

Aerosol Optical Depth Over Nepal: A Comprehensive Review of Spatial and Seasonal Variability, Sources, Meteorological Controls, Regional Transport, and Implications

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ABSTRACT

Nepal experiences a distinctive aerosol pollution problem produced by the interaction of intense local emissions, complex mountain-valley meteorology, seasonal biomass and forest burning, and regional transport from the Indo-Gangetic Plain. This comprehensive narrative review synthesizes readily accessible and available scientific literature with the primary objective of improving understanding of aerosol optical depth (AOD) over Nepal, including its spatial and seasonal variability and the processes that control it. Evidence from ground-based AERONET observations, satellite remote sensing, surface particulate-matter monitoring, aerosol chemical characterization, trajectory analysis, atmospheric modeling, exposure assessment, and health studies is integrated to interpret the broader aerosol environment. Across Kathmandu, Pokhara, Lumbini, Rara, and high-elevation Himalayan sites, aerosol loading is generally greatest during winter and pre-monsoon conditions and is reduced during the summer monsoon by wet scavenging and enhanced atmospheric ventilation. Local emissions, topography, meteorology, biomass and forest fires, and regional transport from the Indo-Gangetic Plain jointly shape observed AOD patterns. Surface PM, chemical, and health evidence is used as complementary information to explain the sources and consequences of columnar aerosol loading. The review identifies important gaps in long-term observations, geographical coverage, vertical profiling, chemical characterization, and integration of ground-based and satellite AOD measurements, and proposes priorities for improving aerosol monitoring and interpretation across Nepal.

KEYWORDS: aerosol optical depth, PM_{2.5}, Kathmandu Valley, Pokhara, Lumbini, Himalayas, source apportionment, transboundary pollution, meteorology, health burden

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INTRODUCTION

Atmospheric aerosols are suspended solid and liquid particles that influence visibility, air quality, cloud processes, radiation, climate, ecosystems, and human health. In Nepal, these effects are amplified by an unusual combination of rapidly growing urban centers, widespread combustion sources, dusty roads and construction, seasonal fires, strong monsoon seasonality, and steep terrain. Kathmandu Valley is a bowlshaped basin in which weak ventilation and nocturnal inversions can retain pollutants near the surface, while Pokhara and Lumbini are influenced by different combinations of rainfall, elevation, local emissions, and proximity to the Indo-Gangetic Plain (IGP). High-elevation Himalayan sites may be cleaner on average, yet they remain vulnerable to transported pollution and episodic fire plumes (Islam et al., 2020; Regmi et al., 2020; Ramachandran & Rupakheti, 2021, 2026).

The literature supplied for this review has an important strength: it approaches the Nepal aerosol problem from multiple observational scales. AERONET studies characterize column aerosol optical depth (AOD), Ångström exponent, single-scattering albedo, size distribution, and related optical properties; surface networks quantify PM_{2.5} and PM₁₀; aerosol mass spectrometry and filter chemistry identify composition and sources; satellite and land-use analyses describe spatial patterns; Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT), Potential Source Contribution Function (PSCF), and Concentration-Weighted Trajectory (CWT) studies examine transport and atmospheric processes; and exposure and burden-of-disease studies translate pollution into human consequences (Zhong et al., 2019; Werden et al., 2022; Islam et al., 2022; Kafle et al., 2025; Adhikari et al., 2026).

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A comprehensive review of aerosol pollution over Nepal is needed because the available evidence remains geographically uneven and fragmented across different observational approaches, locations, and time periods. Nepal's complex topography, ranging from the lowland Terai to enclosed urban valleys and the high Himalaya, together with strong monsoon seasonality, local emissions, biomass and forest fires, and regional transport from the Indo-Gangetic Plain, produces substantial spatial and temporal variability in aerosol loading. Consequently, findings from a single location, particularly the extensively studied Kathmandu Valley, cannot adequately represent aerosol conditions across the country. Moreover, existing studies use different approaches, including ground-based AERONET observations, satellite remote sensing, surface particulate-matter measurements, chemical characterization, trajectory analysis, and atmospheric modeling, making an integrated synthesis necessary to understand the overall aerosol environment. This review therefore brings together the readily accessible and available evidence to develop a comprehensive understanding of AOD over Nepal, while using surface PM, aerosol chemistry, meteorology, and transport studies to explain the processes controlling its variability. Specifically, the review addresses four questions: (1) What are the dominant aerosol sources and characteristics across Nepal? (2) How do seasonality, meteorology, topography, and long-range transport influence AOD and aerosol behavior? (3) How consistent are the findings across measurement approaches and geographic locations? and (4) What major observational and knowledge gaps must be addressed to improve aerosol monitoring, interpretation, and air-quality management in Nepal?

