Review Article

Air Quality under a Changing Climate: A review of Trends and Implications for Respiratory Health in South Asia

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Abstract

Climate change and deteriorating air quality constitute synergistic environmental stressors with profound implications for respiratory health, particularly in South Asia a region grappling with rapid urbanization, industrialization, and transboundary pollution. This review synthesizes a decade (2015-2024) of interdisciplinary research to assess the interplay between climatic shifts and air pollution dynamics, their health consequences, and policy responses. Findings reveal that rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events exacerbate atmospheric stagnation, photochemical ozone formation, and particulate matters ($PM_{2.5}$, PM_{10}) accumulation. South Asia's urban centers, responsible for over 70% of regional emissions, face $PM_{2.5}$ concentrations exceeding WHO guidelines by 4-12 times, contributing to ~2.2 million annual premature deaths. Climate-driven wildfires, agricultural burning, and weakened monsoons further amplify pollution, disproportionately affecting vulnerable populations, including children and the elderly, through heightened risks of asthma, COPD, and acute respiratory infections. Economic analyses indicate pollution-related costs consume 1.36-4.8% of national GDPs, driven by healthcare burdens and productivity losses. While policies like India's National Clean Air Program mark progress, fragmented governance, inadequate monitoring infrastructure, and overemphasis on vehicular emissions hinder efficacy. Strategic recommendations emphasize geospatial hotspot mapping, stringent industrial regulations, and multilateral airshed management to harmonize emission standards. The review underscores the imperative for integrated, data-driven policies that bridge climate adaptation and pollution mitigation, leveraging clean energy transitions and urban greening. Addressing this dual crisis demands urgent regional collaboration, robust health impact assessments, and interdisciplinary innovation to safeguard respiratory health and sustainable development in a warming world.

Keywords: Climate change; Air pollution, $PM_{2.5}$; Respiratory diseases; South Asia; Health policy

1. Introduction

Climate change is driving unprecedented alterations in the Earth's environment. Global surface temperatures have already risen by about 1.1°C above pre-industrial levels, with the past decade (2011-2020) nearly 1.09°C warmer than 1850-1900 (Kim et al., 2025). This warming is accompanied by more frequent and intense heat waves, altered precipitation patterns, rising sea levels, and other extreme weather events (Ganguli & Merz, 2025; Prasad, 2025). These climatic shifts are straining ecosystems and human societies: heat and drought threaten water and food supplies, while storms and floods cause injury and disruption. At the same time, climate change and human activities interact to shape air quality. Ambient air pollution remains one of the leading environmental health risks worldwide; for example, in 2019 about 4.2 million premature deaths were attributed to outdoor fine particulate matter ($PM_{2.5}$) exposure (Sicard et al., 2023; WHO, 2024). Greenhouse-gas driven warming also affects atmospheric chemistry, warmer, stagnant conditions tend to increase the formation of ground-level ozone and exacerbate particulate pollution from wildfires and dust (EPA, 2025; Kim et al., 2025). Thus, climate change and air pollution are entwined hazards with major implications for human health and well-being (Akasha et al., 2023; Alum, 2025).

In Asia and South Asia in particular, these pressures are magnified by rapid economic growth, urbanization, and rising emissions. Over the past decades, Asian economies have expanded quickly, lifting hundreds of millions out of poverty but generating more energy use, transport, and industry. Cities in Asia now produce the vast majority of the region's greenhouse gases and air pollutants. For example, one recent study found that urban areas contribute over 70% of global CO_2 emissions (Crippa et al., 2021; Kim et al., 2025), and generally have much higher pollution levels than surrounding rural areas. South Asian countries have seen especially dramatic change: massive construction, deforestation, and agricultural burning have combined with growing vehicle fleets and coal-fired power to worsen air quality. As one analysis of South Asia notes, *"rapid economic growth, urban sprawl, and unplanned industrialization has increased socioeconomic status but also decreased air quality"*. For example, land-use regression modeling in Pakistan indicates that urbanization via road transport and loss of tree cover is a dominant driver of the country's high $PM_{2.5}$ levels (Shi et al., 2020). More broadly, across South and Southeast Asia the conversion of forests and fields into cities and farms has been identified as a principal factor behind severe pollution in major cities (Vadrevu et al., 2017; Vadrevu et al., 2023). Without strong emission controls, the dual trends of rising energy demand and population growth in South Asia threaten to worsen both climate change and local air quality simultaneously (Abdul Jabbar et al., 2022; Herath Bandara & Thilakarathne, 2025).

Concurrently, Asia is already experiencing clear climate-change trends. Observations show that all of Asia has warmed significantly over the 20^{th} and early 21^{st} centuries (high confidence) (IPCC, 2022). Temperature increases have been uneven but widespread: for example, satellite and station records indicate strong warming across West and Central Asia, and more frequent and intense heat waves in South and East Asia. Notably, extreme heat events in recent years (such as the 2013 heat wave in Eastern China) have been linked to anthropogenic warming, making them much more likely or severe than they would have been in a pre-industrial climate. Precipitation patterns are also shifting. South Asia's summer monsoon rainfall showed a declining trend in the late 20^{th} century, though heavy rainfall events have actually become more common in recent decades. In high-mountain Asia (the Himalayas), some springtime precipitation has decreased, worsening snow shortages in parts of the Himalaya. Changes in circulation are evident too: for example, annual average surface winds have weakened over much of Asia since 1950, which can exacerbate pollution by reducing dispersion. Dust and haze events have grown more frequent in some areas (e.g. intensified dust storms in West/Central Asia) (IPCC, 2021, 2022; Seneviratne et al., 2021).

The Asia's climate has grown hotter and more variable, with increased droughts and floods, altering the setting in which pollutants accumulate. These climate-induced environmental changes have direct and indirect links to public health. Heat waves increase heatstroke and cardiovascular stress and can amplify ozone levels, while floods and droughts affect water- and food-borne diseases. Critically, many climate impacts (higher ozone, more wildfires, and dust storms) degrade air quality, thus magnifying respiratory exposures.

Air quality itself is a pivotal bridge between environmental change and human health. Poor air quality directly causes respiratory and cardiovascular disease – one global analysis estimated that ambient $PM_{2.5}$ and ozone together contributed to ~5.2 million premature deaths in 2021 (Kim et al., 2025), although this is likely an underestimate since only some pollutants are counted. In Asia, outdoor pollution accounts for a disproportionate share of illness and mortality: for example, in 2019 the World Health Organization (WHO) reported that almost 90% of global pollution-related deaths occurred in low- and middle-income countries, with the greatest total burden in the WHO South-East Asia and Western Pacific regions. Respiratory illnesses are especially concerning. Chronic lung diseases like asthma and chronic obstructive pulmonary disease (COPD) affect hundreds of millions worldwide; asthma afflicted an estimated 262 million people in 2019 and COPD caused ~3.5 million deaths in 2021 (WHO, 2024). South Asia shoulders a heavy share of these burdens. Recent modeling studies estimate that ambient $PM_{2.5}$ caused on the order of 2.2 million excess premature deaths in South Asia in 2018 (Wang et al., 2025), reflecting the region's extremely high pollutant levels. These staggering figures underscore a rising global and Asian concern about respiratory diseases linked to air pollution. Moreover, air pollutants can exacerbate infectious respiratory diseases and interact with other climate-sensitive health risks. The convergence of polluted air and a warming climate thus represents a pressing public health nexus.

