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Climate Change Implications of Smog in Pakistan: Amplifying Factors and Health Burden of PM2.5 Exposure

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ABSTRACT

Air pollution and climate change together represent a severe threat to the environment and public health in Pakistan. To clarify this complex interaction, this narrative and integrative review reviews all relevant information from national datasets, international reports, and the most recent climate-related health literature. The results indicate that various climate factors, such as rising temperature anomalies, reshuffling of the monsoon, and more frequent temperature inversions, are not only contributing to the intensification and persistence of smog events in the Indus Basin, but also that the exposure to PM2.5, the main pollutant in this smog, can have serious adverse implications for health: more recent evidence suggests that airborne particulate matter is responsible for a significant fraction of urban adult deaths. The assessment identifies growing risks of metabolic disorders, cardiopulmonary illnesses, and adverse reproductive outcomes associated with cumulative exposure to PM2.5, which is an increased concern when socio-economic and demographic vulnerabilities are taken into consideration. There still exists a substantial gap between science and policy, even in situations of clear and sometimes imminent threats. The assessment noted an urgent need for a framework for integrated mitigation to address both threats simultaneously, whether through the acceptance of Pakistan's clean air commitments and National Climate Change Policy, technological innovation, and/or nature-based solutions, and/or through strong regional cooperation.

INTRODUCTION

Pakistan is at a critical stage with regard to environmental degradation, which is made more complex by climate change as a regional manifestation of a global issue of climate change. The link between the two environmental crises is most evident with the thick layer of toxic smog that blankets the metropolitan cities of Pakistan for months every year. Cities like Lahore, Faisalabad, and Karachi consistently rank among the top polluted cities in the world, and what was once thought of as a seasonal winter nuisance has now transformed into a chronic public health crisis (1). The complexity of the origins of smog in South Asia can be attributed to a mixture of increased local human emissions and shifts in the prevailing meteorological patterns that have led to the creation of a perfect storm of conditions to allow the accumulation of air pollutants. In this case, climate change enhances local conditions through changing atmospheric processes that induce the formation, increase, and duration of airborne pollutants such as PM2.5. As there is a lack of altered patterns of precipitation and wind patterns to disperse the toxic air, climate change continues to compound the threat by increasing surface average temperatures that accelerate the photochemical reactions that generate secondary aerosols, thus ultimately causing people to be trapped under a dangerous umbrella of air (2). Therefore, the activities that generate climate change are also related to generating the pollutants that make up smog, and the related climate change will exacerbate the issues related to air quality.

PM2.5, or fine particulate matter with a diameter under 2.5 micrometers, is a central issue for environmental and public health. These small particles are a potent indicator of climate health, reflecting the volume of fossil fuel combustion resulting from industries and automobiles, and biogenic emissions from agricultural practices in their atmospheric quantity and composition (3). Climate dynamics are also directly induced through physical pollution, where pollutants like black carbon can cause warming within the atmosphere. At the same time, particulates can also directly connect emission events with the health of populations through deep penetration into the respiratory system and bloodstream, evidence of the extensive health impacts neglecting the environment can cause (4). Pakistan's urban areas are at a tipping point, specifically in Punjab, where the smog problem originates. It is evident, based on the closure of business and schools, cancellation of flights, and general stalling of life during peak smog episodes, that there is systemic failure of environmental governance (5).

The rationale for this review is strong and achievable since it will provide a holistic evaluation of the quantified health and socioeconomic burden of PM2.5 exposure in Pakistan's population and will systematically map and explore the mechanistic pathways involving climate change and intensified smog. The review's significance is that it can potentially coalesce independent research fields (e.g., atmospheric science, climate policy, public health, and economics) into a cohesive narrative that demands immediate, evidence-based action. In an effort to provide a comprehensive and targeted discussion of a worsening crisis, this review seeks to incorporate the latest literature from 2020- 2025. In doing so, it will address the linked risks to the population in Pakistan and consider integrated, cross-sector responses commensurate to the scale of the challenge in Pakistan.

METHODOLOGICAL FRAMEWORK

Search Strategy and Data Sources

To find relevant literature that was primarily published from 2010 to 2025, this review employed a systematic search strategy. Specifically, to help capture more recent publishing trends, this review emphasized research originating after 2020. Electronic databases, including PubMed, Scopus, and ScienceDirect, were comprehensively searched using a mixture of keywords and Boolean operators: ("smog" OR "PM2.5" OR "air pollution") AND ("climate change" OR "global warming" OR "meteorology") AND ("Pakistan" OR "South Asia"). Reports on and from the World Health Organization (WHO), United Nations Environment Program (UNEP), the World Bank, Environmental Protection Agency (EPA) Pakistan, and LEAD Pakistan were also reviewed to incorporate more of the national context and grey literature (6).

Inclusion and Exclusion Criteria

We only included studies that explicitly related smog formation, PM2.5 exposure, and climate-related impacts in Pakistan or a larger South Asian context with similar emissions and atmospheric conditions. This included policy analyses, atmospheric modeling papers, and epidemiological research on health outcomes. Studies that are not peer-reviewed, papers that are only technical atmospheric modeling that are not clearly connected to health or climate impacts, or studies focusing on pollutants other than PM2.5 with no clear connections were excluded.

Data Synthesis

To present a well-reasoned argument about the connections between Pakistan's smog emergency, the narratives extracted were grouped thematically under the three climate, environmental, and epidemiological dimensions using a narrative, integrative synthesis process.

Climate Drivers and Atmospheric Dynamics of Smog in Pakistan

In Pakistan, smog is not only produced by emissions but also substantially affected by a series of climate-sensitive meteorological and atmospheric factors that together help create a suitable environment for the accumulation of air pollutants. Over the Indus Basin, the interplay of local topography, regional meteorology, and global climate patterns produces a trapping mechanism, especially during the winter and post-monsoon seasons.

Atmospheric Chemistry and Photochemical Reactions

Primary pollutants (e.g., nitrogen oxides [NOx] from industry and vehicles, sulfur dioxide [SO_2] from coal combustion and industry, volatile organic compounds [VOCs] from fuel evaporation and industrial processes, and ammonia [NH_3] from livestock and agricultural fertilizer use) interact in complicated ways to produce the atmospheric chemistry of smog. These precursors rapidly undergo photochemical reactions to produce secondary pollutants, such as ground-level ozone and secondary aerosols, which make up a significant portion of PM2, under high temperatures, which are becoming more frequent due to climate change (5) (8). A 2024 study found that pollution and climate change are very much linked, showing that in Lahore, the rate of sulfate formation in the atmosphere increases by 2x for every 5° C increase in temperature. Furthermore, a 2025 study demonstrated that high temperatures and humidity significantly elevate the oxidative potential of PM2.5 from Pakistan, or its ability to cause cell damage, leading to a more toxic mix of pollution during smog events (9).

