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Spatiotemporal Analysis of Air Quality Index (AQI) in Pakistan: Implications for Public Health and Policy Interventions

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ABSTRACT

Pakistan's major cities regularly rank among the most polluted in the world, and air pollution has worsened into a serious environmental and public health crisis. This thorough review synthesizes data from several monitoring networks and satellite observations to analyze spatiotemporal AQI patterns throughout Pakistan from 2010 to 2024. Persistent hotspots with significant seasonal degradation during winter smog episodes are identified by the analysis in urban-industrial corridors, especially the Lahore-Sheikhupura-Kasur triangle. The most prevalent pollutant is fine particulate matter ($PM_{2.5}$), which is mostly produced by industrial combustion, agricultural burning, transboundary pollution, and vehicle emissions. Vulnerable populations are disproportionately affected by the review, which demonstrates dose-response relationships between AQI levels and neurological effects, cardiorespiratory morbidity, and all-cause mortality. Implementation issues continue despite policy frameworks because of poor interagency coordination, insufficient monitoring infrastructure, and lax enforcement. To lessen this public health emergency, this review ends with urgent recommendations for evidence-based interventions.

INTRODUCTION

One of the biggest environmental health risks in the world is ambient air pollution, which causes about 6.7 million premature deaths each year from lung cancer, acute respiratory infections, chronic obstructive pulmonary disease, ischemic heart disease, and stroke (1). People and policymakers can now better understand current air quality conditions and related health risks thanks to the Air Quality Index (AQI), a vital public communication tool that converts complicated data on air pollutant concentrations into an easy-to-understand, color-coded numerical scale (2). Long-term spatiotemporal analysis of AQI, which forms the foundation of evidence-based air quality management, offers priceless insights into pollution trends, source contributions, and regulatory effectiveness in addition to its daily advisory role.

Air pollution in Pakistan has become an unprecedented public health emergency, rather than just an environmental issue. Conditions for significantly worsened air quality have been brought about by a number of factors, including unplanned, fast urbanization; the spread of inefficient vehicles; widespread industrialization with few emission controls; energy crises that encourage the use of inferior fuels; and unsustainable agricultural practices (3). Large cities like Lahore and Karachi are regularly ranked among the most polluted in the world, especially in the winter when extended smog episodes cover entire regions. Transboundary pollution exacerbates this degradation, posing a complicated problem that requires immediate attention (4).

The lack of a unified, nationwide perspective that captures both spatial heterogeneity and temporal evolution hinders the development of coherent, effective national strategies. As a result, this review aims to consolidate and analyze available AQI data across Pakistan's diverse geographical and industrial landscape from 2010 to 2024. Our three main goals are to: critically evaluate the relationships between AQI levels and public health outcomes while identifying vulnerable populations; identify critical policy gaps while proposing evidence-based interventions for sustainable air quality management; and to gain a thorough understanding of air pollution patterns throughout Pakistan remains fragmented despite the severity of this crisis.

Overview of Air Quality and AQI Measurement

A standardized metric for measuring and informing the public about ambient air pollution levels is the Air Quality Index. In order to calculate the AQI, measured concentrations of important criterion pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ground-level ozone (O_3), and particulate matter ($PM_{2.5}$ and PM_{10}) are converted into a single, easily comprehensible number (5). The overall AQI value is the highest value among these sub-indices, and this calculation usually uses piecewise linear functions that define sub-indices for each pollutant (6). This "one-out, all-out" strategy guarantees that the index always represents the most important pollutant. An efficient risk communication tool is produced by classifying the final numerical value into scales (e.g., 0-50 "Good," 51-100 "Moderate," 101-150 "Unhealthy for Sensitive Groups"), each of which has corresponding color codes and health advisories (7).

A diverse range of national and international data sources make up Pakistan's AQI monitoring infrastructure. Federal and provincial Environmental Protection Agencies are primarily in charge of this, and they primarily keep a small number of ground-based monitoring stations in large cities (8). Researchers are increasingly using data from international platforms such as IQAir, satellite-derived aerosol optical depth measurements from MODIS (NASA) and TROPOMI (Copernicus), and modeled estimates from WHO and IHME databases to make up for the limitations of spatial coverage. Despite infrastructure limitations, a more thorough spatial analysis is made possible by this multi-source approach (9).

