary contaminants are $PM_{2.5}$, PM_{10}, SO_2, NO_x, CO, NH_3, black carbon, and VOCs. The secondary contaminants have ground-level ozone (O_3), sulphate and nitrate aerosols and photochemical smog of these substances, $PM_{2.5}$ is the to pose a major health risk, as it penetrates the circulatory system across pulmonary apex, leading to inflammation, oxidative injury, and multi-organ injury (WHO, 2021; HEI, 2024).

3.2 Major Atmospheric Pollutants

- **Particulate Matter (PM2.5 and PM10):** PM2.5 can travel thoroughly into the pulmonary system and enter the circulatory system; it is a significant cause of cardiovascular and respiratory illnesses (WHO, 2021).
- **Nitrogen Dioxide (NO_2):** Mainly produced from automobiles, thermal power plants and industrial combustion. That interferes with the respiratory tract and is responsible for the production of ozone and secondary particulate material (WHO, 2021).
- **Sulphur Dioxide (SO_2):** It originates from the burning of fossil fuels and coal, which is responsible for the generation of $PM_{2.5}$ by forming sulphate particles in the environment (Seinfeld, & Pandis, 2016).
- **Earth-level Ozone (O_3):** A secondary contaminant formed by the photochemical interaction of NO_x and VOCs in the existence of sunlight. Higher temperatures contribute to its production (IPCC, 2023).
- **Carbon Monoxide (CO):** It is generated when carbon-based fuels do not burn completely and reduces the ability of blood to supply oxygen (WHO, 2021).

- **Volatile Organic Compounds (VOCs):** produced from manufacturing operations, petroleum-based products, paints, and biomass burning; they are an important contributor to ozone formation (EPA, 2023).
- **Black Carbon:** Released from the insufficient burning of traditional fossil fuels and renewable energy sources. It is a major element of PM2.5 and also is responsible for global warming (IPCC,, 2023; UNEP, 2021).

3.3 Major Anthropogenic Sources

- Combustion of fossil fuels
- Coal-based thermal power plants
- Vehicle emissions
- Industrial manufacturing
- Construction activities
- Biomass combustion
- Domestic cooking and heating
- Burning of agricultural residues

3.4 Natural Sources

- Desert dust
- Volcanic eruptions
- Sea salt aerosols
- Forest fires
- Biological matter

4. Human Exposure Assessment

People's exposure analysis are fundamental component of ecological epidemiological studies which defines levels, duration and frequency of susceptibility to air pollutants a person is exposed to in everyday life. In contrast to static based air quality observation stations where it measures real-time individual exposure in different micro-environments including residences, workplaces, educational institutions, transportation, and outdoor environments. Factors influencing individual exposure include the indoor air quality, workplace routines, travel habits, living accommodations, and time-based activity trends (Diao, et al., 2019; Lee,, 2020).An accurate exposure evaluation is fundamental to ecological risk identification, disease load analysis, and response-based exposure investigations. Modern methods that involve satellite imagery, land-use regression (LUR), GIS, wearable devices, and machine learning (ML) are now being used to boost the quality of exposure analysis (Hammer et al., 2023).

Global warming is impacting the formation, transport and dispersion of pollutants caused by increased temperatures, wildfires, droughts and changes in weather patterns. Thus, today's exposure scientific literature highlights the need for a comprehensive assessment framework, which integrates atmospheric sciences, geospatial technologies, and epidemiological studies to better estimate continuous and real-world exposure (IPCC, 2023).

5. Health Impacts of Air Pollution

5.1 Respiratory Diseases

The pulmonary system is a major objective of air pollution. Long-term exposure to $PM_{2.5}$, PM_{10}, NO_2, O_3, and SO_2 is associated with an increased risk of severe asthma, chronic obstructive pulmonary disorder (COPD), pneumonia, lung capacity reduction, and lung tumours. Such contaminants cause oxidative strain, irritation of the airways, and tissue destruction, leading to the risk of respiratory illnesses (WHO, 2021; Su, et al., 2024).

5.2 Cardiovascular Diseases

Air contamination is a significant health risk associated with heart problems. Continuous exposure to $PM_{2.5}$, ultrafine particles and black carbon increases the risk of high blood pressure, ischemic cardiac arrest, by promoting endothelial abnormalities, oxidative damage, vascular inflammation, and propensity to coagulation. Recent research findings have shown how even prolonged contact at low doses can impact cardiac function (Brook, et al., 2010; Wang et. al., 2024).