Meteorological Trapping and Stagnation

The trapping of these pollutants is primarily governed by climate feedbacks. Temperature inversions, when a warm air mass rests over a cooler, surface-based air layer, inhibit the vertical dispersion of pollutants. In a recent study, the authors reported a 30 percent increase in the intensity and frequency of wintertime inversions in the Indo-Gangetic Plain, which is a significant portion of Pakistan's breadbasket, over the past 20 years (10). Due to low wind speeds, there is less horizontal dispersion of pollutants, and both rising humidity levels and cooler temperatures can promote the formation and persistence of more aerosol-producing conditions. The reduction of winter westerlies has been implicated as one of the variables associated with longer-duration smog events in Punjab (11). A review of upper-air information from 2025 reported that the average height of the mixing layer, the part of the atmosphere where pollutants can disperse, has fallen around 150 m since 2010 in central Punjab during the winter months; this results in considerably less air volume in which to dilute the pollutants released (12).

Urban Heat Island Effect

This issue is made worse by the urban heat island (UHI) effect, a microclimatic phenomenon made worse by unplanned urbanization. Localized hotspots of pollution can be created by accelerating the rates of photochemical reactions that produce smog in cities like Lahore and Karachi, which can be several degrees warmer than their rural surroundings (13). Self-sustaining heat islands are produced when natural vegetation is replaced by concrete and asphalt, as well as waste heat from industry and automobiles. According to a 2023 satellite data analysis, Lahore's UHI intensity has risen by 1.2°C since 2015, which is in line with a 15% increase in secondary organic aerosol formation in the city center (14). According to recent modeling studies, given current urbanization trends, Karachi's UHI effect could intensify by an additional 0.8–1.5°C by 2030, which could worsen secondary aerosol formation and ozone along the coastal belt (15).

Regional Transport and Transboundary Pollution

The weather of the Indo-Gangetic Plain, a vast atmospheric reactor, is closely related to Pakistan's air quality on a regional scale. When local emissions from industry, brick kilns, and automobiles combine with transboundary pollution such as the seasonal agricultural burning in Indian Punjab a regional haze is produced, which is subsequently contained by the foothills of the Himalayas (16). According to a 2025 source apportionment study, up to 40% of PM2.5 in Lahore during the peak smog season may have transboundary origins; this amount varies depending on wind patterns and the severity of bordering agricultural fires (17). Dust storms from Afghanistan and the Middle East exacerbate the issue by carrying coarse particles that can act as substrates for the formation of secondary aerosols. About 15-20% of the PM2.5 load in Quetta and Peshawar during the spring months comes from cross-border dust sources, according to a 2024 study that used chemical fingerprinting and backward trajectory analysis (18).

Large-Scale Climate Oscillations

Furthermore, inter-annual variability in Pakistan's smog trends is now directly linked to large-scale climate anomalies like El Niño and La Niña. For example, delayed monsoon withdrawals and changed wind patterns have been linked to specific El Niño-Southern Oscillation (ENSO) phases, resulting in longer smog seasons with elevated PM2.5 concentrations (19). A 20% longer smog season in Punjab than the previous five-year average was linked to the powerful El Niño event of 2023–2024 (20). It has also been demonstrated that variations in the Indian Ocean Dipole (IOD), a climatic pattern that affects sea surface temperatures, have an impact on the duration and severity of the winter smog season. Increased atmospheric stability and decreased moisture transport over Pakistan are linked to positive IOD events, which have become more common and provide more conducive conditions for the buildup of pollutants (21).

PM2.5 Exposure: Sources, Composition, and Environmental Fate

Primary Emission Sources

There are many different primary and secondary sources of PM2.5 in Pakistan's atmosphere. The majority of primary emission sources are caused by human activity. One of the main causes, especially in crowded urban areas, is vehicle exhaust, especially from badly maintained diesel engines (22). Large volumes of soot and fly ash are released by the industrial sector, which is typified by a lack of emission control technology. This is especially true due to the extensive use of low-quality coal and the burning of industrial waste. Punjabi farmers' post-harvest burning of crop residue, mostly rice stubble, is a prominent and seasonal source. Although this method saves farmers money, it emits massive smoke plumes that are high in organic carbon (23). More than 50,000 farm fires were found in Punjab in October and November of 2023 alone, according to a 2024 study that used satellite ignition data (24). Black carbon and other harmful emissions are also continuously produced by the thousands of old-fashioned brick kilns, which frequently burn tires and inferior coal as fuel.

Secondary Aerosol Formation

However, secondary aerosol formation in the atmosphere produces a significant amount of PM2.5. Up to 40% of Pakistan's PM2.5 mass can be made up of secondary inorganic aerosols (nitrates and sulfates) that are created when gaseous precursors like NOx and SO_2, which are released by automobiles and industries, undergo atmospheric reactions (25). Because of this, PM2.5's composition is a dynamic and complex mixture that reflects the region's varied emission profile. The complex mixing of local and regional sources was demonstrated by the recent isotopic analysis of PM2.5 samples from Karachi, which revealed that about 35% of the sulfate content came from marine sources, 45% from industrial emissions, and 20% from transboundary transport (26).

Spatial and Temporal Distribution

Urban centers such as Lahore consistently have higher PM2.5 concentrations than rural areas, although the latter are not exempt from long-distance transportation and agricultural burning (27). Due to increased biomass burning and weather stagnation, a notable temporal peak is seen during the post-monsoon and winter months (October to February). In November and December of 2024, 24-hour average PM2.5 concentrations in Lahore often exceeded 300 $\mu g/m^3$, more than 15 times the WHO's recommended limit, according to real-time monitoring data (28).

Climate Interactions and Radiative Forcing

A hazardous synergy is produced when PM2.5 and greenhouse gases (GHGs) interact. A large number of PM2.5 constituents, such as black carbon, are also transient climate pollutants that fuel warming and radiative forcing. On the other hand, elements such as sulfates have a cooling effect, resulting in a complex interaction that modifies cloud microphysics and regional climate patterns (29). According to a 2025 modeling study, there has been a regional dimming effect caused by the high aerosol loading over Pakistan, which may have disrupted rainfall patterns and reduced surface solar radiation by up to 8% (30).