There are still major issues with data comprehensiveness and reliability. Critical coverage gaps in secondary cities and rural areas, operational outages, and irregular calibration plague Pakistan's ground monitoring network (10). Although satellite data is useful for providing spatial context, it is not always able to accurately capture near-surface pollutant concentrations, especially for complex terrains and certain pollutants like NO_2 and O_3 (11). Moreover, careful harmonization and validation are necessary when integrating data from various sources, each of which has unique methodologies and possible biases. These restrictions highlight the critical need for updated and expanded monitoring infrastructure as a cornerstone of efficient air quality management and call for careful interpretation of AQI trends (12).

Spatiotemporal Patterns of AQI in Pakistan

Spatial Distribution: Significant variation in Pakistan's AQI is revealed by spatial analysis, with distinct pollution hotspots. During peak pollution episodes, the province of Punjab, especially the Lahore metropolitan area, regularly records the highest annual average AQI values in the country, often surpassing WHO $PM_{2.5}$ guidelines (5 µg/m^3) by more than 15 times (13). Karachi, Faisalabad, Gujranwala, and Multan are other notable urban-industrial hotspots where chronic air quality deterioration is caused by high traffic density, population concentration, and ongoing industrial activity (14). Although air quality is still alarming and frequently exceeds national standards, cities such as Islamabad and Quetta have somewhat better air quality in comparison (15).

The Lahore-Sheikhupura-Kasur industrial triangle, which is home to numerous steel mills, fertilizer plants, and traditional brick kilns, has been identified as a region with high levels of pollution by geographic information system (GIS) analyses and satellite imagery (16). The necessity of regional airshed management strategies is highlighted by this spatial clustering. Although there is still a noticeable rural-urban divide, it is closing as transboundary dust, long-distance urban pollution transport, and localized agricultural burning practices have a greater influence on rural areas (17). The growing geographic reach of Pakistan's air quality problem is further evidenced by recent studies that pinpoint new hotspots in formerly under-observed regions like Hyderabad and Peshawar (18). Figure 1.0 shows the factors which effect the AQI;

Figure 1

Factors Effecting the AQI in Pakistan

Temporal Trends: Over a number of timescales, Pakistan's AQI shows significant and consistent temporal variability. Particularly in the Indus Basin, seasonal patterns are especially noticeable, with severe smog episodes occurring during the post-monsoon and winter months (October–February) (19). These occurrences are caused by a combination of increased emissions from burning agricultural residue, increased combustion of fossil fuels for heating, and increased industrial activity, as well as by weather inversions that trap pollutants close to the surface (20). During the summer, there are usually higher levels of coarse particulate matter (PM_{10}) because of frequent dust storms from the Thar and Cholistan deserts, as well as contributions from local sources. Wet deposition, which efficiently scavenges particulate pollutants from the atmosphere, offers a brief reprieve during the monsoon season (July to September) (21).

Analyzing long-term trends shows alarming trends. The majority of monitoring sites exhibit statistically significant increases in annual mean $PM_{2.5}$ concentrations between 2010 and 2024, with especially noticeable gradients since 2016. Event-based spikes are clearly associated with episodic forest fires, religious fireworks celebrations, and agricultural burning periods (April-May and October-November) (22). By modifying atmospheric conditions that affect pollutant formation, transport, and deposition, recent data indicate that the effects of climate change, such as altered precipitation patterns and more extreme temperatures, may be aggravating these temporal patterns. Complex temporal dynamics are produced by the combined effects of these meteorological and emission factors, necessitating advanced modeling for precise forecasting and efficient management (23).

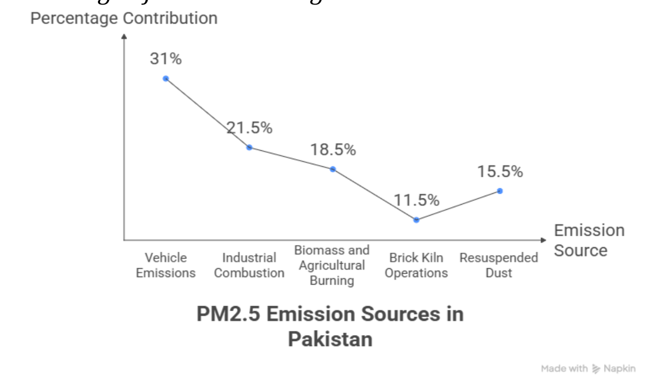
Major Pollutants and Emission Sources

Particulate Matter ($PM_{2.5}$ and PM_{10}): The main cause of Pakistan's poor air quality index (AQI) and the pollutant of greatest health concern is particulate matter, especially fine $PM_{2.5}$ (24). Vehicle emissions (24–38%), industrial combustion (15–28%), biomass and agricultural burning (12–25%), brick kiln operations (8–15%), and resuspended dust (10–20%) are among the major sectors that contribute, according to source apportionment studies and it is illustrated in figure 2.0 (25). Significant spatial and temporal variation can be seen in the relative contributions of these sources; in major metropolises such as Karachi and Lahore, vehicle emissions are the main source, whereas in peri-urban and rural Punjab and Sindh, brick kilns and agricultural burning are the main sources (26).