5.3 Neurological Disorders

Recent investigations have suggested airborne pollutants as a novel risk indicator for neurodegenerative diseases. PM2.5 and ultrafine particles enter into the brain through blood vessels or olfactory pathways, resulting in oxidative stresses and neuroinflammation and disrupting the performance of the vascular barrier (BBB). These changes are linked to a higher risk for cognitive degeneration, Alzheimer's disease, Parkinson's illness, and various other neurodegenerative conditions (Abolhasani, et al., 2023; Peter's et. al., 2023).

Air pollutants inhalation in long-term periods has adverse effects on psychological wellness. Exposure to PM2.5, NO2 and O3 has been associated with a higher risk of anxiety, depression, and mental health problems. Some key cellular processes responsible for such impacts involve oxidative damage, cellular and brain irritation, and HPA pathway dysfunction (Borroni, et al., 2022; Braithwaite, et al., 2019).

5.4 Diabetes and Metabolic Disorders

Chronic exposure to air pollution, particularly PM 2.5, has been linked to a greater likelihood of Type 2 diabetes, also known (T2DM). It causes insulin resistance, abnormalities associated with glucose synthesis, oxidative damage, and prolonged inflammation, which are factors in the progression of metabolic diseases (Bowe, et al., 2018; Li et al., 2024).

5.5 Cancer

IARC has classified air pollution as a Group 1 human carcinogen. $PM_{2.5}$, diesel exhaust, and PAHs promote carcinogenesis through oxidative stress, DNA damage, and epigenetic changes. In addition to lung cancer, recent studies have also confirmed an increased risk of bladder, breast, and colorectal cancers (IARC, 2013; 2024 Meta-analysis).

5.6 Pregnancy and Reproductive Health

Exposure to $PM_{2.5}$, NO_2, and O_3 during pregnancy has been linked to preterm birth, low birth weight, fetal growth restriction, and pre-eclampsia. These effects primarily arise from oxidative stress, inflammation, and vascular disorders in the placenta. Recent studies also indicate that fine particles can cross the placental barrier and affect fetal development.

5.7 Children's Health

Children are more susceptible to air pollution due to their developing respiratory and immune systems. Long-term exposure to $PM_{2.5}$, NO_2, and O_3 has been linked to childhood asthma, reduced lung growth, respiratory infections, neurodevelopmental disorders, and impaired cognitive function. Some studies have also noted a potential risk of childhood cancer, although further long-term research is required (WHO, 2021). 5.9 Older Adults and Vulnerable Populations. Older adults, pregnant women, children, and individuals with pre-existing cardiovascular, respiratory, or metabolic diseases are more vulnerable to air pollution. Long-term exposure to $PM_{2.5}$ and other pollutants increases the risk of cardiovascular disease, respiratory disorders, cognitive decline, and premature death. The WHO has identified the protection of these vulnerable groups as a key priority in air pollution control (WHO, 2021; WHO, 2023).

5.8 Immune Dysfunction and Infectious Diseases

Air pollution affects both innate and adaptive immune systems by inducing oxidative stress and chronic inflammation, thereby increasing susceptibility to respiratory infections. During the COVID-19 pandemic, high exposure to $PM_{2.5}$ and NO_2 was also linked to an increased risk of severe infection and death (WHO, 2021; HEI, 2024).

5.9 Epigenetic Modifications

Long-term exposure to air pollution can induce changes in DNA methylation, histone modification, and micro-RNA expression without altering the DNA sequence. These changes affect genes associated with inflammation, oxidative stress, immune regulation, and carcinogenesis, contributing to the development of various chronic diseases (Breton et al., 2021; Jiang et al., 2023).

5.10 Neuroinflammation and Blood–Brain Barrier Dysfunction

$PM_{2.5}$ and ultrafine particles reach the brain via blood circulation or the olfactory pathway, affecting the blood–brain barrier (BBB) and inducing neuroinflammation. Long-term exposure to these particles has been linked to an increased risk of cognitive decline, dementia, Alzheimer's disease, and Parkinson's disease (Abolhasani et al., 2023; Wilker et al., 2023).

5.11 Molecular Signaling Pathways

The health effects of air pollution are primarily driven by molecular pathways associated with oxidative stress and inflammation. The NF-κB pathway increases the expression of pro-inflammatory cytokines (TNF-α, IL-6, IL-1β), whereas the Nrf2 pathway protects cells from oxidative damage by activating antioxidant enzymes such as HO-1, SOD, and GPx (Bellezza et al., 2018).