REVIEW APPROACH AND SCOPE

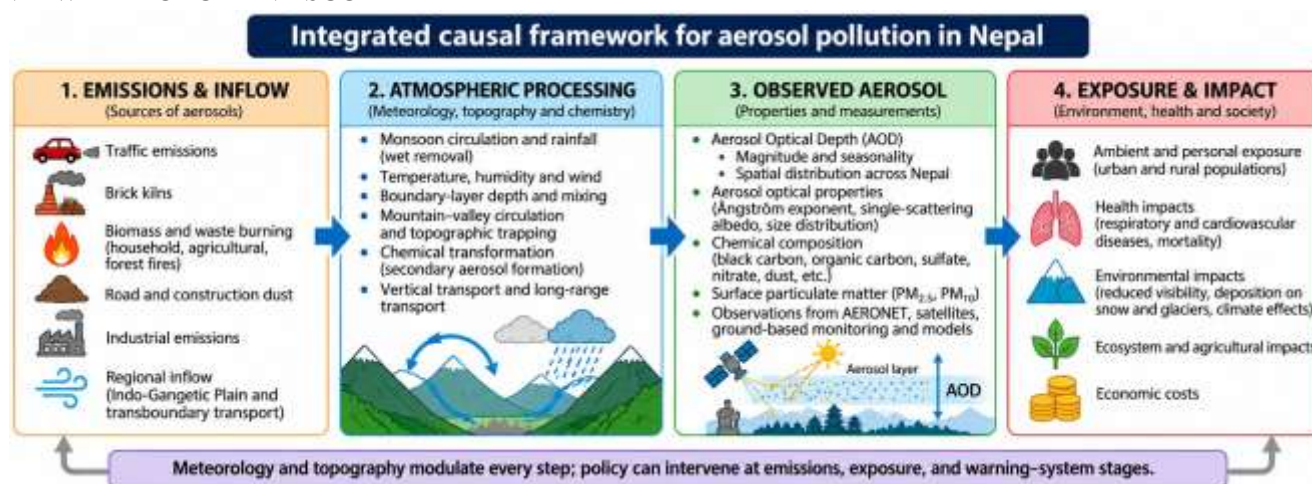


Figure 1. Integrated causal framework for aerosol pollution in Nepal. The review is organized around the pathway from emissions and regional inflow through atmospheric processing and observed aerosol to exposure and health/climate consequences.

This article presents a comprehensive narrative review of aerosol optical depth (AOD) and aerosol pollution over Nepal, with the primary objective of improving understanding of the spatial and temporal characteristics of AOD across the country. Relevant studies were collected from the scientific literature based primarily on their relevance to aerosol characteristics over Nepal and their accessibility and availability to the authors. The evidence includes ground-based AERONET observations, satellite remote sensing, surface particulate-matter measurements, aerosol chemical characterization, meteorological observations, trajectory analysis, and atmospheric modeling. Studies addressing particulate matter, aerosol composition, regional transport, exposure, and health impacts were also considered when they provided complementary evidence useful for interpreting AOD patterns and the broader aerosol environment of Nepal. The literature was organized thematically to synthesize AOD magnitude and seasonality, aerosol optical properties, geographical differences, meteorological influences, emission sources, and regional transport. This article is therefore a comprehensive narrative review rather than a systematic review or meta-analysis. The literature was not identified through a predefined systematic-review protocol, exhaustive multi-database search, or formal PRISMA-based screening procedure; instead, the aim was to bring together readily accessible and available scientific evidence relevant to aerosol loading over Nepal and synthesize it into a coherent understanding of AOD, its controlling processes, associated pollution characteristics, and remaining research gaps.