Given these overlapping crises, understanding the interconnections between climate change, air quality, and respiratory health is critically important. Changes in climate can reshape pollution patterns (for example, by lengthening smog seasons or increasing wildfire smoke), which in turn may affect the incidence and severity of lung diseases. There is therefore a strong imperative to synthesize existing research on how a changing climate is already altering air quality in South Asia and what this implies for respiratory health burdens. This review article aims to fill that need by providing a comprehensive assessment of climate–air quality-health linkages in Asia, with a focus on South Asia.

For this review, the research conducted a broad literature search covering the past ten years (2015–2024) using scientific databases such as Google Scholar, Scopus, and Web of Science. Search terms included combinations of "climate change," "air quality," "air pollution," "respiratory health," "respiratory diseases," and country or region names (e.g. "South Asia," "India," "Southeast Asia"). We prioritized (only included) peer-reviewed journal articles, review papers, and official assessment reports (e.g. from WHO, WMO, and the IPCC). Studies were selected based on relevance to Asia and to the interactions among climate, pollution, and health. Quantitative data on trends, as well as narrative discussions of mechanisms, were extracted and organized by topic. The investigation is structured into thematic sections (see **Figure 1**): first covering the observed and projected climate influences on air quality, and then reviewing links to respiratory outcomes, before concluding with discussion of policy and research needs. By adopting this systematic approach, we aim to capture the state of knowledge and trace emerging consensus or controversies on these critical issues.

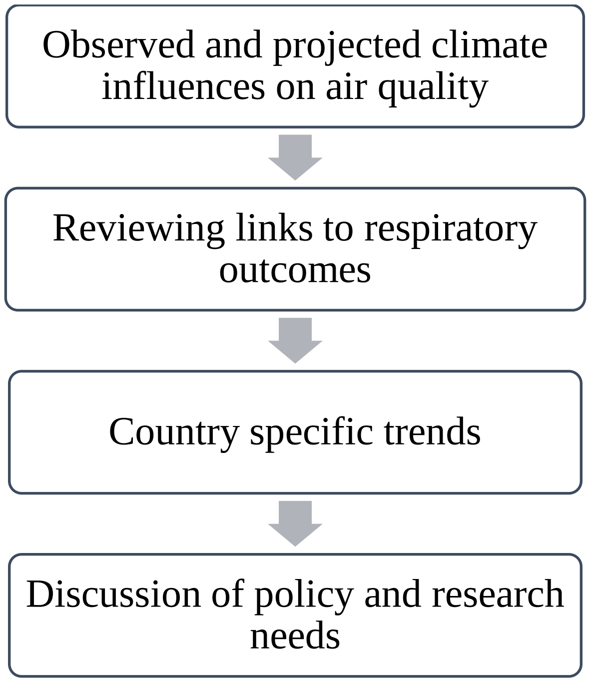

Figure 1. Stages diagram to construct thematic sections for review.

2. Effect of Climate Change on Air Quality in South Asia

Climate change affects air quality through several interrelated pathways. In general, warmer temperatures and altered meteorology can change pollutant chemistry, transport, and removal. For example, higher surface temperatures increase the rate of photochemical reactions that generate ozone (O_3) from its precursors like nitrogen oxides and volatile organic compounds (VOCs) (Dewan & Lakhani, 2022; EPA, 2025; Li et al., 2023). Thus heat waves and more frequent hot sunny days tend to worsen summertime ozone peaks. Similarly, stable atmospheric conditions (weak winds, temperature inversions) often occur during extreme heat and can trap pollutants near the surface, leading to stagnation episodes. Climate-driven changes in precipitation also matter: reduced rainfall during dry seasons can let particulate matter accumulate, whereas extreme downpours can temporarily scrub pollutants but then raise humidity and mold growth (Liu & Matsui, 2023). In South Asia, these climate effects are superimposed on already high emissions. A number of studies project a climate penalty on regional air quality: for instance, machine-learning analysis of future climate fields predicts that under strong warming scenarios, near-surface ozone concentrations will rise across much of Asia, including South India and the Indo-Gangetic Plains (by up to 5-20% by 2100) (Li et al., 2023). The driving factors are warmer temperatures, more solar radiation, and modest declines in humidity and cloud cover, all of which enhance ozone formation (Bais et al., 2019). Likewise, some model studies find that each degree of warming could raise background ozone by about 1-2 parts per billion over South Asia (Li et al., 2023). These findings suggest that even without increases in emissions, climate change alone will tend to worsen ozone pollution in South Asia's urban and downwind regions.

Particulate matter (PM) is also sensitive to climate change. Higher temperatures can promote wildfires and biomass burning by drying out forests and fields. In South Asia, agricultural residue burning (e.g. post-harvest stubble fires) is already a major seasonal source of $PM_{2.5}$; hot, dry conditions (sometimes linked to El Niño or drought) can intensify these burns. Similarly, climate variability affects dust storms: vegetation loss and drier soils under warming can increase the frequency of dust events in arid regions of South Asia and the Middle East. A recent multi-country study (including Southeast Asia) found that fine particles from wildfire smoke had substantial respiratory impacts – in Thailand and Vietnam, for example, a 1 $\mu g/m^3$ increase in wildfire-derived $PM_{2.5}$ was associated with a roughly 0.4% higher risk of respiratory hospital admissions (Zhang et al., 2025). This underscores how climate-amplified biomass burning may contribute directly to lung disease. In the Indo-Gangetic Plain, satellite analyses show persistently high $PM_{2.5}$ during winter and dry seasons, when local emissions combine with stagnant air sheds. As climate change is projected to increase the length and intensity of heat waves and possibly reduce winter air flow, such pollution episodes may become more severe. For instance, modeling studies estimate that in 2018 ambient $PM_{2.5}$ exposure in South Asia caused on the order of 2.2 million premature deaths (Wang et al., 2025); any climate-driven increase in $PM_{2.5}$ would compound this health burden.