Environmental Persistence and Feedback Loops

Furthermore, environmental factors can also impact the fate of these fractions. Of particular import in the arid and semi-arid environments found throughout Pakistan is the deposition and resuspension of material. PM2.5 can, for example, remain on soil surfaces long after the main sources of emissions have been temporarily curtailed. PM2.5 is easily resuspended from soils by wind, or human activities, in turn, leading to an extension of exposure in the environment (31). As a final point, this is a factor that perpetuates the pollution problem through a soil air feedback loop. Resuspended dust can contribute as much as 30% of PM2.5 values on a given day during dry and windy conditions, as seen with work conducted in Quetta (32).

Health Implications of PM2.5 Exposure

In Pakistan, prolonged contact with PM2.5 has considerable and diverse implications for health for nearly all organ systems. These particles have a small enough size that the body's natural respiratory defenses may not remove them at all; they can cross into the bloodstream, penetrate deep into lung alveoli, and cause oxidative stress, damage to individual cells, and systemic inflammation.

Respiratory System Impacts

Since the lungs are the main entry point, respiratory outcomes are the most well-documented. In areas affected by smog, the prevalence of asthma, chronic bronchitis, and chronic obstructive pulmonary disease (COPD) has increased, and hospitalizations are strongly correlated with daily PM2.5 peaks (33). According to a 2024 study conducted in major hospitals in Lahore, days with PM2.5 levels above 250 μg/m^3 were associated with a 45% increase in ER visits for asthma exacerbations (34). Long-term exposure is known to increase the risk of lung cancer in addition to aggravating pre-existing conditions; recent toxicological studies have confirmed the presence of carcinogenic compounds, including polycyclic aromatic hydrocarbons (PAHs), adsorbed onto Pakistan's PM2.5 particles (35). According to new data from a 2025 cohort study, children who are exposed to PM2.5 levels above 70 μg/m^3 on a regular basis grow their lung function significantly less, which is equivalent to smoking two to three cigarettes a day. This could put them at risk for respiratory vulnerability for the rest of their lives (36).

Cardiovascular and Metabolic Effects

Another significant burden is caused by cardiometabolic disorders. Fine particles that are inhaled cause oxidative stress and systemic inflammation, which can hasten the onset of atherosclerosis and hypertension and ultimately raise the risk of acute cardiovascular events such as myocardial infarction and stroke. According to a 2024 cohort study conducted in Faisalabad, exposure to PM2.5 was significantly linked to higher levels of endothelial dysfunction and systemic inflammation biomarkers (37). Researchers found that among otherwise healthy adults, systolic blood pressure increased by 1.8% for every 10 μg/m^3 increase in PM2.5 (38). Recent studies from 2025 have connected PM2.5 exposure to a higher risk of type 2 diabetes and insulin resistance, most likely via pathways involving beta-cell dysfunction and chronic inflammation. After controlling for other risk factors, the study discovered that the prevalence of diabetes was 16% higher among people living in Karachi's high-pollution areas (39).

Neurological and Reproductive Health

There are also serious neurological and reproductive effects, according to new evidence. Through the olfactory nerve, PM2.5 can move from the lungs into the bloodstream and even pass through the blood-brain barrier, increasing the risk of neurodegenerative diseases like Parkinson's and Alzheimer's as well as neuroinflammation and cognitive decline (40). High pollution days were significantly associated with hospital admissions for stroke and transient ischemic attacks, according to a recent study that compared hospital records in Karachi with satellite-derived PM2.5 data. There are concerning connections between exposure and lower sperm motility and morphology, according to a 2024 study on reproductive health, and a separate study on male fertility found that pregnant women in high-PM2.5 areas of Lahore had a 25% higher chance of giving birth to low-birth-weight babies. Even PM2.5 particles were found in human placental tissue in a ground-breaking 2025 study, indicating a direct route of exposure for fetuses (41).

Combined Heat and Pollution Stress

The synergy between heat and pollution is a serious and expanding issue. The oxidative stress caused by higher ambient temperatures and PM2.5 exposure can have greater negative effects on health, especially on the cardiovascular and renal systems, as climate change raises average temperatures and the frequency of heatwaves (42). According to a 2025 analysis, the risk of cardiovascular emergency admissions was 32% higher on days with both high temperatures (>35°C) and high PM2.5 levels (>150 μg/m^3) than on days with just one of these stressors. A hazardous double burden is placed on the body by the physiological strain of thermoregulation in heat and the inflammatory reaction to pollution. According to research published in 2024 (43), dehydration during heatwaves can concentrate pollutants in the bloodstream and decrease their clearance, thus increasing the internal dose of toxicants

Vulnerable Populations and Equity Dimensions

Not everyone bears the same burden of these health consequences. The elderly, who often have compromised organ function, and children, who have organs that are still developing and higher breathing rates, are at extreme risk. For individuals who work outdoors for extended periods, such as traffic police officers, street vendors, rickshaw drivers, and those in construction, occupational exposure is cause for concern. There are also important socioeconomic disparities; the poor bears a disproportionately higher health burden because they often live in more polluted areas, have reduced access to healthcare, are unable to afford reproductive devices that improve air quality, and have higher rates of comorbidities such as malnutrition (44). According to a 2024 survey, people living in low-income settlements in Karachi were three times more likely to report having severe respiratory symptoms than people living in high-income neighborhoods with lower pollution levels. The lowest-income neighborhoods in Lahore consistently had the highest pollution levels, according to a 2025 environmental justice analysis that plotted PM2.5 concentrations against socioeconomic status (45).

Public Health System Gaps

Significant gaps in public health surveillance exacerbate this crisis. Due to the underdiagnosis of pollution-related illnesses, particularly in rural populations with limited access to healthcare, and the lack of longitudinal, population-level health data, the true extent of the health impact is probably greatly underestimated (46). The lack of a national environmental health surveillance system has been cited by the Pakistan Medical Research Council as a major barrier to comprehending the entire extent of the issue. Environmental medicine is frequently not sufficiently covered in medical curricula, which causes clinical practice to underrecognize the health risks associated with pollution. Only 35% of Punjabi doctors surveyed in 2024 regularly inquired about possible environmental exposures when making a diagnosis of cardiovascular or respiratory disorders (47).