Concerning amounts of black carbon (8–15%), organic carbon (20–35%), sulfate (12–20%), and heavy metals like lead, arsenic, and cadmium are revealed by the chemical composition of $PM_{2.5}$ (27). These components have different health effects; heavy metals are carcinogenic and neurotoxic, while black carbon is linked to cardiovascular effects (28). During dust storm events, concentrations of coarse particulate matter (PM_{10}) often surpass 500 $\mu g/m^3$, indicating greater seasonal variability and a stronger correlation with crustal elements (29). Particulate matter's size distribution and chemical speciation have significant ramifications for creating focused control plans and comprehending the related health effects.

Figure 2

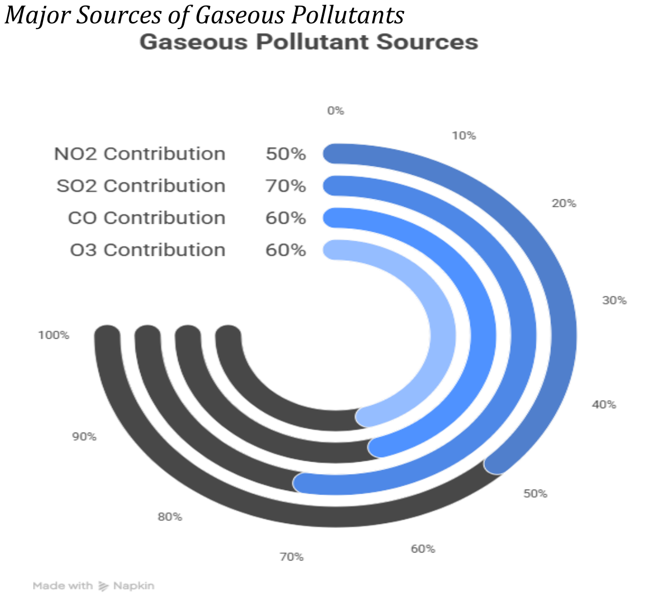
Percentage of Sources through which $PM_{2.5}$ Emits



Gaseous Pollutants (NO_2, SO_2, CO, O_3): The burden of air pollution and related health hazards in Pakistan is largely caused by gaseous pollutants. Fuel combustion processes are the main source of nitrogen dioxide (NO_2), with the transportation sector accounting for the largest share (48–62%), followed by power generation (18–25%) and industrial activities (12–20%) and it is illustrated in figure 3.0 (30). Growing emissions from these sectors are reflected in the NO_2 tropospheric columns over major urban centers, which are shown to be steadily increasing by satellite observations. The main sources of sulfur dioxide (SO_2) emissions are the combustion of coal and oil in thermal power plants and industrial processes; major point sources can be identified using remote sensing (31). As a helpful tracer for pollution linked to transportation, carbon monoxide (CO) exhibits a strong correlation with traffic density and incomplete combustion processes (32). The complex formation mechanisms of ground-level ozone (O_3), a secondary pollutant produced by photochemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs), are influenced by precursor emissions and meteorological conditions (33). Peak O_3 concentrations typically occur during summer months when intense sunlight and high temperatures accelerate photochemical reactions, though recent studies document elevated wintertime O_3 in some regions, indicating changing atmospheric chemistry. Regulatory strategies that must address both primary emissions and secondary formation processes face difficulties due to the changing mix of these gaseous pollutants (34).