Meteorological shifts under climate change will alter pollutant dispersion. Observations indicate that average surface winds over Asia have weakened in recent decades (IPCC, 2022), and climate models project continued reductions in large-scale wind speeds and mixing heights. Such changes mean pollutants remain concentrated over source regions for longer periods. At the same time, changes in precipitation patterns can influence wet deposition of aerosols: some parts of South Asia may see less rain in dry seasons, allowing smoke and dust to accumulate (Sadavarte et al., 2016). Conversely, more intense monsoon downpours could occasionally flush pollutants but then create humidity for mold and secondary aerosol formation (Li et al., 2016). Generally, many climate projections suggest that South Asia will experience more stagnant, high-pressure systems in future summers, especially over northern India. This would trap ozone and $PM_{2.5}$ at dangerous levels. Indeed, climate modeling for India predicts that high-pressure "anti-cyclonic" conditions become more frequent under warming, inhibiting vertical mixing of pollutants (Li et al., 2023). On the other hand, stronger monsoon flows and convective activity in extreme cases could also lead to episodes of dust uplift or flood-driven emissions (e.g. of sewage or landfill gases), showing that the net effect is complex and spatially variable.

Extreme weather events, which are becoming more common with climate change, also degrade air quality in South Asia. Heat waves themselves can increase ozone and secondary aerosol formation (Barriopedro et al., 2023). Wildfire and forest fire risk grows with heat and drought: for example, recent years have seen record forest fires in the Himalaya and Indo-Malayan region, spiking fine particle levels downwind. These events typically occur when tropical cyclones or western disturbances fail to bring rain, leading to large uncontrolled burns. Agricultural fires often set intentionally for crop clearing also worsen during dry conditions, and climate change can shift the timing and severity of these fire seasons (Vadrevu et al., 2019). The smoke plumes from biomass burning can spread across regional boundaries, creating transboundary haze; such episodes in Southeast Asia have been linked to a surge in hospital admissions for respiratory distress (Adam et al., 2021; Cush et al., 2021). Even tropical cyclones, whose tracks are changing slightly in Asia, can have air quality impacts: heavy winds can loft dust from desiccated land areas, and floods can mobilize roadside waste into waterways that later contribute to ozone precursor emissions (Maji & Sonwani, 2022).

Land-use change and the urban heat island effect are additional factors that connect climate change with air quality. Urbanization itself has already been noted as a driver of Asia's pollution: densely built areas with little vegetation – common in rapidly growing South Asian cities – tend to be hotter than surrounding countryside, an effect further amplified by climate warming. This urban heat island raises local temperatures, which can accelerate ozone-forming reactions and raise pollutant concentrations in city centers. Studies in South Asia indicate that reduced tree cover and increased road networks (as seen in Pakistan) correlate strongly with higher ambient $PM_{2.5}$ (Shi et al., 2020). Likewise, conversion of rural land to agriculture or urban uses often releases dust and changes local wind flow, compounding regional pollution. South Asia has also seen deforestation in parts of the Himalayas and conversion of wetlands, which can alter regional hydrology and climate feedbacks. These land cover changes can feed back onto climate (e.g. by modifying local rainfall) and on air quality (by changing emissions of biogenic VOCs or dust).

It is evident from above discussion that the South Asia's air quality is tightly coupled to a changing climate. Warming-driven meteorological shifts (higher heat, weaker winds, and variable precipitation) tend to worsen ozone and particulate pollution, while climate-induced extremes (wildfires, dust storms, and intensified burning) inject additional pollutants into the air. Urbanization and land-use change, interwoven with climate change, create local hotspots of pollution (such as intense urban smog and regional haze) that disproportionately affect human health. The evidence suggests that without targeted interventions, climate change will amplify South Asia's already severe air pollution problem.

Figure 2. Annual average $PM_{2.5}$ concentrations in South Asian countries (Abdul Jabbar et al., 2022).

3. Trends in Key Air Pollutants across South Asia

South Asia's air quality has worsened in recent decades, with urbanization, population growth, and energy use driving higher concentrations of $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO and ozone. Across the region, the burden of outdoor air pollution (largely $PM_{2.5}$) ranks among the world's highest

(Hahad, 2024; Islam et al., 2024), also shown in **Figure 2**. The main sources are fossil-fuel combustion (traffic, power plants, industry), biomass and waste burning (household cooking, agricultural/forestry residue, garbage), and natural dust. In many areas wildfire smoke and transboundary haze also contribute seasonally. For example, the Global Burden of Disease (GBD) 2019 data highlight that Afghanistan, India, Pakistan and Bangladesh all face very high ambient $PM_{2.5}$ and ozone burdens compared to developed nations (Amer et al., 2024; Hahad, 2024). Specific South Asian pollutants and sources by country are summarized below.

3.1. Trends and Statics from Afghanistan

Afghanistan's air is among the most polluted in Asia, especially in winter. Recent analysis indicates that ambient $PM_{2.5}$ and PM_{10} are high in cities (often >50–100 µg/m³) due to unchecked vehicular traffic, diesel generators, brick kilns and industry. The primary anthropogenic sources are motor vehicles, brick-making and other industry, and open burning of waste and agricultural residue (Hahad, 2024). Rural regions rely on wood and dung for cooking, contributing to particulate and CO emissions (indoor and outdoor). A key natural source is mineral dust from Afghanistan's arid lands, lifted in dust storms and transported into urban airsheds (Janick D. Lalonde, 2015). GBD reports stress that Afghanistan's overall air-pollution mortality is among the highest in South Asia, driven largely by $PM_{2.5}$. Unfortunately, monitoring data are sparse, so trends are inferred from models: general increases in $PM_{2.5}$ have been reported since the 1990s in Afghanistan due to growth in energy use and vehicles. Seasonal dry-winter inversions trap pollutants, causing persistent smog and high NO_2 and CO in cities. Sulfur dioxide (SO_2) has risen as industries and power generators emit more sulfur; though no national emission controls have been enforced, some coal power imports and diesel imports changed fuel mixes. Climate change (hotter summers, drier soils) may intensify dust storms, while higher energy demand in winter (for heating) likely keeps particulate pollution high (Salehie et al., 2024; Waseq, 2020).