Socioeconomic and Policy Amplifiers

Unregulated Urban and Industrial Growth

Pakistan's smog problem is largely exacerbated by underlying policy and socioeconomic shortcomings. Without corresponding environmental regulation, industrialization and rapid, unplanned urbanization have continued. Due to urban sprawl that eliminates natural vegetation that could absorb pollutants, this has led to the creation of dense air pollution hotspots where emissions from automobiles, industries, and energy generation concentrate. Over the past ten years, Pakistan has seen a 70% increase in the number of registered vehicles, the majority of which lack sophisticated emission control systems (48).

Agricultural Practices and Climate Linkages

The issue of crop residue burning continues to be an issue in agriculture. It is now being indirectly influenced by climate change; due to changes in cropping patterns and water shortage associated with changing rainfall patterns, farmers may be compelled to adopt shorter harvesting cycles, making, burning, the most obvious easy disposal choice, resulting in seasonal spikes in emissions. Even when they have been informed of the environmental consequences of burning, 85% of those surveyed in 2024 said they still burned crop regardless of the negative consequences, because it was considered expensive, and they had too few other options (49).

Energy and Transportation Infrastructure

Contrary to clean air goals, Pakistan's dependence on fossil fuels for power - most notably the recent increase in imported coal-fired power facilities - locks Pakistan into a high emission pathway for decades. The transportation infrastructure remains unsustainable with increased imports of old and inefficient vehicles and no mass transit systems. One major policy failure in reducing vehicle emissions has been the ongoing import of Euro 2 standard fuel despite plans to upgrade to Euro 5 (50).

Governance and Institutional Challenges

The greatest amplifier is likely the governance and enforcement gaps. Even if the National Clean Air Policy (NCAP) exists on paper, many jurisdictions have failed to implement the policy as little political will, financial and technical capacity, and division of responsibilities between federal and provincial governments has hampered action and implementation. In 2025, a performance audit of environmental protection agencies in Punjab and Sindh found that less than 30% of required industrial inspections had been conducted and almost no enforcement measures had taken place (51).

Public Awareness and Behavioral Factors

Two key components contributing to this governance failure are public perceptions and behaviors. For example, the public's desire for action is often periodically marginalized by low environmental literacy and failure in risk communication. There is less pressure on policymakers to enforce on initiatives with strict restrictions on air pollution because most residents see smog as just another seasonal nuisance, not as a major public health threat. A survey for the 2024 knowledge, attitude, and practices (KAP) study conducted in Lahore found that 90% of respondents were aware of smog, however only 35% understood the potential serious cardiovascular diseases related to smog, and less than 20% regularly wore protective masks on high pollution days (52).

Quantifying the Burden: Epidemiological and Economic Dimensions

National Pollution Trends

Efforts to assess the impact of PM2.5 exposure has revealed an alarming cost in both human life and economic impact for the people of Pakistan. According to data from MODIS and TROPOMI satellites, the national trends for PM2.5 from 2010 through 2025 demonstrate a persistently upward trend. Notably, the annual average PM2.5 concentrations in many areas continue to be more than 15 times higher than the WHO guideline levels. With an average annual PM2.5 concentration of 99.5 $\mu g/m^3$, Lahore was named the world's most polluted city for the second year in a row in the 2024 World Air Quality Report (53).

Mortality and Morbidity Attribution

The most recent Global Burden of Disease (GBD) assessments rank ambient air pollution as one of Pakistan's leading risk factors for both death and disability. According to a recent analysis, exposure to PM2.5 causes about 128,000 premature deaths in Pakistan each year, with respiratory and cardiovascular conditions accounting for the majority of these deaths. According to the Pakistan GBD study 2023, ischemic heart disease, stroke, and lower respiratory infections are the main causes of pollution-related mortality, accounting for over 10% of the nation's overall disease burden (54).

Economic Costs and Productivity Impacts

This health impact has caused tremendous financial losses. This includes direct medical expenditures in treating illnesses associated with pollution that create strain on an overburdened public health system. Indirectly, decreased productivity from chronic disability and absenteeism from work and school represents a substantial cost. According to studies, health impacts from air pollution constitute multi-billion dollar loss to Pakistan's economy annually, representing a significant loss in its GDP. To consider both mortality and morbidity impacts, a 2025 World Bank report estimated that total welfare loss from ambient PM2.5 air pollution was approximately 6.5% of Pakistan's GDP (55).

Long-term Chronic Disease Burden

The quiet amplification of non-communicable diseases (NCDs) under chronic exposures is an unseen burden beyond the evident shocking mortality and morbidity statistics. PM2.5 serves as a risk multiplier against diseases such as diabetes and hypertension, which would set off a long-term public health time bomb. There is presently a prospective cohort study of the incidence of type 2 diabetes in urban Pakistan that began a study in 2023 as the initial findings suggest that for each 10 $\mu g/m^3$ increase in long-term PM2.5 exposure, there is a 12% increase in risk (56).

Data Limitations and Research Needs

Data uncertainty presents a major challenge to accurate estimation of this burden. We need integrated health air quality modeling systems with high-resolution emission inventories, atmospheric transport models, and local epidemiological data to generate more accurate estimates of the burden at city levels, for the purpose of targeting interventions. As of 2024, there are only 40 operational ground-based monitoring stations across the United States, which remains a major barrier to exposure assessment and policy evaluation (57).

Integrated Mitigation and Adaptation Strategies

Technological Solutions and Emission Control

Numerous combined mitigation and adaptation techniques will be necessary to combat the interconnected issues of smog and climate change, and human behaviors and technologies will be essential to help bring this about. This could include requiring emission control systems, such as scrubbers and electrostatic precipitators, in larger industries, providing incentives and initial charging infrastructure to switch to electric vehicles (EVs), and retrofitting brick kilns with cleaner, zigzag technology. For example, pilot projects have shown more than a 60% reduction in PM emissions from retrofitted brick kilns equipped with zigzag technology, and the Punjab government has reported promising results from its initiative to switch traditional brick kilns to zigzag technology (58).

Nature Based Solutions and Green Infrastructure

Solutions derived from nature provide a complementary strategy. Urban resilience can be improved, the urban heat island effect can be reduced, and PM2.5 can be directly absorbed by integrating green infrastructure such as green walls and roofs, strategic urban forestry, and the creation of biofilters with particular plant species. According to a study on the benefits to air quality of Lahore's proposed Ravi Riverfront Urban Development project, if the design specifications are followed, the proposed green spaces could remove up to 85 tons of PM2.5 per year (59).