The studies were grouped into eight evidence domains: (a) aerosol optical properties and climatology; (b) $PM_{2.5}$, PM_{10} , and urban–remote contrasts; (c) chemical composition and source apportionment; (d) meteorological, land-use, wildfire, and long-range transport controls; (e) vertical structure and radiative effects; (f) regional and long-range transport; (g) personal and microenvironmental exposure; and (h) mortality, health burden, and economic consequences. Greater interpretive weight was given

to multiyear measurements, chemically resolved observations, multi-site studies, and analyses that combined independent data streams.

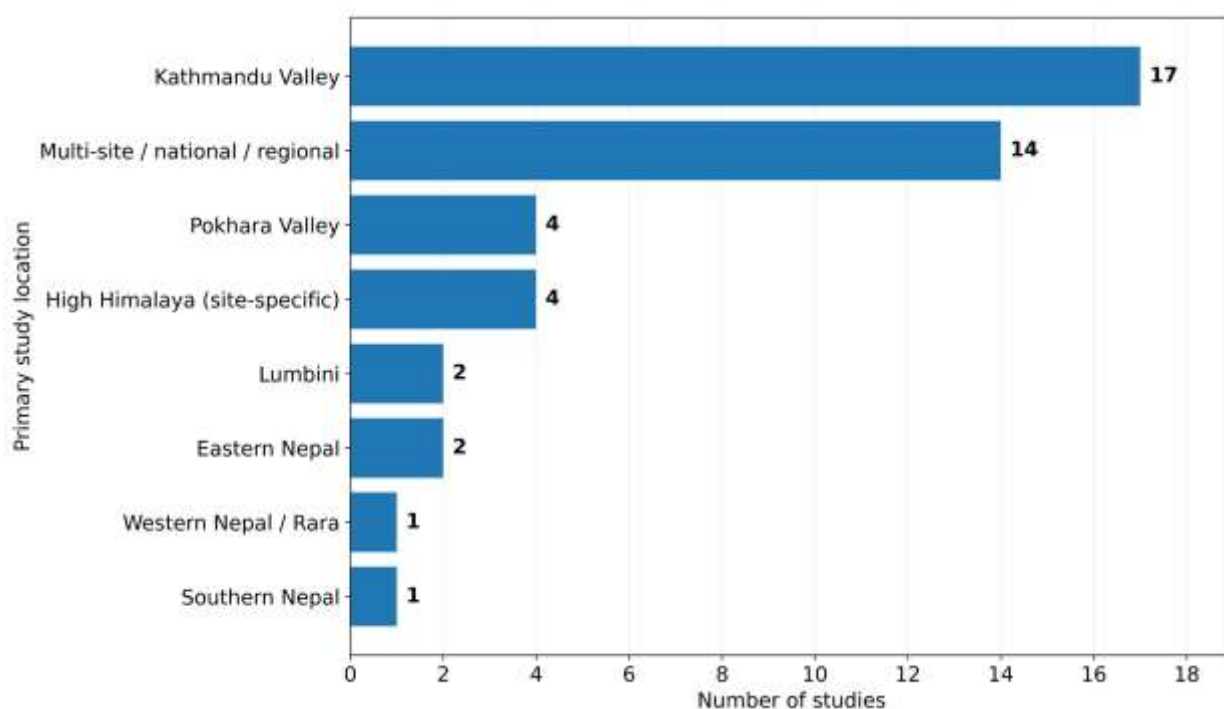


Figure 2. | Geographic distribution of the reviewed aerosol studies in Nepal. Studies are grouped according to their primary geographic focus; multi-site, national, and regional studies are shown separately to avoid duplicate counting.

The geographic distribution of the reviewed literature is uneven, with the largest concentration of sitespecific studies focused on Kathmandu Valley. Pokhara Valley and high-Himalayan locations form smaller evidence clusters, whereas Lumbini, eastern Nepal, western Nepal/Rara, and southern Nepal are represented by comparatively fewer location-specific studies. Multi-site, national, and regional investigations provide broader spatial context but do not replace sustained observations at underrepresented locations. This imbalance should be considered when interpreting national aerosol patterns and highlights the need for expanded long-term AOD and complementary aerosol monitoring beyond Kathmandu.