3.2. Trends and Statics from Bangladesh

Bangladesh, with 165 million people suffers extreme chronic pollution. Dhaka and other cities routinely see daily $PM_{2.5}$ well above WHO guidelines. A recent review notes that air pollution caused ~173,500 deaths in 2019, and that fine particles ($PM_{2.5}$ and PM_{10}) from brick kilns, vehicle exhausts and biomass burning "surpass safe thresholds" across Bangladesh (Islam et al., 2024). In Dhaka, mean $PM_{2.5}$ often exceeds 65 µg/m^3 on many days, with episodic smog lasting weeks

(Sarwar et al., 2023). Major sources are brick kilns (insufficiently regulated kilns contribute soot and SO_2), heavy traffic (diesel trucks and buses produce NO_2, CO, black carbon), and widespread burning of rice straw and waste (PM_{10}/$_{2.5}$, CO). Vehicular NO_x and CO emissions have grown steadily with the vehicle fleet, and despite some adoption of CNG buses, NO_2 levels remain well above WHO targets much of the year. Seasonal factors like winter temperature inversions and seasonal crop-stubble fires from upstream India exacerbate $PM_{2.5}$ spikes. Ground ozone is generally lower than urban India, but is still a concern; rising temperatures and intensified sunlight in climate-warmed summers are expected to increase ozone and photochemical smog episodes. Recent trends suggest only slight air-quality improvements; lockdowns temporarily cut $PM_{2.5}$, but after 2020 levels climbed back, reflecting persistent emissions (Hossain et al., 2021). Although Bangladesh banned old vehicles and attempted cleaner cook stoves, $PM_{2.5}$ improvements have been modest (Khandker et al., 2023).

3.3. Trends and Statics from Bhutan

Bhutan generally has cleaner air than its neighbors, thanks to low population and large forests (Hossain & Jami, 2023). Ambient $PM_{2.5}$in Thimphu and other towns is much lower compared to South Asian megacities, but local sources still matter (Yangzom et al., 2024). The main contributors are household heating and cooking using wood, small-scale industrial boilers and cement plants, and increasing vehicle emissions along major roads. Transboundary haze from Indian forest fires or dust from the south occasionally raises pollution levels. Because most heating in winter is from wood burning, wintertime $PM_{2.5}$ and PM_{10} are highest (often 2-3 times higher than summer). Ozone in Bhutan remains low (due to high background ozone uptake by forests and lower NO_x), but could rise if NO_x increases (Baruah et al., 2022). The lacking comprehensive studies, trends are inferred: as Bhutan's economy grows, vehicle and industry emissions have been rising slowly, while forest cover and the transmission of cleaner hydropower help keep urban SO_2 low (Bhutan's energy is almost entirely hydroelectric) (Lad & Jaybhaye, 2025). Moreover, the Bhutan's rural areas have mild pollution dominated by biofuel and dust, and urban Thimphu sees moderate PM and NO_2 from traffic and wood heaters. Climate change impacts (e.g. warmer winters) may reduce the seasonality of $PM_{2.5}$, but increased droughts could make biomass burning more frequent (Yin, 2023).

3.4. Trends and Statics from India

India has seen a marked deterioration in air quality over the past decades. Satellite and ground analyses show that the annual national average $PM_{2.5}$ has *steadily increased* from the 1990s through 2019 (Guttikunda & Nishadh, 2022; Singh et al., 2021). Delhi and NCR remain among the world's worst-polluted, but many smaller cities (e.g. Kanpur, Lucknow) have risen to top-100 global worst by $PM_{2.5}$. Guttikunda and Nishadh (2022) estimate that only ~28% of Indians lived below the old national standard (40 µg/m³) by 2020, down from 60% in 1998 (Guttikunda & Nishadh, 2022). Over 80% of $PM_{2.5}$ in India is attributed to fuel combustion (coal in power and industry; diesel and petrol vehicles; biomass and waste burning for cooking and heating) (Mukherjee et al., 2022). The seasonal pattern is notable: northern India faces severe winter smog combining stagnant air (due to cool temperatures and crop-burning haze) with high emissions from domestic heating and industry. In summer, dust transport from the Thar Desert raises $PM_{10}/_{2.5}$ in northwest India. Overall, nearly all of India's major cities exceed WHO $PM_{2.5}$ guidelines by large margins. PM_{10} also rose with construction and road dust, although cement kilns and some regulations have lately reduced some SO_2 and PM_{10} sources (Paul, 2023; Venkata Sudhakar & Reddy, 2023).

CO and NO_2 in India have generally risen with economic growth and vehicle traffic (especially diesel). Power plant pollution controls (low-sulfur coal, scrubbers) have lowered SO_2 in some regions, but thermal capacity has grown so ambient SO_2 remains above guidelines in many industrial areas. Ground-level ozone is an increasing concern: measurements across India show ozone rising 2-5% per year in many regions, driven by hotter days and abundant precursors (VOCs and NO_x) from urban/industrial sources (Guttikunda & Nishadh, 2022). India has implemented stricter vehicle and fuel standards (Bharat Stage VI since 2020), and 2020 lockdowns showed how severe baseline pollution was: $PM_{2.5}$ fell temporarily by ~30–60%, but rebounded as activities resumed. Projections suggest that without strong intervention, rising energy demand will cause further increases in $PM_{2.5}$-related mortality by mid-century (Nandi et al., 2025; Narla et al., 2021; Saadat et al., 2021).

3.5. Trends and Statics from Maldives

As a low-lying island nation, the Maldives has no heavy industry, but air quality is affected by local and transported pollution (Sandaruwan et al., 2022). Male (the capital) has high population density and relies on diesel power plants and vehicle emissions, so its local $PM_{2.5}$ and NO_2 levels can exceed WHO limits (IQAir data suggest annual $PM_{2.5}$ around 12-15 µg/m³, roughly 2-3× the 5 µg/m³ guideline) (Herath Bandara & Thilakarathne, 2025). Particulate sources in the Maldives include vehicle exhaust, diesel generators (CO, NO_2, and $PM_{2.5}$), open burning of waste, and re-suspended road dust. However, long-range transport dominates: seasonal wildfire smoke (e.g. Indonesian peat fires) or dust (from Arabian or Thar deserts) often elevates background $PM_{2.5}$ over the islands. A modelling study for 2020 showed that anthropogenic $PM_{2.5}$ sources in the Maldives are relatively small; regional contributions (from India and Africa) make up most of the year's particulate load (Hameed & Ajmal, 2019). Ozone levels in the Maldives typically track regional tropical background (moderate), but could climb slightly with rising NO_x (Uddin et al., 2025).