Figure 3

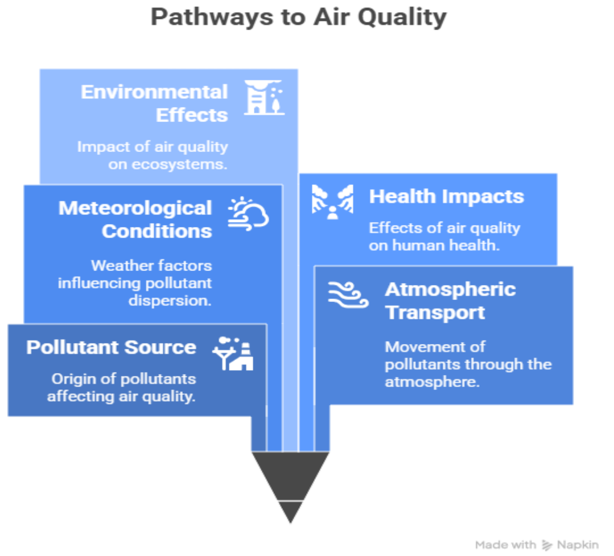
Major Sources of Gaseous Pollutants



Regional Source Contributions: As a helpful tracer for pollution linked to transportation, carbon monoxide (CO) exhibits a strong correlation with traffic density and incomplete combustion processes (35). The complex formation mechanisms of ground-level ozone (O_3), a secondary pollutant produced by photochemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs), are influenced by precursor emissions and meteorological conditions (36). Peak O_3 concentrations typically occur during summer months when intense sunlight and high temperatures accelerate photochemical reactions, though recent studies document elevated wintertime O_3 in some regions, indicating changing atmospheric chemistry (37). Regulatory strategies that must address both primary emissions and secondary formation processes face difficulties due to the changing mix of these gaseous pollutants.

Figure 4

Major pathways of Air Quality



Westerly disturbances, convective mixing, and orographic influences are some of the atmospheric mechanisms that enable long-range transport by establishing pathways for the entry and distribution of pollutants (38). According to recent modeling research, these transport patterns may be changing due to climate change, which could lead to an increase in the frequency and severity of transboundary pollution episodes. It will take concerted international efforts that recognize the commonality of atmospheric systems and establish collaborative research, monitoring, and mitigation plans throughout South Asia to address these regional contributions (39).

Public Health Implications

Strong correlations between high AQI levels and unfavorable health outcomes are regularly shown by epidemiological data throughout Pakistan. Daily PM_2 concentrations and hospitalizations for exacerbations of asthma (relative risk [RR]: 1.12, 95% CI: 1.08-1.16 per 10 $\mu g/m^3$ increase), chronic obstructive pulmonary disease (RR: 1.08, 95% CI: 1.04-1.12), and pneumonia (RR: 1.05, 95% CI: 1.02-1.08) are significantly correlated, according to time-series analyses carried out in several cities (40). Residents of high-pollution areas have a higher incidence of life-threatening conditions, such as ischemic heart disease (hazard ratio [HR]: 1.24, 95% CI: 1.16-1.33) and stroke (HR: 1.19, 95% CI: 1.11-1.28), according to long-term exposure studies (41).

There are worrying neurological effects in addition to cardiorespiratory ones, according to new research. According to prospective cohort studies, exposure to $PM_{2.5}$ is linked to increased risk of neurodegenerative diseases, neurodevelopmental disorders in children, and cognitive decline in older adults (42). Systemic inflammation, oxidative stress, and direct translocation of ultrafine particles to the central nervous system are the mechanisms that underlie these effects. Negative pregnancy outcomes (low birth weight, preterm birth), metabolic disorders, and elevated all-cause mortality are additional health endpoints associated with exposure to air pollution. The multisystem nature of this public health threat is highlighted by the various pathophysiological pathways through which air pollutants impact human health (43).

Exposure to air pollution disproportionately affects vulnerable populations' health. Because their organs are still developing, their breathing rates are higher, and they spend more time outside, children are more vulnerable (44). Children in high-exposure environments have been shown to have neurodevelopmental deficits, a higher incidence of asthma, and impaired lung function growth. Acute exacerbations and mortality after pollution episodes are more likely to occur in older people and those with pre-existing cardiorespiratory disorders (45). Due to occupational exposures, restricted access to healthcare, and residential proximity to pollution sources, socioeconomically disadvantaged communities face increased risks (46). The environmental justice aspects of air pollution and the necessity of specific protective measures for vulnerable subgroups are highlighted by these disparities.

Policy Framework and Future Directions

Strategic interventions in a number of areas are needed to transform Pakistan's air quality management system. Priority tasks ought to consist of:

- **Monitoring Infrastructure Improvement:** Create a high-density nationwide network for monitoring air quality by combining satellite data, inexpensive sensors, and reference-grade stations via a centralized open-data platform (47). Improved chemical speciation capabilities and source-oriented monitoring close to significant emissions sources should be part of this.
- **Transportation Sector Transformation:** Prioritize investments in mass transit and non-motorized transport infrastructure, expedite the transition to Euro 5/6 equivalent vehicle standards, establish thorough vehicle inspection and maintenance programs, and encourage the adoption of electric vehicles through targeted incentives (48).
- **Industrial Emission Control:** Encourage clean production technologies, support brick kiln modernization with financial incentives and technical assistance, and enforce National Environmental Quality Standards through continuous emission monitoring systems at significant industrial facilities (49).
- **Agricultural Management:** Use technology promotion (e.g., happy seeders), financial incentives for residue collection, and regulatory enforcement in conjunction with farmer education to implement alternatives to burning crop residues (50).
- **Energy Transition:** To lower emissions linked to combustion, hasten the switch from fossil fuels to utility-scale renewable energy, encourage distributed solar generation, and increase energy efficiency across

all sectors (51).