Pollutant	Major Sources	Principal Health Effects
$PM_{2.5}$	Traffic, industry, biomass burning, coal combustion	Cardiovascular disease, COPD, stroke, lung cancer, diabetes, premature mortality
PM_{10}	Construction, road dust, mining, agriculture	Respiratory irritation, asthma, reduced lung function
NO_2	Vehicles, power plants, industries	Asthma, respiratory inflammation, cardiovascular disease
SO_2	Coal combustion, refineries, smelters	Bronchoconstriction, respiratory disease
O_3	Secondary pollutant (NO_x + VOCs + sunlight)	Asthma, reduced lung function, hospital admissions
CO	Incomplete combustion, household fuels, traffic	Hypoxia, cardiovascular disease, neurological impairment
VOCs	Solvents, fuel evaporation, industries	Cancer, neurological toxicity, ozone formation

Black Carbon	Diesel engines, biomass burning	Climate warming, cardiovascular and respiratory diseases

Table: 1 Major pollutant, Sources and their impact on Human health and Environment.

6. Air Pollution, Disease Burden, and Life Expectancy

6.1 Global Disease Burden of Air Pollution

Air pollution is a major environmental risk factor for premature death and disease burden worldwide. According to the State of Global Air Report 2024, air pollution caused approximately 8.1 million deaths in 2021, with the majority linked to non-communicable diseases such as ischemic heart disease, stroke, COPD, lung cancer, and type-2 diabetes. A high risk of death due to air pollution was also observed among children under the age of five (HEI, 2024).

6.2 Disability-Adjusted Life Years (DALYs) and Years of Life Lost (YLLs)

The health impacts of air pollution are primarily assessed using DALYs and YLLs. DALYs represent a combined measure of premature mortality (YLLs) and years lived with disability (YLDs). According to the WHO and GBD, air pollution contributes significantly to DALYs through cardiovascular diseases, stroke, COPD, lung cancer, diabetes, and respiratory infections (WHO, 2021; GBD, 2024).

6.3 Air Pollution and Life Expectancy

Long-term exposure to $PM_{2.5}$ increases the risk of premature death and reduces life expectancy. Fine particles enter the bloodstream from the lungs, affecting the cardiovascular, respiratory, and nervous systems. According to the State of Global Air and GBD, air pollution is a major cause of significant reductions in life expectancy (HEI, 2024; GBD, 2024).

6.4 DNA Damage and Genomic Instability

Air pollution induces genomic instability through oxidative stress and disruption of DNA repair mechanisms. $PM_{2.5}$, NO_2, O_3, diesel exhaust particles, and PAHs are associated with DNA damage, chromosomal abnormalities, and elevated levels of oxidative DNA damage biomarkers such as 8-OHdG. These changes increase the risk of mutations, cellular senescence, lung cancer, cardiovascular diseases, and other chronic conditions (Valavanidis et al., 2020; Hou et al., 2023; Zhao et al., 2024).

7. Climate Change–Air Pollution Interactions

Climate change and air pollution are linked to common emission sources, such as fossil fuels, industry, transport, and biomass combustion. Rising temperatures and altered meteorological conditions influence the formation, transport, and dispersion of pollutants, while black carbon and tropospheric ozone further intensify climate change. Their combined interaction exacerbates adverse effects on human health (IPCC, 2023; WHO, 2023).

7.1 Heat Stress and Air Pollution

High temperatures enhance the formation of ground-level ozone and photochemical reactions, leading to deteriorated air quality during heatwaves. Combined exposure to extreme heat and $PM_{2.5}$ or O_3 increases the risk of cardiovascular and respiratory diseases as well as premature death (IPCC, 2023; Chen et al., 2024).

7.2 Wildfires, Dust Storms, and Extreme Weather Events

Climate change is increasing the frequency of wildfires, droughts, and dust storms, thereby raising levels of pollutants such as $PM_{2.5}$, CO, and VOCs. These events heighten the risk of respiratory and cardiovascular diseases (WHO, 2023; Johnston et al., 2024).

7.3 Urban Heat Island and Vulnerable Populations

The Urban Heat Island (UHI) effect intensifies high temperatures and the accumulation of pollutants. Health impacts are more severe among children, the elderly, pregnant women, and individuals with cardiovascular or respiratory conditions (IPCC, 2023).

7.4 Feedback Mechanisms and Public Health Implications

Environmental pollution and global warming accelerate the favourable response mechanism. Renewable energy, sustainable mobility, decreased fossil fuel consumption, and greening cities are strategies that contribute to improving air quality and decreasing greenhouse gas emissions and the impact of pollution-related illnesses (WHO, 2023; UNEP, 2024).