3.6. Trends and Statics from Nepal

Nepal has among the worst air pollution in South Asia, especially in the Kathmandu Valley (Islam et al., 2020; Saud & Paudel, 2018). Recent monitoring shows that Kathmandu's annual $PM_{2.5}$ routinely exceeds the 2021 WHO guideline (5 µg/m³) by 4-12 times (i.e. 20-60 µg/m³ or more during 2017–2021) (N. T. K. Oanh, 2023). Outside Kathmandu, the densely populated Terai plains (Biratnagar, Bharatpur) also face $PM_{2.5}$ above 70 µg/m³ for much of winter (Avis, 2024). The chief local sources in Kathmandu are vehicular exhaust, brick kilns, road/soil dust, garbage burning and biomass combustion. An FHI/WHO report notes that residential (domestic) combustion is the largest $PM_{2.5}$ contributor nationwide, reflecting widespread wood and dung burning for cooking. Seasonal factors dominate: winter inversions trap pollutants and thousands of crop residues burned in nearby India bring haze, driving acute smog episodes. Diesel vehicles and two-stroke taxis emit large NO_2 and black carbon in Kathmandu's narrow valley, while brick kilns outside the city add soot. Kathmandu also receives some transboundary ozone and $PM_{2.5}$ from northern India (Balyan, 2021). Over time, Kathmandu's pollution has generally been worsening with population and vehicle growth, despite some regulation of kilns (Pradhan et al., 2020). During 2020 COVID lockdowns, Kathmandu saw ~20% lower $PM_{2.5}$ than 2019, but by 2021 values had rebounded above pre-2020 levels, reflecting insufficient controls. PM_{10} levels follow similar patterns but are usually exceeded by coarse road dust in summer. Ozone in Kathmandu is moderate but likely rising due to warmer conditions and VOC/NO_x precursors from traffic; health analyses link about half of Nepal's pollutant burden to ambient $PM_{2.5}$ and tropospheric ozone increases since 1990 (N. T. K.

Oanh, 2023). Notably, Nepal has the highest per-capita premature deaths from air pollution in South Asia, driven by fine particles (Das, 2022).

3.7. Trends and Statics from Pakistan

Pakistan experiences very high particulate and NO_2 pollution, especially in winter (Anjum et al., 2021; Khan et al., 2024). Lahore, Karachi and other large cities often see 24-hour $PM_{2.5}$ around 100–200 µg/m³ in winter 2020s (well above WHO's 15 µg/m³ daily guideline) (Ashraf et al., 2022). Major sources include transportation (cars, trucks, two- and three-wheelers), industry (power plants, brick kilns, manufacturing), and widespread biomass and waste burning (crop stubble, orchard pruning, landfill fires). A national study reports that 58% of NO_x emissions come from Pakistan's ~23.6 million vehicles, with industry and power plants providing most of the rest (Bilal et al., 2021). Vehicular emissions also produce large black carbon and CO. Rural areas contribute via open burning of animal dung and agricultural residues, raising background PM and NH_3 (which can form secondary ammonium nitrate aerosols) (Subhani et al., 2021). Natural dust from the Thar Desert and Middle East storms periodically raises PM_{10} (e.g. hot dry spring storms) (Jain et al., 2025; Santra et al., 2018).

In general, ambient $PM_{2.5}$ and PM_{10} have increased in recent decades in Pakistan, paralleling India (Anwar et al., 2021; Mehmood et al., 2020). Kathmandu Valley, Islamabad and Karachi have all recorded upward trends, despite intermittent government controls. Ozone levels are increasingly problematic in summer, as sunlight and heat drive photochemistry amid abundant NO_x and VOCs (similar to trends in Delhi). A source apportionment review notes that in Pakistan (and nearby Afghanistan), natural and industrial sources dominate $PM_{2.5}$ as much as vehicles (Singh et al., 2017), reflecting the high dust/dry soil component. Nonetheless, one analysis of sources in South Asia emphasizes that vehicles and industry are also key in Pakistan, along with agricultural ammonia emissions (fertilizer and livestock) (Qureshi et al., 2016). Pakistan's pollutant trends show chronic high PM (especially in Punjab and Sindh in winter), rising NO_2 with expanding cities, and significant CO. Climate change may worsen winter smog (if temperature inversions strengthen) and increase biomass burning (heat waves and droughts cause more forest and crop fires) (Iram et al., 2025).

3.8. Trends and Statics from Sri Lanka

Sri Lanka generally has the lowest urban pollutant levels among South Asian countries, but indoor and seasonal pollution still poses concerns (Rathnayake et al., 2023). Nationally, average $PM_{2.5}$ is on the order of 10–15 µg/m³ today (a few times the WHO guideline), with peaks in Colombo and suburban areas during dry season or biomass-burning events (Dhammapala et al., 2022; Ileperuma, 2020). Key sources are distinct: the vast majority of Sri Lankan households – mainly rural poor – use wood fuel for cooking (Elledge et al., 2012). This contributes both indoor PM and ambient $PM_{2.5}$ around villages. In cities like Colombo, traffic (petrol cars, aged diesel buses) dominates NO_2 and CO emissions; two-stroke three-wheelers used to be common CO sources, but their phase-out has helped. Industry in Sri Lanka is limited, so SO_2 levels are comparatively low except near coal-fired power plants (the Lakvijaya plant was equipped with low-sulfur coal only in the last decade). Seasonal crop residue burning in Tamil Nadu, India sometimes brings haze (westerly winds) that marginally raises the regional PM values (Sahu et al., 2021).

The Sri Lanka's air pollution trend has been relatively stable (Jegathesan et al., 2022). A gradual increase in vehicles has pushed CO and NO_2 up in the 2010s, but $PM_{2.5}$ in Colombo has not shown the explosive growth seen in South Asia's big cities. For example, one study found Colombo's $PM_{2.5}$ to be substantially lower than Delhi's, though still exceeding WHO targets a few-fold (Dhital, 2024). The dominance of domestic wood-burning means that any efforts to improve clean cooking (e.g. LPG, electric stoves) could yield significant public health gains. Importantly, Sri Lanka's tropical climate (high humidity and rain) helps disperse pollutants, but rising temperatures may lengthen pollen and mold seasons. Increased heat and UV radiation from climate change could also modestly boost ozone formation in urban areas (Gamage et al., 2025; Udawattha & Perera, 2025).

4. Respiratory Health Burdens: Evidence from South Asian Studies

The air pollution causes health risks to especially vulnerable population of the world. In South Asia, spikes in air pollution reliably precipitate acute respiratory episodes. Epidemiological studies in India have found that every 10 µg/m³ increase in ambient $PM_{2.5}$ is associated with approximately a 23% rise in reported acute respiratory infections among children (Adhikary et al., 2024). Similarly, regional analyses consistently link peaks in particulate matter and ozone to surges in asthma attacks and hospital visits. For example, a systematic review of Pakistan studies found highly significant correlations between daily $PM_{2.5}$, PM_{10}, SO_2 or NO_x levels and emergency asthma admissions in children and adults (Iram et al., 2025). Comparable findings have emerged in Bangladesh and Nepal, where smog episodes coincide with increased pediatric emergency visits and ARI diagnoses. In practical terms, this means that on days of very poor air quality – often due to wintertime inversions or agricultural burning – clinicians see an uptick in bronchitis, pneumonia and wheezing illnesses among young patients, underscoring the acute health burden of pollution in the region. The details and percentage diseases caused by air pollution are mentioned in **Figure 3**.