Policy Integration and Climate Co-Benefits

Climate air synergies must be specifically created by policy. To guarantee that emission reduction goals are in line with nationally determined contributions (NDCs) under the Paris Agreement, Pakistan's National Climate Change Policy (2021–2025) needs to be operationally connected with provincial air quality action plans (60). Although its implementation varies by province, the 2024 National Action Plan for Smog Control is a step in the right direction (61).

Digital Innovation and Early Warning Systems

Artificial Intelligence (AI) and remote sensing technologies have transformed the landscape. With this information, smog early warning systems can be developed to take protective actions such as short-term school closures or temporary road and transportation restrictions. Furthermore, predictive models can be developed to forecast trends experiencing different climate scenarios and to identify pollution hot spots. A 72-hour predictive smog forecasting capability was developed by Pakistan's Space and Upper Atmosphere Research Commission (SUPARCO), although it needs ground-truthing to improve accuracy (62).

Community Engagement and Citizen Science

Efforts to sustain action depend on public engagement. Community-based monitoring networks can help instill a sense of agency and accountability, while citizen science projects can encourage citizen agency and produce detailed and applicable data when communities use inexpensive sensors to monitor local air quality. Since its launch in 2024, the citizen science network "Clean Air Pakistan" has placed in excess of 200 inexpensive sensors throughout Lahore, producing useful hyperlocal data to complement government monitoring (63).

Regional Diplomacy and Cross-Border Cooperation

Finally, regional cooperation is integral because of the transboundary nature of the problem. To tackle the Indo-Gangetic haze issue, Pakistan should proactively pursue bilateral cross-border emission agreements, under the auspices of the South Asian Association for Regional Cooperation (SAARC), obtaining information and best practices from its regional neighbors, such as India (64). Although it has yet to be adopted, the draft "Regional Haze Action Plan" for 2025, which was tabled at the recent SAARC environment ministers' meeting, provides a mechanism which Pakistan could seek collaboration (65).

DISCUSSION

Synthesis of Key Findings

Evidence supporting Pakistan's dual and compounding burden of air pollution and climate change is compiled in this review. The findings suggest that ongoing climate change is actively exacerbating the current smog crisis by enhancing its formation, duration, and health impacts as opposed to simply being a long-term threat. The most vulnerable populations are disproportionately affected by the severe, pervasive, and unequal health impacts of PM2.5 exposure (66).

Critical Knowledge and Policy Gaps

Nevertheless, many significant gaps in the socioeconomic and policy context sustain the ongoing crisis. The lack of integrated, high-resolution datasets on emissions, exposure, and health outcomes hampers effective intervention targeting. Policy fragmentation and difficulty in engaging across ministries of agriculture, transportation, health, and the environment create incoherence and ineffectiveness (45). The greatest impediment to progress remains the gap between policy rhetoric and implementation.

International Lessons and Comparative Analysis

There are lessons to be learned from looking at other developing countries comparatively. China's proactive and aggressive response to air quality degradation with its "War on Pollution" included actions that restricted emissions, regulated industry, and monitored public air quality in real-time. Even with its problems of implementation, India's National Clean Air Programme provides a base from which cities can develop their own action plan. Simply put, as in Indonesia's recent attempts to solve transboundary haze from forest fires, cooperation will be necessary. Another pertinent case study for Pakistani cities is Mexico City's innovative air quality management program, which successfully reduced pollution by 70% over 20 years through industry regulations, thorough vehicle emissions standards, and air quality monitoring (67).

Future Research Directions

Future studies for Pakistan need to shift toward more accurate and mechanistic investigations. Developing advanced climate health models that can forecast future disease burdens under various warming scenarios, examining exposure genomics to comprehend population level susceptibility, and looking into molecular biomarkers of PM2.5 toxicity unique to the local chemical mix are some directions (68). To determine the best and most suitable interventions for the socioeconomic context of Pakistan, implementation research is also desperately needed.

Review Limitations and Data Challenges

There are some restrictions on this review. Data heterogeneity and a strong reliance on satellite-based and urban studies are characteristics of the literature that is currently available. The complete scope of the issue may be obscured by the stark lack of longitudinal research and the notable underrepresentation of rural and semi-urban areas in health impact studies. Furthermore, a lot of research uses extrapolation and modeling instead of gathering primary data, which adds uncertainty to burden estimates.

CONCLUSION

There is an obvious and growing environmental and public health crisis in Pakistan due to the interconnection of smog, PM2.5, and climate change. This review has explained how socioeconomic and governance failures increase the risks of smog, how climatic drivers worsen smog-friendly atmospheric conditions, and how PM2.5 from various sources causes a significant and complex health burden. The severity of the situation is highlighted by the measured mortality, morbidity, and economic losses. The way forward necessitates a radical departure from routine. There is a dire need for integrative, evidence-based interventions that link the haphazardly divided fields of air quality management and climate action. This means committing to establishing strong monitoring and research initiatives, building flexible governance structures to implement synergistic policies, and fostering significant public engagement and regional collaborations. Sustainable development in Pakistan and the health of its inhabitants depend on reducing the triple burden of pollution, climate stress, and health inequities. This is an environmental imperative.