8. International and National Policy Responses

- Numerous policies have been implemented at global and national levels to control air pollution. Coordinated efforts across the energy, transport, industry, and public health sectors are essential for effective air quality management. Studies indicate that pollution control policies lead to improved air quality and reductions in both the disease burden and health-related expenditures (WHO, 2021; UNEP, 2023).
- In its 2021 Global Air Quality Guidelines, the WHO established stricter standards for $PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2, and CO, serving as a key benchmark for global air quality management (WHO, 2021).
- Air pollution is regulated to achieve the objectives of SDGs 3, 7, 11, and 13, as well as the Paris Agreement, as sustainable energy sources and low-carbon-footprint technologies reduce air pollutants and greenhouse gas concentrations (United Nations, 2015; IPCC, 2023).
- India has committed to reducing PM2.5 and PM10 levels under the National Clean Air Program (NCAP) (2019) by strengthening monitoring systems, encouraging clean shipping, and managing factory emissions. The CPCB and SPCBs are executing this program (MoEFCC, 2023; CPCB, 2024).
- Furthermore, measures like BS-VI emission norms, electric automobiles, green energy, and Pradhan Mantri Ujjwala Yojana (PMUY) assist in lowering emission levels and positive outcomes for well-being and the environment (IEA, 2023). Economic analyses reveal that investment in clean air leads to a reduction of healthcare expenses, an increase in output, and a decline in premature death (World Bank, 2022; OECD, 2020).

9. Air Pollution in India

India is among the world's most polluted countries due to rapid urbanization, industrialization, vehicular emissions, coal-based energy, biomass combustion, and the burning of agricultural residues. In many cities, $PM_{2.5}$ and PM_{10} levels still exceed WHO (2021) guidelines and CPCB national standards (WHO, 2021; CPCB, 2024).

9.1 Current Air Quality Status

According to IQAir (2024), India remains one of the countries most affected by $PM_{2.5}$ globally. Meteorological conditions, particularly in the Indo-Gangetic Plain, exacerbate the accumulation of pollutants. Long-term exposure to $PM_{2.5}$ increases the risk of respiratory and cardiovascular diseases, diabetes, and premature death (IQAir, 2024; HEI, 2024).

9.2 Air Quality Monitoring and National Initiatives

The Central Pollution Control Board along with State Pollution Control Boards in India regularly monitoring $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3 using a NAMP and CAAQMS networks (CPCB, 2024). The National Clean Air Program (NCAP) was launched in 2019 to reduce PM2.5 and PM10 concentrations by implementing emission management, healthy transport, manufacturing regulations and better surveillance (MoEFCC, 2023).

9.3 Latest Epidemiological Research Studies about India

Indian studies have linked long-term exposure to $PM_{2.5}$ with asthma, COPD, cardiovascular disease, stroke, diabetes, adverse pregnancy outcomes, and premature death. GBD analyses indicate that air pollution is a major driver of DALYs and healthcare expenditure in India (India State-Level Disease Burden Initiative Air Pollution Collaborators, 2020; HEI, 2024).

10. Emerging Technologies and Future Directions

Artificial Intelligence (AI) and Machine Learning (ML) are increasingly being used in air quality prediction, detecting pollutants, and health risk assessment. Artificial intelligence models can improve the accuracy of PM2.5 and O3 predictions by combining meteorological, satellite imagery, and ground-based observation data (Zhang et al., 2023; Gupta et al., 2024).

10.1 Low-Cost Sensors and Wearable Technologies

Cost-effective sensors and wearable gadgets are capable of being used to monitor individual exposure to pollutants such as PM2.5, PM10, NO2, and CO in real time. They are relatively inexpensive and can be used for community surveillance and environmental epidemiology purposes, but they must undergo a calibration procedure towards laboratory-grade instruments (Morawska et al., 2021).

Conventional methods pertaining to exposure assessment depend heavily on stationary-based air quality monitoring stations to estimate ambient pollutant levels but do not yield reliable estimations of individual exposure levels. In this respect, the implementation of individual exposure monitoring techniques relying on handheld detectors, wearable gadgets, GPS, cellular phones, and activity diary data has gained momentum in recent years, enabling the evaluation of real-time exposure to PM2.5, PM10, NO2, O3, and VOCs with a resolution of high temporal and spatial (Diao et al., 2019; Lee, 2020).