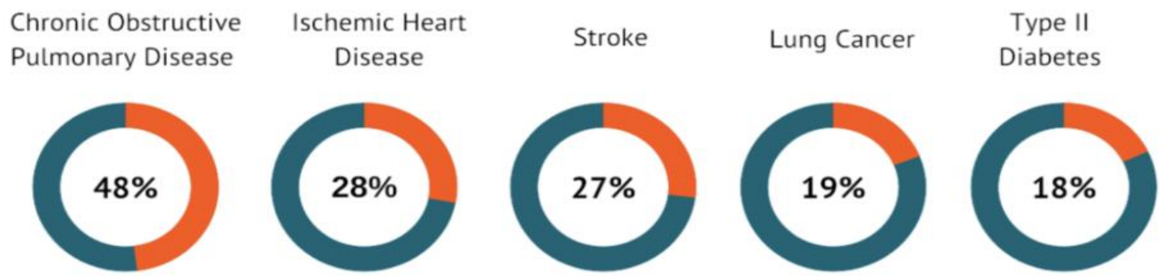

Figure 3. Worldwide deaths related to air pollution (SoGA, 2021).

Beyond these acute events, long-term exposure contributes to chronic respiratory disease. South Asia already bears disproportionately high baseline rates of asthma, chronic bronchitis and COPD, much of which is attributable to lifetime pollutant burdens (Akashanand et al., 2025; Irfan, 2024; Rana & Ghose, 2024). Air quality studies document that sustained exposure to $PM_{2.5}$, PM_{10} and other pollutants causes' progressive airway inflammation and lung function decline (Li et al., 2022). In Pakistan, for instance, decades of heavy pollution have been linked to rising incidence of chronic lung ailments: a recent review noted "documented adverse effects of air pollution on inflammation as well as the development and progression of chronic illnesses such as asthma and other respiratory diseases" (Iram et al., 2025). In Bangladesh the same fine particulates that trigger acute asthma also impair healthy development; high $PM_{2.5}$ has been associated with low birthweight and stunted growth – evidence of disrupted lung and immune development implying that polluted air in early life will underlie premature COPD in the coming decades (Daniel Nesan, 2025).

Certain groups suffer disproportionate impacts. Children, with developing lungs and higher minute ventilation rates, have the highest exposures per body weight. The Bangladeshi assessment of $PM_{2.5}$ notes that among children, pollution "exacerbates asthma, stunting, and cognitive impairment" (Daniel Nesan, 2025), illustrating how poor air leads to both more asthma attacks and lifelong deficits. The elderly and those with pre-existing respiratory or cardiovascular diseases are also heavily affected. In Pakistan, for example, community studies found that severe smog could reduce lung capacity by up to 40% in already-vulnerable patients (such as those with asthma or tuberculosis) (Iram et al., 2025). People with chronic bronchitis or heart disease experience proportionally greater declines in function on polluted days. Even social factors play a role: urban slum dwellers and rural women cooking with biomass for decades face extremely high chronic exposures, resulting in unusually high COPD prevalence among these groups (Zahra Naqvi et al., 2025).

Compounding the problem, climate extremes amplify pollution's impact. High heat and stagnant air bolster ozone formation and trap particles, imposing an extra burden on the lungs. Recent evidence underscores this synergy: a nationwide study in China found that days with concurrent heat waves and high ozone had much higher respiratory mortality than days with heat or ozone alone (Du et al., 2024). Biologically, heat stress and pollution converge on the same inflammatory pathways. Experiments show that heat induces reactive oxygen species (ROS) and heat-shock proteins that activate the NF-κB/NLRP3 inflammasome pathway, releasing pro-inflammatory cytokines, in the same way that pollutant-triggered ROS does (Sampath et al., 2023). Thus, a South Asian heat wave combined with haze can inflict far worse respiratory strain (heat stroke plus bronchitis) than either factor separately. The **Figure 4** shows the representation of global air pollution related deaths in 2021.

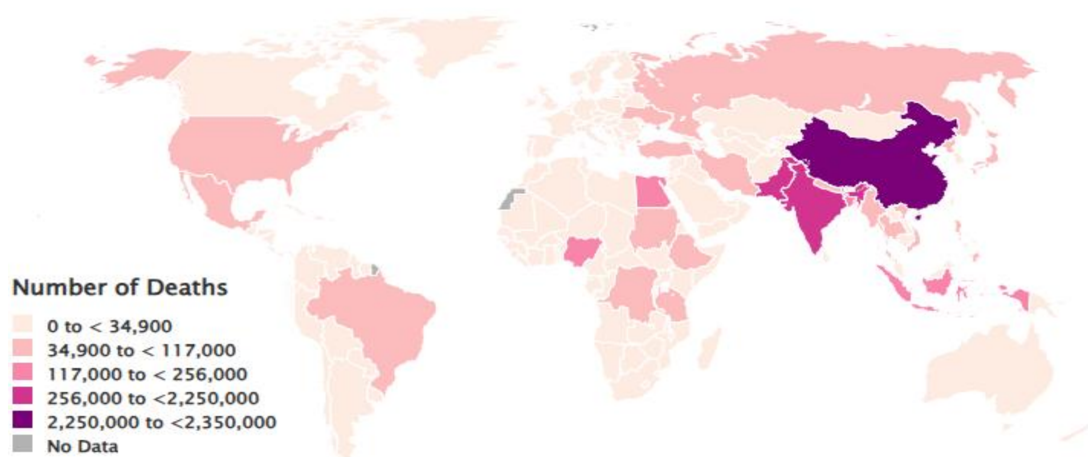

Figure 4. Geographical representation of deaths caused by air pollution in 2021 (SoGA, 2021).

5. Mechanisms of Injury and Climate–Pollutant Interplay

Air pollutants injure the respiratory tract through well-characterized molecular and cellular pathways. By far the dominant mechanism is oxidative stress. Inhaled particles and gases generate ROS in the airway lining fluid and in lung cells, overwhelming local antioxidant defenses and triggering cell injury. The World Health Organization notes that breathing air pollutants "leads to inflammation, oxidative stress, immunosuppression" and even mutagenicity in respiratory tract cells (WHO, 2024). For example, fine particulates ($PM_{2.5}$ and smaller) often carry adsorbed metals and organics; once deposited deep in the alveoli, these particles induce lung macrophages and epithelial cells to release ROS and pro-inflammatory mediators. This creates a self-amplifying cascade: pollutant-induced ROS activate the transcription factor NF-κB and the NLRP3 inflammasome, driving production of cytokines such as IL-1β, IL-6, IL-8 and TNF-α (Jin et al., 2024; Sampath et al., 2023; Zhang et al., 2023). In practical terms, each bout of pollution inhalation produces a local inflammatory response very similar to an infection, the airway is flooded with neutrophils, the endothelium becomes leaky, and mucus secretion increases. Repeated activation of these pathways damages airway tissue, impairs mucociliary clearance, and weakens the barrier against pathogens, explaining both the direct cell injury from pollutants and the heightened risk of infections or asthma exacerbations in exposed populations (Beentjes et al., 2022; Goossens et al., 2021; Woodby et al., 2021).