Geographic Context: Why Nepal Produces Strong Aerosol Gradients

Nepal spans the southern Himalayan foothills, deeply incised valleys, densely populated urban basins, and high-elevation environments within a short north–south distance. This geography creates sharp gradients in emissions, boundary-layer depth, rainfall, and transport. Kathmandu Valley concentrates population, vehicles, construction, industry, brick kilns, waste burning, and household combustion within terrain that restricts dispersion. The result is a persistent urban enhancement superimposed on a regional South Asian aerosol background (Islam et al., 2020, 2022; Werden et al., 2023).

Pokhara has a different atmospheric setting. It is a rapidly urbanizing valley but receives very high monsoon rainfall and is directly adjacent to steep Himalayan terrain. Long-term AERONET analyses show that its aerosol column is nevertheless substantially affected by biomass burning, urban-industrial emissions, dust, and transported pollution, especially in the pre-monsoon season (Regmi et al., 2020; Ramachandran & Rupakheti, 2021). Lumbini, by contrast, lies at low elevation close to the IGP and is exposed to local industrial and traffic sources as well as regional inflow; optical studies consistently characterize it as a comparatively polluted Nepalese site (Jha et al., 2021; Sapkota et al., 2023a; Rijal et al., 2025).

The contrast with remote environments is equally important. Comparative observations show much lower particle concentrations at Rara Lake than in central Kathmandu, while high-elevation Himalayan sites generally have lower AOD than the IGP and foothill locations. Yet remote does not mean isolated: Western Nepal measurements at Rara demonstrate that regional forest fires and southerly transport can produce substantial episodic PM_{2.5} enhancements (Chalise et al., 2025; Maharjan et al., 2026; Ramachandran & Rupakheti, 2026).

AEROSOL OPTICAL PROPERTIES AND CLIMATOLOGY

Historical and high-elevation perspective

Longer historical records broaden the geographic and process context beyond the recent AERONETcentered literature. Early observations in the Nepal Himalaya showed that both carbonaceous aerosol and mineral dust contribute strongly to seasonal aerosol

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properties, establishing that Himalayan aerosol is a mixed system rather than a purely urban combustion plume (Carrico et al., 2003). At the Nepal Climate Observatory–Pyramid, continuous observations documented synoptic-scale dust transport to >5 km elevation, while later regional work demonstrated pre-monsoon accumulation of aerosol along the Indo-Gangetic Plain and southern Himalayan slopes (Duchi et al., 2011; Gautam et al., 2011). These studies are important because they show that elevated and remote sites can receive episodic aerosol from distant source regions even when local emissions are weak.

Additional Nepal studies reinforce the spatial heterogeneity of column aerosol. Acharya et al. (2020) compared AERONET sites in Nepal using spectral AOD analysis, while measurements at Jomsom and other high-mountain locations demonstrate that elevation, valley geometry, and season produce optical regimes distinct from lowland and urban basins (Shrestha et al., 2015). The supplied evidence therefore supports treating Nepal as a connected vertical transect—from the Terai and IGP-influenced lowlands through urban valleys to the high Himalaya—rather than as a single air-quality domain.

Pokhara Valley

The most internally consistent optical evidence comes from Pokhara. Regmi et al. (2020) analyzed AERONET observations from 2010–2018 and reported the highest seasonal AOD during pre-monsoon conditions, followed by winter, post-monsoon, and monsoon. Their trajectory, fire, and size-distribution analyses pointed to a mixture of biomass-burning, urban-industrial, and dust aerosols, including longrange transport. Ramachandran and Rupakheti (2021), using 2010–2017 observations, independently found a recurring annual AOD maximum in the pre-monsoon and minimum during the monsoon, with fire counts closely aligned with enhanced aerosol loading. The exceptionally strong 2016 pre-monsoon aerosol episode coincided with unusually high fire activity, strengthening the source interpretation.

The consistency across nonoverlapping time windows is important: the seasonal pattern is not an artifact of a single year or instrument campaign. It reflects a robust interaction among seasonal burning, regional transport, urban emissions, aerosol growth, and monsoon removal.