- **Regional Cooperation:** Create official frameworks for managing transboundary air pollution via diplomatic channels. These frameworks should include data sharing, shared monitoring, and coordinated mitigation plans with surrounding nations (52).
- **Public Engagement:** Put in place thorough health literacy campaigns about air pollution, set up explicit procedures for communicating risks, and encourage community involvement in advocacy and monitoring (53).

Research Gaps and Recommendations

Even though Pakistan's air quality crisis is becoming more widely acknowledged, there are still large knowledge gaps that make it difficult to create and implement effective policies. Priorities for critical research include:

- **High-Resolution Source Apportionment:** To measure contributions from various sectors and determine priority sources for intervention, conduct source apportionment studies using chemical speciation throughout the year in all major urban centers (54). Seasonal variability in source profiles and sophisticated receptor modeling techniques should be used in these investigations.
- **Advanced Exposure Assessment:** To produce high-resolution exposure maps, develop complex exposure models that combine satellite observations, ground monitoring, weather information, and land use characteristics (55). Use wearable sensors to conduct personal exposure monitoring studies in order to record activity patterns and microenvironments.
- **Health Impact Research:** Create longitudinal cohorts to look into how exposure to air pollution affects health over the long run, especially for vulnerable groups (56). Boost the capacity for health impact assessments to measure the burden of disease caused by various contaminants and sources.
- **Atmospheric Process Studies:** Examine secondary pollutant formation mechanisms, atmospheric transformation processes, and pollutant transport pathways using modeling and focused field campaigns (57). Increase knowledge of how changing weather patterns brought about by climate change affect air quality.
- **Intervention Effectiveness Evaluation:** Create reliable methods for evaluating the success of pollution control initiatives using controlled comparisons and before-and-after intervention studies (58). Create monitoring systems that are especially intended to assess the effects of policies.
- **Implementation Science Research:** Examine the behavioral, political, and economic factors that influence the success of policy implementation, such as stakeholder analysis, institutional capacity evaluation, and barrier identification (59). Create context-specific tactics to get past implementation obstacles.
- **Integrated Assessment Modeling:** To determine the best course of action, develop thorough models that connect emission scenarios, atmospheric processes, exposure patterns, health effects, and economic ramifications (60). Co-benefits from mitigating climate change should be included in these models.

Coordinated investments in scientific capacity, improved data infrastructure, and improved cooperation between academic institutions, governmental organizations, and foreign partners are necessary to address these research priorities. To move from general pollution control strategies to focused, economical interventions that optimize public health protection, this body of evidence must be expanded.

CONCLUSION

According to this thorough analysis, Pakistan is dealing with a serious and worsening air quality crisis that has significant ramifications for environmental sustainability, economic growth, and public health. Our analysis shows distinct spatiotemporal trends, with hazardous conditions, particularly during winter smog episodes, occurring in established pollution hotspots in urban-industrial corridors, especially Punjab's Lahore-Sheikhupura-Kasur triangle. The most concerning pollutant is fine particulate matter ($PM_{2.5}$), which comes from a variety of sources such as industrial combustion, agricultural burning, transboundary contributions, and vehicle emissions. With proven links between exposure to air pollution and elevated cardiorespiratory morbidity, neurological impairment, and premature mortality, the public health repercussions are widespread and dire, disproportionately impacting vulnerable populations.
Implementation issues, such as lax enforcement, poor monitoring systems, and little interagency coordination, have halted significant advancements despite established policy frameworks. Urgent, coordinated action is needed to address this crisis on several fronts, including bolstering air quality monitoring networks, enforcing sector-specific emission controls, encouraging the switch to renewable energy, developing regional cooperation, and increasing public participation. Building solid scientific evidence through focused research, enhancing institutional capability, and gaining ongoing political support at all governmental levels are essential for future success. To mitigate this public health emergency and guarantee healthier, more sustainable development for present and future generations, Pakistan must adopt comprehensive, evidence-based, and vigorously implemented strategies. The time for incremental approaches is over.

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