Beyond acute inflammation, these processes lay the groundwork for chronic airway disease (Goossens et al., 2021). Oxidative injury and cell signaling lead to long-term alterations in tissue structure. For instance, ozone a powerful oxidant – can directly damage epithelial cells and deplete antioxidants, contributing to bronchial hyper-responsiveness. Pollutant-driven inflammation also stimulates airway remodeling: repeated injury promotes subepithelial fibrosis, smooth-muscle hypertrophy and goblet-cell hyperplasia. Mechanistic studies show that components of particulate matter (such as polyaromatic hydrocarbons) can activate specific receptors in airway cells – for example, the aryl hydrocarbon receptor (AhR), which triggers overproduction of mucus (via genes like MUC5AC) (Holme et al., 2023; Sampath et al., 2023). This helps explain why chronic exposure leads not just to inflammation but to permanent functional changes (chronic bronchitis, fixed obstruction) in susceptible individuals. Systemically, very small particles can pass into the circulation, where they stimulate vascular oxidative stress and endothelial dysfunction, linking air pollution to cardiovascular and neurological harms as well. Thus, at the cellular level, inhaled pollutants initiate a chain of oxidative damage and immune signaling that can culminate in cell death, structural remodeling and immune dysfunction, the hallmarks of asthma, COPD and related diseases (Bezerra et al., 2023).

Importantly, many of the same pathways are also triggered by climatic stressors, highlighting the pollution–climate interplay. Heat stress, for example, independently generates ROS and heat-shock proteins that activate NF-κB and the NLRP3 inflammasome (Beentjes et al., 2022). In other words, high ambient temperature can initiate the same pro-inflammatory cascade as pollution. Studies in environmental immunology show that ozone exposure by itself increases bronchial inflammation and neutrophil influx in the lungs, and heat similarly elevates inflammatory mediators – thus, when heat and ozone co-occur, their effects on oxidative stress and inflammation can be additive or even synergistic. Furthermore, pollutants can alter immune balance: chronic $PM_{2.5}$ exposure tends to skew the airway immune response toward a Th2 (allergic) profile, exacerbating allergic asthma risk, while simultaneously impairing antiviral defense mechanisms (Wu et al., 2023). This immune modulation means that pollution and climate effects (like heat or allergen loads) often compound each other.

Climate change can also alter the nature and toxicity of air pollutants. Higher temperatures and more intense sunlight accelerate photochemical reactions, driving ozone formation from precursors that otherwise would have been harmless. Warmer, stagnant air also allows particulate pollution to accumulate near ground level longer. Perhaps most dramatically, climate-driven wildfires and dust storms inject new sources of toxic aerosol into the South Asian air. Wildfire smoke is a complex mixture of gases and ultra-fine particles laden with organic toxins and metals; particles ≤ 2.5 μm in wildfire smoke penetrate deeply into the lungs and carry potent inflammatory chemicals (Sampath et al., 2023). These climate-amplified pollutants can provoke severe oxidative stress far beyond typical urban PM. For example, South Asia has seen unprecedented smoke events from forest fires and massive dust storms, both of which carry particles that trigger intense inflammation (Kelly & Fussell, 2020). Models and experiments suggest that particles from biomass or fire have different, often higher, oxidative potential than traffic emissions, partly because they are rich in black carbon and organic radicals. Thus, as climate change increases the frequency of extreme events (heat waves, wildfires, dust storms), it simultaneously ramps up the toxicity and health impact of air pollution. In practice this means that not only does climate change worsen pollution levels, it changes pollutant composition toward more dangerous mixtures, a double whammy for lung health (Ofremu et al., 2024).

6. Economic Impacts of Air Pollution

The economic toll of polluted air in South Asia is immense. In Bangladesh, for example, the health-related costs of ambient $PM_{2.5}$ including hospital treatments and lost work – were estimated at about USD 11 billion in 2019 (roughly 4.4–4.8% of national GDP) (Daniel Nesan, 2025). India's losses are similarly staggering: the World Bank reports that in 2019 India lost about USD 28.8 billion in economic output due to premature deaths from pollution and another USD 8 billion from morbidity, for a total of USD 36.8 billion (about 1.36% of GDP) (Group, 2024). These calculations include not only direct healthcare spending on treatments for respiratory and cardiovascular illness, but also the value of lost lives and production. To put this in context, a global assessment estimated that air pollution cost the world an astonishing USD 8.1 trillion (6.1% of global GDP) in 2019 (Wang et al., 2024). Thus, South Asia's share of this burden is vast, reflecting both its large population and extremely poor air quality.

Beyond the headline GDP losses, air pollution inflicts measurable productivity declines. Workers exposed to dirty air take more sick days and experience decreased physical and cognitive performance. One analysis noted that globally about 2.6 trillion USD workdays are lost each year due to air pollution-related illness (Goyal, 2023; Kapoor et al., 2024; Kateja, 2021). In India alone, reduced labor productivity, absenteeism and pollution-caused mortality were estimated to cost the economy roughly USD 95 billion in 2019 (Kapoor et al., 2024). The impacts extend to education as well: studies in South Asia have found that on highly polluted day's school attendance drops and academic performance suffers, implying long-term human capital losses as ill children fall behind their peers. In rural and urban informal economies, chronic exposure also forces some workers (especially outdoor laborers) to scale back or forgo strenuous work, further shrinking household incomes. Although rigorous economic data on school and productivity loss in Asia remain limited, existing estimates clearly indicate that poor air translates directly into lost working and learning days, compounding the country-level economic losses (Wang et al., 2024).

Public health metrics further underscore the economic impact via years of healthy life lost. Air pollution is already among the leading risk factors for disease burden in South Asia. Disabilityadjusted life years (DALYs) – which combine premature mortality and years lived with disability are extremely high for pollution-related illnesses in the region. Forecasting studies show that India, Pakistan and Bangladesh have the highest particulate matter–attributable DALY rates in the SAARC countries (Amer et al., 2024). In other words, a large and growing fraction of healthy life years in these countries is being lost to chronic respiratory disease and cardiovascular events caused by air pollution. Moreover, ozone pollution contributes substantial respiratory DALYs in Bangladesh and Pakistan.