LUMBINI AND MULTI-SITE COMPARISONS

Evidence from eastern Nepal

The archive also adds evidence from eastern Nepal, an area underrepresented in many national syntheses. Dahal et al. (2022a) reported festival-associated perturbations in AOD and column CO over Birtamode, illustrating how short-lived changes in local activity can be detected jointly by ground and satellite observations. A second study from the eastern Himalayan foothills characterized post-monsoon and winter aerosol optical behavior and source influences, further showing that the eastern border region is affected by a mixture of local emissions and regional transport (Dahal et al., 2022b). These studies strengthen the case for a national network that includes eastern Nepal rather than concentrating monitoring only in Kathmandu and central Nepal.

Lumbini studies reveal both similarities and contrasts. Jha et al. (2021) compared seven Nepalese tourist and high-altitude locations and found spring or winter enhancement at many sites, with vegetation fires, land clearing, biomass burning, brick kilns, factories, and vehicles offered as major explanations. Sapkota et al. (2023a) examined Lumbini from 2013–2019 and reported high AOD outside the monsoon, low visibility, and seasonal changes consistent with mixtures of biomass-burning and anthropogenic aerosol. Rijal et al. (2025) further examined AOD, Ångström parameters, rainfall, and relative humidity in Lumbini, emphasizing that meteorological variables alter aerosol loading and optical behavior but do not act independently of emissions.

A direct comparison of Lumbini, Pokhara, and Langtang Base Camp found substantially lower aerosol loading and much greater visibility at the high-elevation Langtang site, while Lumbini exhibited stronger pollution sites (Sapkota et al., 2023b). This elevation gradient is reinforced by the regional synthesis of Ramachandran and Rupakheti (2026), who found AOD across much of the IGP and Himalayan foothills to be markedly higher than at high-altitude Himalayan locations. Together, these studies show that altitude and distance from dense emission regions are major determinants of background aerosol burden, although transported pollution can episodically erode the high-altitude advantage.

AOD, Water Vapor, and Interpretation Limits

Satellite and data-fusion advances

Recent data-fusion work extends the surface–column comparison problem into areas with sparse monitoring. Lamichhane et al. (2026) integrated satellite AOD, trace gases, and meteorological reanalysis to estimate PM_{2.5} and long-term trends in southern Nepal, reporting substantially better predictive performance for a multivariable model than for a simple linear approach. This direction is promising for the Terai and Dun valleys, but it does not remove the need for ground calibration: satellite AOD is a column quantity, and its translation to surface PM_{2.5} remains sensitive to humidity, aerosol type, boundary-layer height, and vertical structure.

Sapkota et al. (2023c) compared AERONET AOD and precipitable water at Kathmandu-Bode and four international sites. The study demonstrates that aerosol–water relationships vary by climatic regime and season. This is an important caution for interpreting correlations: a positive AOD–water-vapor association can arise from hygroscopic particle growth, common seasonal forcing, or

coincident transport, whereas rainfall can rapidly remove particles. Consequently, AOD should not be treated as a direct surrogate for surface PM_{2.5} without accounting for vertical aerosol distribution, humidity, boundary-layer structure, and aerosol type. Regmi et al. (2023) addressed this issue directly by comparing low-cost surface PM_{2.5} with satellite column AOD over Kathmandu, showing both the value and the limitations of cross-platform relationships.

Surface Particulate Matter: Magnitude, Seasonality, and Spatial Contrast

Surface measurements show that the aerosol problem is not only a column-integrated optical phenomenon. In Kathmandu, winter and pre-monsoon PM_{2.5} frequently reach levels associated with serious health concern. Islam et al. (2022) measured daily winter PM_{2.5} at urban Ratnapark, suburban Lalitpur, and rural Dhulikhel and found high concentrations at all three sites, with the urban and suburban locations substantially more polluted than the rural rim site. Their PM₁₀ measurements were even higher, demonstrating an important coarse-particle contribution from road and crustal material in addition to combustion-derived fine particles.

Regmi et al. (2023) reported a strong seasonal cycle in Kathmandu low-cost sensor PM_{2.5}, with winter highest and summer lowest, as well as a bimodal diurnal pattern associated with morning and evening activity and shallow mixing. A 2021–2023 observational analysis similarly identified meteorology as a major driver of day-to-day Kathmandu air quality, reinforcing the role of temperature, humidity, rainfall, and wind in controlling accumulation and removal (Telee et al., 2026). These studies are consistent with the chemical campaigns: emissions remain substantial throughout the year, but meteorological ventilation and wet scavenging strongly determine the concentrations people actually breathe.