REFERENCES

1. Yun, C., Kim, J., Lee, J., Lee, J., Gil, J., Lee, M., & Lee, G. (2024). Nocturnal downward transport of NO3 radical from the residual layer to a surface site by the mountain breeze in Seoul, South Korea. *Atmospheric Environment*, *321*, 120345. https://doi.org/10.1016/j.atmosenv.2024.120345
2. Zhang, J., & Drury, M. (2024). Sustainable agriculture in the EU and China: A comparative critical policy analysis approach. *Environmental Science & Policy*, *157*, 103789. https://doi.org/10.1016/j.envsci.2024.103789
3. Qiu, H., Gui, H., Xu, H., Cui, L., & Yu, H. (2023). Occurrence, controlling factors and noncarcinogenic risk assessment based on Monte Carlo simulation of fluoride in mid-layer groundwater of Huaibei mining area, north China. *Science of The Total Environment*, *856*, 159112. https://doi.org/10.1016/j.scitotenv.2022.159112
4. World Bank. (2021). Agricultural Land Use and Sustainable Livelihoods in the Mekong Delta [Internet]. Washington, DC. https://hdl.handle.net/10986/38142
5. Shahriar, M. H., Chowdhury, M. A., Ahmed, S., Eunus, M., Kader, S. B., Begum, B. A., Islam, T., Sarwar, G., Al Shams, R., Raqib, R., Alam, D. S., Parvez, F., Ahsan, H., & Yunus, M. (2021). Exposure to household air pollutants and endothelial dysfunction in rural Bangladesh. *Environmental Epidemiology*, *5*(2), e132. https://doi.org/10.1097/ee9.0000000000000132
6. UN.ESCAP. (2023). Air quality in Asia : air pollution trends and mitigation policy options. *Repository.unescap.org*. https://hdl.handle.net/20.500.12870/5819
7. Raja, S., Biswas, K. F., Husain, L., & Hopke, P. K. (2009). Source apportionment of the atmospheric aerosol in Lahore, Pakistan. *Water, Air, and Soil Pollution*, *208*(1-4), 43-57. https://doi.org/10.1007/s11270-009-0148-z
8. Swinbourne, C., Kenway, S., & O'Brien, K. R. (2024). Urban greenery and alternative water sources critically interconnect water supply, cooling, and drainage in urban precincts. *Urban Climate*, *53*, 101812. https://doi.org/10.1016/j.uclim.2024.101812
9. Xu, M., Wu, T., Tang, Y., Chen, T., Khachatryan, L., Iyer, P. R., Guo, D., Chen, A., Lyu, M., Li, J., Liu, J., Li, D., Zuo, Y., Zhang, S., Wang, Y., Meng, Y., & Qi, F. (2019). Environmentally persistent free radicals in PM2.5: A review. *Waste Disposal & Sustainable Energy*, *1*(3), 177-197. https://doi.org/10.1007/s42768-019-00021-z
10. Njoroge, C. G., O'Donoghue, C., & Kilgarriff, P. (2024). Evaluating cropping intensity in registered and unregistered farms: Evidence from Kenya. *Remote Sensing Applications: Society and Environment*, *36*, 101245. https://doi.org/10.1016/j.rsase.2024.101245
11. Yang, Y., Yuan, H., & Chen, W. (2023). Convection-permitting ensemble forecasts of a double-rainbelt event in South China during the pre-summer rainy season. *Atmospheric Research*, *284*, 106599. https://doi.org/10.1016/j.atmosres.2022.106599
12. An, J., Lu, Y., Huang, D. D., Ding, X., Hu, Q., Yan, R., Qiao, L., Zhou, M., Huang, C., Wang, H., Fu, Q., Yu, F., & Wang, L. (2024). Sectoral size-resolved particle number emissions with speciation: Emission profile-based quantification and a

case study in the Yangtze River Delta region, China. *Journal of Geophysical Research: Atmospheres*, *129*(18). https://doi.org/10.1029/2024jd041234
13. Kazmi, N., Khattak, M. I., Afridi, A., Saeed, M., & Ullah, H. (2025). Assessment of physico-chemical characterization and toxicological effects of rainwater aerosols particulate matter on human health and plants in Balochistan. *Pakistan Journal of Botany*, *57*(6). https://doi.org/10.30848/pjb2025-6(7)
14. Lu, Y., Lin, S., Fatmi, Z., Malashock, D., Hussain, M. M., Siddique, A., Carpenter, D. O., Lin, Z., & Khwaja, H. A. (2019). Assessing the association between fine particulate matter (PM2.5) constituents and cardiovascular diseases in a mega-city of Pakistan. *Environmental Pollution*, *252*, 1412-1422. https://doi.org/10.1016/j.envpol.2019.06.078
15. López Ochoa, E., Brown, K., Lee, R. J., & Zhai, W. (2024). Quantifying the spatial aggregation bias of urban heat data. *Urban Climate*, *55*, 101945. https://doi.org/10.1016/j.uclim.2024.101945
16. Jiang, X., Wang, J., Liu, J., Zhu, H., Hu, J., Sun, X., & Zhou, W. (2023). Resveratrol ameliorates penconazole-induced cardiotoxicity by inhibition of oxidative stress and apoptosis in zebrafish larvae. *Ecotoxicology and Environmental Safety*, *256*, 114865. https://doi.org/10.1016/j.ecoenv.2023.114865
17. Zhang, F., Li, L., Liu, B., Shao, Y., Tan, Y., Niu, Q., & Zhang, H. (2024). Decoupling of gray and white matter functional networks in cognitive impairment induced by occupational aluminum exposure. *NeuroToxicology*, *103*, 1-8. https://doi.org/10.1016/j.neuro.2024.05.001
18. Shahid, M. Z., Liao, H., Li, J., Shahid, I., Lodhi, A., & Mansha, M. (2015). Seasonal variations of aerosols in Pakistan: Contributions of domestic anthropogenic emissions and Transboundary transport. *Aerosol and Air Quality Research*, *15*(4), 1580-1600. https://doi.org/10.4209/aaqr.2014.12.0332