7. Policy Responses and Public Health Strategies in South Asia

Recognizing the severe health and economic toll, South Asian countries have begun to implement comprehensive air quality strategies. India's National Clean Air Programme (NCAP) is a prominent example: launched in 2019, it mandates time-bound improvements in air quality across the country, focusing initially on around 132 cities that consistently violate national standards (Guttikunda et al., 2025). NCAP provides each city with a framework to develop localized action plans and guidance for cross-sector policies. Legislative action has complemented these programs; for example, India's Parliament in 2021 approved the Commission for Air Quality Management (CAQM) to coordinate pollution control across the National Capital Region and adjoining states (Jain & Mittal, 2022). Bangladesh has similarly enacted a Clean Air Act and begun rolling out urban clean air action plans, while Nepal and Sri Lanka are tightening vehicle emission norms and expanding monitoring networks (Ness et al., 2021). At the regional level, multilateral agencies emphasize airshed-wide approaches. The World Bank notes that India and its neighbors are developing a first-ever regional air-quality plan for the Indo-Gangetic Plain, a vast air shed spanning seven states, recognizing that air pollution does not respect political boundaries (Group, 2024).

Community-level adaptation and surveillance are also advancing. Many South Asian cities now host real-time monitoring networks and alert systems to inform the public on hazardous air days. For instance, government and civil society have deployed thousands of low-cost sensors and air quality forecast systems (such as India's SAFAR network in Delhi and other metros) to issue alerts before severe smog events. Public health programs are integrating these data into practice: India's National Program on Climate Change and Human Health, for example, has begun surveillance of pollution- and heat-related illnesses in partnership with local hospitals, providing early warning capabilities (Kumar et al., 2020). State and municipal governments are developing climate-health action plans that incorporate air quality monitoring, ensuring that vulnerable communities (children, the elderly) receive timely warnings and guidance on mitigating exposure. Grassroots efforts are also important: community tree-planting, urban green buffers and clean-cooking campaigns help reduce local concentrations and provide some relief from heat. The local adaptation strategies in South Asia increasingly combine technological fixes (sensors and forecasts) with public education and infrastructure changes (better stoves, shaded playgrounds) to protect health in the short term as broader pollution controls take effect (Purohit et al., 2024; Sterrett, 2011).

Finally, mitigation measures are being pursued for their dual climate and health co-benefits. South Asia's development policies are increasingly aligned with cleaner air goals. India, for example, has aggressively expanded its use of liquefied petroleum gas (LPG) for household cooking and subsidized cleaner vehicles: millions of households have been shifted from biomass stoves to LPG, and incentives for electric vehicles are being rolled out nationwide. These steps cut both carbon emissions and particulate pollution. Similar policies in other countries such as phasing out coal-fired power, improving fuel quality and moving transit to electric or CNG vehicles – offer a double dividend of improved air quality and reduced greenhouse gases. Analysts emphasize that targeting the common sources of air pollution and carbon (transport, energy, waste burning) yields large combined gains. For example, better waste management that eliminates open burning can reduce black carbon and methane at once. In practice, mitigation strategies often include expanding renewable energy, enforcing stricter industrial emission standards, promoting public transit and enhancing urban planning (e.g. planting trees to cool cities). These measures reduce concentrations of $PM_{2.5}$, NO_x and ozone precursors while moving South Asian economies toward cleaner growth (Abdul Jabbar et al., 2022; Herath Bandara & Thilakarathne, 2025).

8. Recommendations

The current environmental policies, while demonstrating progress in pollution mitigation, inadequately address population-weighted exposure to airborne particulate matter (PM2.5/PM10), which is projected to increase by over 50% by 2030 under current economic growth trajectories. Accelerated urbanization and industrial expansion across South Asia threaten to expose approximately four billion individuals to ambient pollution levels exceeding WHO safety thresholds. However, integrating emissions-control technologies and regionally coordinated clean air initiatives could enable over 650,000 residents to attain compliant air quality standards within this timeframe.

A critical barrier to progress lies in urban air quality governance, particularly in low- to middle-income South Asian nations where financial constraints hinder large-scale deployment of reference-grade monitoring infrastructure. While automated analyzers reduce operational labor, their prohibitive costs incentivize exploration of low-cost sensor networks. These emerging systems, however, face technical limitations including cross-sensitivity to non-target pollutants, meteorological interference, and progressive calibration drift, necessitating robust quality assurance protocols. Effective pollution management further requires institutional frameworks for continuous data interpretation, regulatory enforcement, and cross-jurisdictional collaboration between national and provincial authorities. Sectoral emission apportionment studies reveal disproportionate focus on vehicular sources, exemplified by India's decades-old inspection and maintenance program, which has yielded limited air quality improvements despite its regional longevity. While all South Asian governments maintain vehicular emission task forces, systemic gaps persist in addressing parallel contributors: industrial point-source emissions, traffic congestion, and diffuse community-level pollution from biomass combustion and open waste incineration.

Strategic interventions should prioritize:

- Deployment of geospatial mapping technologies to localize emission hotspots in urban centers.
- Mandatory emissions compliance certifications for high-polluting industries and annual in-use vehicle inspections.
- Establishment of a multilateral technical consortium to standardize monitoring practices, share mitigation strategies, and harmonize emission thresholds across the region.

This integrated approach underscores the necessity of transcending sector-specific policies in favor of holistic, data-driven governance frameworks that align economic development with atmospheric carrying capacities. Future research should quantify the cost-benefit ratios of hybrid monitoring systems and evaluate policy efficacy through broad health impact assessments.

9. Conclusion

The intricate interplay between climate change and air quality degradation in South Asia presents a formidable public health challenge, with profound implications for respiratory health. This synthesis underscores that rising temperatures, shifting meteorological patterns, and climate-amplified extreme events exacerbate atmospheric stagnation, photochemical ozone formation, and particulate pollution, disproportionately affecting vulnerable populations. Regional urbanization, industrialization, and biomass combustion coupled with transboundary pollution—have entrenched South Asia as a global hotspot for $PM_{2.5}$ and ozone exposure, driving alarming rates of asthma, COPD, and premature mortality. Economic analyses reveal staggering losses, with pollution-related health costs consuming 1.36-4.8% of national GDPs, underscoring the urgency of intervention.

Current policies, though progressive, remain fragmented, often prioritizing vehicular emissions while neglecting industrial, agricultural, and community-level sources. The region's limited air quality monitoring infrastructure and financial constraints further impede effective governance. Strategic integration of geospatial hotspot mapping, stringent emission controls, and multilateral cooperation is critical to address pollution's transboundary nature. Simultaneously, climate adaptation measures such as urban greening and clean energy transitions offer co-benefits for both air quality improvement and carbon mitigation. Future efforts must prioritize data-driven policymaking, emphasizing health impact assessments and cost-benefit analyses of hybrid monitoring systems.

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Dear Client, add the statement here…

Conflict of Interest

The author(s) has no conflict of interest to declare.

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