Pokhara surface monitoring provides an important second-city perspective. Pandey et al. (2024) compared three monitoring stations and found the clearest PM_{2.5} deterioration in winter, while PM₁₀ patterns were less uniformly severe. This spatial heterogeneity within one valley cautions against representing an entire city with a single monitor. In a national urban–remote comparison, Chalise et al. (2025) found much higher PM_{2.5} and PM₁₀ at Ratnapark in Kathmandu than at Rara Lake, with minima during the rainy season at both sites. The PM_{2.5}/PM₁₀ ratio also suggested a stronger fine-particle dominance at the urban site, consistent with combustion sources.

CHEMICAL COMPOSITION AND SOURCE APPORTIONMENT IN KATHMANDU VALLEY

Vertical structure and radiative effects

Airborne and radiative studies add a dimension that surface monitoring cannot provide. Microlight aircraft measurements over the Pokhara region showed strong vertical gradients in aerosol number, size and absorption, with the largest concentrations concentrated in the lower atmosphere and substantial changes with altitude (Singh et al., 2019). In Kathmandu, SusKat-ABC observations linked winter aerosol optical properties to radiative effects under severe pollution conditions (Cho et al., 2017), while Thapa et al. (2017) quantified aerosol-related modification of solar radiation in the mid-hills. At a remote site near Yala Glacier, Rai et al. (2019) estimated aerosol radiative forcing, demonstrating that aerosol climate effects extend into cryospheric environments.

The regional climate implication is now clearer. Ramachandran et al. (2023) showed that aerosol absorption and radiative effects can warm the Himalayan atmosphere, while Ramachandran and Rupakheti (2026b) synthesized aerosol composition and radiative forcing across the IGP–Himalaya system. These findings expand the policy relevance of Nepal aerosol research beyond visibility and cardiopulmonary health: absorbing aerosol can alter atmospheric heating, stability, snow/ice energy balance, and potentially regional circulation. Climate and air-quality objectives are therefore partly coupled, particularly for black carbon and other light-absorbing particles.

Pre-Monsoon Composition

The NAMaSTE campaign provides the most detailed chemical picture of Kathmandu aerosol. Islam et al. (2020) measured PM, inorganic gases, carbon-containing gases, and a large suite of non-methane volatile organic compounds during the 2015 pre-monsoon. Source markers indicated contributions from poorly maintained vehicles, biomass burning, garbage burning, cooking, dung burning, and secondary organic aerosol formation. The study also showed that temperature and relative humidity influenced aerosol liquid water, gas–particle partitioning, and aerosol acidity, demonstrating that meteorology changes not only concentration but also chemical state.

High-resolution aerosol mass spectrometry further resolved the submicron mixture. Werden et al. (2022) found organic aerosol to be the largest nonrefractory component during the pre-monsoon and identified traffic, biomass burning, trash burning, local/brick-kiln-related emissions, and secondary oxygenated organic aerosol. Werden's (2021) dissertation integrates these source-apportionment datasets and emphasizes the coexistence of strong primary combustion sources with substantial atmospheric processing. The key policy implication is that controlling only one source category cannot eliminate Kathmandu's PM burden.

Winter Composition and Spatial Heterogeneity

Winter observations show an even stronger accumulation regime. Werden et al. (2023) conducted sequential measurements at Dhulikhel, Ratnapark, and Lalitpur and found organic aerosol and black carbon to be major components, with a clear urban enhancement. Positive matrix factorization identified hydrocarbon-like organic aerosol associated with traffic, biomass-burning aerosol, trash-burning aerosol, a sulfate-containing local source, and multiple oxygenated secondary factors. Traffic was a prominent primary source, while brick kilns contributed importantly to black carbon, sulfate, and organic aerosol. The spatial differences among the three sites demonstrate that source influence varies substantially over short distances.