Advanced portable monitors contain optical sensors, electrochemical gas sensors, GPS, and cloud-based data systems to help identify high-exposure zones and track them in real time. Devices like AirPen have been shown to be effective in atmospheric epidemiology studies measuring personal PM 2.5 and VOC exposure in both location and time.

In addition, the reliability of such affordable sensors can be hampered by technical restrictions like humidity, temperature, detector drift, and calibration issues. Hence, their use as a supplementary instrument to standardized stations for observation appears to be more suitable (Morawska et al., 2021).

10.2 Satellite Remote Sensing and GIS

Satellite platforms such as MODIS, Sentinel-5P, and TROPOMI continuously monitor $PM_{2.5}$, NO_2, SO_2, and AOD. Their integration with GIS enhances the effectiveness of pollution mapping, hotspot identification, and exposure assessment (Hammer et al., 2023).

Key applications of satellite data and GIS:

- Comprehensive spatial and daily monitoring.
- Mapping of pollution hotspots and disease patterns.
- Assessment of health risks and population vulnerability.
- Use in exposure modeling and epidemiological studies

10.3 Big Data and Precision Public Health

Integrating environmental monitoring, electronic health records (EHRs), and mobile data strengthens the identification of vulnerable populations, risk assessment, and evidence-based public health decision-making (Khreis et al., 2023).

10.4 Land-Use Regression (LUR) Models

This Land-Use Regression (LUR) model is a comprehensive and statistical approach for determining prolonged exposure to air pollution, especially from traffic-related sources. It models levels of pollutants dependent on geographical variables, including traffic volume, highways, industries, demographics, and land utilization. LUR models are commonly utilized to measure household exposure to PM2.5, NO2, black carbon, and extremely fine particles because of their high spatial resolution, as well as for longitudinal cohort studies (Hoek et al., 2008; Hammer et al., 2023).

10.5 Challenges and Future Research Directions

Faster development, growing vehicle numbers, dependence on fossil fuels, weak enforcement of emission requirements, and restrictions in accurate assessment of individual exposure levels are major obstacles for air pollution analysis. In the future, the integration of AI, machine learning, satellite remote sensing, GIS, IoT-based sensors, wearable sensors, exposome science, multi-omics, and electronic health records (EHRs) will enable more accurate, personalized, and real-time exposure assessment. Additionally, it is essential to prioritize long-term cohort studies, standardized exposure assessment, the expansion of monitoring networks, and the promotion of clean energy and low-emission transport. These technologies will play a pivotal role in strengthening precision public health, evidence-based air quality management, and effective public health policies (WHO, 2021; IPCC, 2023; Khreis et al., 2023; CPCB, 2024).

11. Recommendations:

- Air Quality Management: Air quality standards should be strengthened in alignment with WHO guidelines, and measures such as emission control, real-time monitoring, and satellite-based monitoring should be promoted (WHO, 2021; CPCB, 2024).
- Clean Energy and Transport: Priority should be given to renewable energy, clean fuels, and low-emission transport to reduce reliance on fossil fuels (IPCC, 2023).
- Public Health Surveillance: Disease surveillance, early warning systems, and the protection of vulnerable populations should be integrated into public health policy (WHO, 2023).

- Research and Innovation: Exposure assessment and environmental health research should be strengthened through the use of AI, GIS, remote sensing, wearable sensors, and long-term cohort studies (Hammer et al., 2023).
- International Cooperation: Air quality management and climate adaptation should be integrated through data sharing, technology transfer, and coordinated policies to achieve SDGs and public health goals (UNEP, 2024).

12. Conclusion

Air pollution is a major environmental risk factor globally, contributing to the disease burden, premature mortality, and reduced life expectancy. Long-term exposure to $PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, and CO induces oxidative stress, inflammation, and immune and cellular disorders, thereby increasing the risk of respiratory, cardiovascular, neurological, and metabolic diseases, as well as cancer (WHO, 2021; HEI, 2024). Climate change exacerbates the impacts of air pollution, as heat waves, wildfires, and increased ozone formation heighten health risks. Children, pregnant women, the elderly, and individuals with chronic diseases are the most vulnerable (IPCC, 2023). Hence, emissions management, renewable energy, efficient air quality monitoring, evidence-based regulations, and interdisciplinary research are important for the prevention of air pollution. The SDGs, WHO guidelines and India's National Clean Air Program (NCAP) are key policy models for enhancing air quality and safeguarding public health (WHO, 2021; MoEFCC, 2023).

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