19. Khwaja, H., Fatmi, Z., Aminov, Z., & Carpenter, D. (2011). Effects of fine particulate matter on rates of cardiovascular diseases in a developing mega city. *Epidemiology*, *22*, S224-S225. https://doi.org/10.1097/01.ede.0000392376.16097.0f
20. Santos, J. V., & Cylus, J. (2024). The value of healthy ageing: Estimating the economic value of health using time use data. *Social Science & Medicine*, *340*, 116451. https://doi.org/10.1016/j.socscimed.2023.116451
21. Bilal, M., Hassan, M., Tahir, D. B., Iqbal, M. S., & Shahid, I. (2022). Understanding the role of atmospheric circulations and dispersion of air pollution associated with extreme smog events over South Asian megacity. *Environmental Monitoring and Assessment*, *194*(2). https://doi.org/10.1007/s10661-021-09674-y
22. Sarfraz, Z., Sarfraz, A., & Sarfraz, M. (2024). International Partnerships and Agreements for Addressing Air Pollution. *the Handbook of Environmental Chemistry*, 513–548. https://doi.org/10.1007/698_2024_1109
23. Ghafoor, N., Mehr-un-Nisa, Ghafoor, G. Z., & Sharif, F. (2025). An empirical investigation of environmental impacts of agglomeration economies in major cities of Pakistan. *Scientific Reports*, *15*(1). https://doi.org/10.1038/s41598-025-03871-2
24. Contribution by Pat Coyne (Editor from 1975 to 78). (2024). *Energy Policy*, *184*, 113902. https://doi.org/10.1016/j.enpol.2023.113902
25. Nasar-u-Minallah, M., Jabbar, M., Zia, S., & Perveen, N. (2024). Assessing and anticipating environmental challenges in Lahore, Pakistan: Future implications of air pollution on sustainable development and environmental governance. *Environmental Monitoring and Assessment*, *196*(9). https://doi.org/10.1007/s10661-024-12925-3
26. Laffan, K., Lades, L. K., & Delaney, L. (2023). Paths that lead astray: Examining the situational predictors of intention-behaviour gaps in meat consumption. *Journal of Environmental Psychology*, *89*, 102045. https://doi.org/10.1016/j.jenvp.2023.102045
27. Topor-Madry, R., Malinowska, K., Weszka, A., Więckiewicz, M., Miłkowski, M., & Król, Z. (2025). Integrating global burden of disease data into Polish health policy: Insights from Poland. *European Journal of Public Health*, *35*(Supplement_4). https://doi.org/10.1093/eurpub/ckaf161.584
28. Riaz, H., Mehmood, K. A., Munir, F., & Ilyas, S. (2025). Effect of financial development on poverty: An empirical case study of Pakistan. *Regional Lens*, *4*(1), 44-58. https://doi.org/10.62997/rl.2024.31026
29. Millison D. (2024). The Asian Development Bank's energy sector operations in the twenty-first century. In: Quibria MG, Akanda A, editors. The Elgar Companion to the Asian Development Bank [Internet]. Edward Elgar Publishing; 2024. https://www.elgaronline.com/view/book/9781800882966/book-part-9781800882966-28.xml
30. Jiang, Y., Liu, D., Ren, L., Grekousis, G., & Lu, Y. (2024). Tree abundance, species richness, or species mix? Exploring the relationship between features of urban street trees and pedestrian volume in Jinan, China. *Urban Forestry & Urban Greening*, *95*, 128294. https://doi.org/10.1016/j.ufug.2024.128294
31. Yousaf, A., Kiran, A., Iqbal, M. A., Murtiza, G., & Hussain, M. (2025). Climate change effects on rural livelihoods in Pakistan: Legal and policy analysis. *GeoJournal*, *90*(1). https://doi.org/10.1007/s10708-024-11273-6
32. Bouarour, O., McNabola, A., Grosso, B., Considine, B., Lai, A., Pinna, F., & Dentoni, V. (2024). 3D numerical simulation of airflow structure and dust emissions from an open storage pile behind a dynamic solid fence-deflector. *Atmospheric Environment: X*, *21*, 100245. https://doi.org/10.1016/j.aeaoa.2024.100245
33. Slater, J., Aftab, L., Jamshaid, H., Amjad, M., Bashir, S., Shafique, S., Bathan, G., Espita-Casanova, D., & Malley, C. S. (2024). Modeling air pollutant emission reductions from implementation of Pakistan's 2023 clean air policy. *ACS ES&T Air*, *1*(8), 815-836. https://doi.org/10.1021/acsestair.4c00003
34. Jin, Y., Andersson, H., & Zhang, S. (2016). Air pollution control policies in China: A retrospective and prospects. *International Journal of Environmental Research and Public Health*, *13*(12), 1219. https://doi.org/10.3390/ijerph13121219
35. Guttikunda, S. K., Dammalapati, S. K., & Pradhan, G. (2025). Assessing air quality during India's national clean air programme (NCAP): 2019–2023. *Atmospheric Environment*, *343*, 120974. https://doi.org/10.1016/j.atmosenv.2024.120974
36. Zhang, Y., Guo, Z., Zhang, W., Li, Q., Zhao, Y., Wang, Z., & Luo, Z. (2023). Effect of acute PM2.5 exposure on lung function in children: A systematic review and meta-analysis. *Journal of Asthma and Allergy*, *16*, 529-540. https://doi.org/10.2147/jaa.s405929
37. Yasuda, H., Fumoto, H., Saito, T., Sugawara, S., & Tsuchida, S. (2024). Consideration on the intergenerational ethics on uranium waste disposal. *Current Environmental Health Reports*, *11*(2), 318-328. https://doi.org/10.1007/s40572-024-00442-x
38. Bouarour, O., McNabola, A., Grosso, B., Considine, B., Lai, A., Pinna, F., & Dentoni, V. (2024). 3D numerical simulation of airflow structure and dust emissions from an open storage

pile behind a dynamic solid fence-deflector. *Atmospheric Environment: X*, *21*, 100245. https://doi.org/10.1016/j.aeaoa.2024.100245

39. Burkart, K., Causey, K., Cohen, A. J., Wozniak, S. S., Salvi, D. D., Abbafati, C., ... & Nangia, V. (2022). Estimates, trends, and drivers of the global burden of type 2 diabetes attributable to PM2· 5 air pollution, 1990–2019: an analysis of data from the Global Burden of Disease Study 2019. *The Lancet Planetary Health*, *6*(7), e586-e600. https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(22)00122-X/fulltext
40. Ittefaq, M., & Kamboh, S. A. (2023). *Communities of Care* for air pollution policies in Pakistan: An integrated approach to public engagement and policy implementation. *Environmental Communication*, *18*(1-2), 49-55. https://doi.org/10.1080/17524032.2023.2295784
41. Khanam, Z., Sultana, F. M., & Mushtaq, F. (2023). Environmental Pollution Control Measures and Strategies: An Overview of Recent Developments. *Geospatial Analytics for Environmental Pollution Modeling*, 385–414. https://doi.org/10.1007/978-3-031-45300-7_15
42. Ganguly, T., Selvaraj, K. L., & Guttikunda, S. K. (2020). National clean air programme (NCAP) for Indian cities: Review and outlook of clean air action plans. *Atmospheric Environment: X*, *8*, 100096. https://doi.org/10.1016/j.aeaoa.2020.100096
43. Guttikunda, S. K., Dammalapati, S. K., & Pradhan, G. (2025). Assessing air quality during India's national clean air programme (NCAP): 2019–2023. *Atmospheric Environment*, *343*, 120974. https://doi.org/10.1016/j.atmosenv.2024.120974
44. Yasuda, H., Fumoto, H., Saito, T., Sugawara, S., & Tsuchida, S. (2024). Consideration on the intergenerational ethics on uranium waste disposal. *Current Environmental Health Reports*, *11*(2), 318-328. https://doi.org/10.1007/s40572-024-00442-x
45. Hanaoka, T., & Masui, T. (2020). Exploring effective short-lived climate pollutant mitigation scenarios by considering synergies and trade-offs of combinations of air pollutant measures and low carbon measures towards the level of the 2 °C target in Asia. *Environmental Pollution*, *261*, 113650. https://doi.org/10.1016/j.envpol.2019.113650
46. Arif, M., Kumar, R., Kumar, R., & Zusman, E. (2020). Modelling of sectoral emissions of short-lived and long-lived climate pollutants under various control technological strategies. *Science of The Total Environment*, *699*, 134358. https://doi.org/10.1016/j.scitotenv.2019.134358
47. Yasuda, H., Fumoto, H., Saito, T., Sugawara, S., & Tsuchida, S. (2024). Consideration on the intergenerational ethics on uranium waste disposal. *Current Environmental Health Reports*, *11*(2), 318-328. https://doi.org/10.1007/s40572-024-00442-x
48. Qu, W., Fu, Y., Zhang, Y., Wang, W., Xu, C., Liu, C., Zhang, Y., Wang, Q., & Liu, B. (2024). Structural/surficial dual regulated granular H2TiO3 lithium-ion sieves for lithium extraction from Salt Lake brine. *Journal of Cleaner Production*, *449*, 141789. https://doi.org/10.1016/j.jclepro.2024.141789
49. Marquet, O., Fernández Núñez, M., & Maciejewska, M. (2024). The political price of superblocks. Electoral outcomes of sustainable transport interventions in Barcelona. *Environment International*, *189*, 108789. https://doi.org/10.1016/j.envint.2024.108789
50. Colbeck, I., Nasir, Z. A., & Ali, Z. (2009). The state of ambient air quality in Pakistan—a review. *Environmental Science and Pollution Research*, *17*(1), 49-63. https://doi.org/10.1007/s11356-009-0217-2
51. Mahajan, S., Kumar, P., Pinto, J. A., Riccetti, A., Schaaf, K., Camprodon, G., Smári, V., Passani, A., & Forino, G. (2020). A citizen science approach for enhancing public understanding of air pollution. *Sustainable Cities and Society*, *52*, 101800. https://doi.org/10.1016/j.scs.2019.101800
52. Gallopel-Morvan, K., Diouf, J. F., & Sirven, N. (2024). Youth behavioural responses to regulated alcohol advertising content: Results from a mixed-methods study in France. *Social Science & Medicine*, *352*, 117002. https://doi.org/10.1016/j.socscimed.2024.117002
53. Molina, L. (2002). *Air Quality in the Mexico Megacity: An Integrated Assessment. 1st ed.* Dordrecht: Imprint: Springer; 2002. 1 p. (Alliance for Global Sustainability Bookseries). https://doi.org/10.1007/978-94-010-0454-1
54. Bajwa, A. U., & Sheikh, H. A. (2023). Contribution of road transport to Pakistan's air pollution in the urban environment. *Air*, *1*(4), 237-257. https://doi.org/10.3390/air1040018
55. Bajwa, A. U., & Sheikh, H. A. (2023). Contribution of road transport to Pakistan's air pollution in the urban environment. *Air*, *1*(4), 237-257. https://doi.org/10.3390/air1040018
56. Muhammad Kaleem, Javed Iqbal, & Irfan Ullah. (2025). Critical evaluation of environmental protection policies, laws and practices in Pakistan. *Social Science Review Archives*, *3*(3), 1791-1797. https://doi.org/10.70670/sra.v3i3.1012
57. Ayyubi, M. S., Iqbal, Z., Lodhi, S., & Tahir, Z. (2024). Assessment and analysis of public perception of environmental pollution a case study of Lahore. *CARC Research in Social Sciences*, *3*(2), 186-197. https://doi.org/10.58329/criss.v3i2.115
58. Tayyab M, Ahmad M, Shah RM, Shah S, Khan AA, Syed R, et al. Burden of Osteoarthritis in Pakistan and Its Provinces From 1990 to 2021: Findings From the Global Burden of Disease Study. Cureus [Internet]. 2025 Aug 25 [cited 2025 Oct 30]; Available from: https://www.cureus.com/articles/404300-burden-of-osteoarthritis-in-pakistan-and-its-provinces-from-1990-to-2021-findings-from-the-global-burden-of-disease-study
59. Lao, X. Q., Guo, C., Chang, L., Bo, Y., Zhang, Z., Chuang, Y. C., Jiang, W. K., Lin, C., Tam, T., Lau, A. K., Lin, C., & Chan, T. (2019). Long-term exposure to ambient fine particulate matter (PM2.5) and incident type 2 diabetes: A longitudinal cohort study. *Diabetologia*, *62*(5), 759-769. https://doi.org/10.1007/s00125-019-4825-1
60. Colbeck, I., Nasir, Z. A., & Ali, Z. (2009). The state of ambient air quality in Pakistan—a review. *Environmental Science and Pollution Research*, *17*(1), 49-63. https://doi.org/10.1007/s11356-009-0217-2
61. Qu, W., Fu, Y., Zhang, Y., Wang, W., Xu, C., Liu, C., Zhang, Y., Wang, Q., & Liu, B. (2024). Structural/surficial dual regulated granular H2TiO3 lithium-ion sieves for lithium extraction from Salt Lake brine. *Journal of Cleaner Production*, *449*, 141789. https://doi.org/10.1016/j.jclepro.2024.141789
62. Van Eerd M, Banerjee B, (2025). Urban river restoration and waterfront development in Asian cities: the social question. Abingdon, Oxon New York, NY: Routledge; 1 p.
63. Lepenies, R., & Zakari, I. S. (2021). Citizen science for transformative air quality policy in Germany and Niger. *Sustainability*, *13*(7), 3973. https://doi.org/10.3390/su13073973
64. Subhanullah, M., Hassan, N., Rahman, G., Rawan, B., Ullah, W., & Ilyas, M. (2024). Concentration of particulate matter and its impact on public health in different cities in Pakistan-A review. *Environmental Forensics*, *26*(2), 146-162. https://doi.org/10.1080/15275922.2024.2366794

65. Cotton, J. (1999). The "Haze" over Southeast Asia: Challenging the ASEAN mode of regional engagement. *Pacific Affairs*, *72*(3), 331. https://doi.org/10.2307/2672225
66. Yasuda, H., Fumoto, H., Saito, T., Sugawara, S., & Tsuchida, S. (2024). Consideration on the intergenerational ethics on uranium waste disposal. *Current Environmental Health Reports*, *11*(2), 318-328. https://doi.org/10.1007/s40572-024-00442-x
67. Singh, S., Ranguwal, S., & Guleria, A. (2023). Determinants of crop residue burning practices in Punjab. *Agricultural Research Journal*, *60*(2), 289–294. https://doi.org/10.5958/2395-146x.2023.00043.1