Islam et al. (2022) reached a complementary conclusion using fine and coarse particulate chemistry. Organic and elemental carbon dominated much of PM2.5, while resuspended crustal material contributed strongly to PM10. Chemical mass balance modeling identified garbage burning, biomass burning, and fossil-fuel combustion as major organic-carbon sources, together with secondary organic aerosol. This result is especially important because it connects visible urban dust with less visible but health-relevant combustion and secondary fine particles: both coarse and fine fractions require management, but their sources and controls differ.

Vehicles and Brick Kilns

Zhong et al. (2019) quantified emissions from vehicles and brick kilns and evaluated their effects with WRF-Chem. Updating the vehicle inventory reduced model bias for elemental carbon, while updating brick-kiln emissions improved sulfur dioxide simulation. The study demonstrates a recurring problem in South Asian air-quality modeling: generic regional inventories can substantially misrepresent local technologies and operating conditions. Nepal-specific emission factors and activity data are therefore essential for credible policy modeling.

Traffic exposure is also visible at the microenvironment scale. Dhital et al. (2014) measured air pollution inside Kathmandu public transport vehicles and found severe particulate pollution, especially PM10, along with BTEX compounds and evidence that congestion increased gaseous pollutant exposure. This older study remains relevant because it shows that ambient monitoring alone may underestimate exposure for commuters who spend time directly within traffic plumes.

Meteorological Controls, Topography, and Seasonal Removal

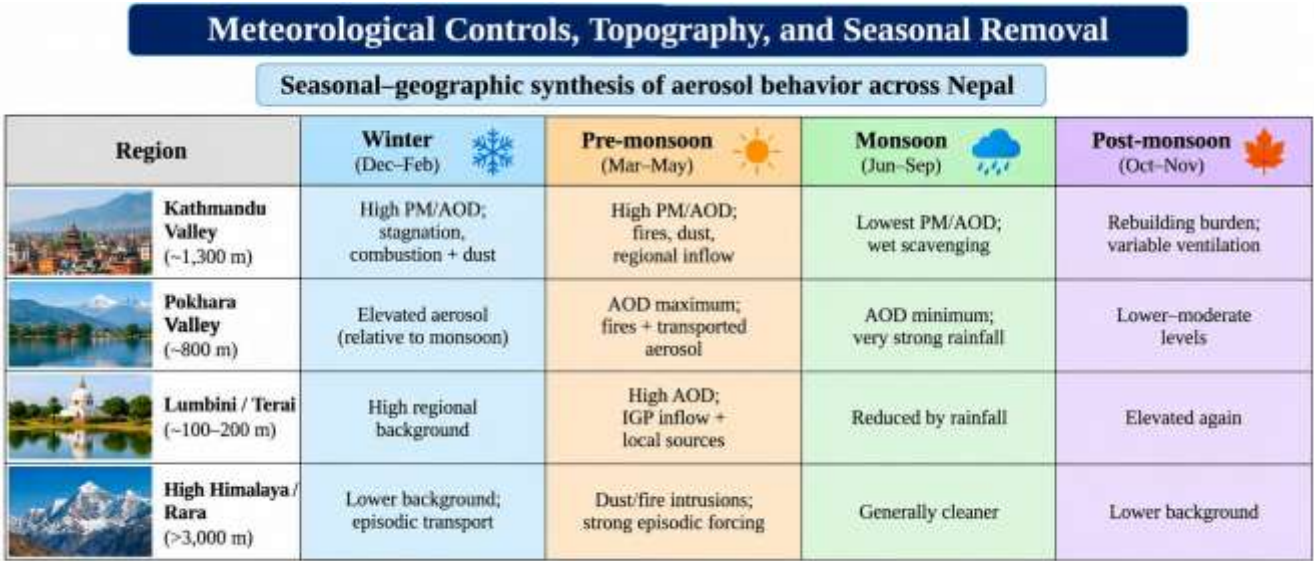


Figure 3. | Seasonal–geographic synthesis. The matrix summarizes recurring relative patterns across the supplied studies and should not be interpreted as a quantitative inter-site comparison.

Across the evidence base, meteorology acts as a multiplier of emissions. During winter, shallow boundary layers, stable nighttime conditions, weak winds, and basin confinement favor accumulation. During pre-monsoon months, stronger mixing can coexist with major seasonal sources, especially forest and vegetation fires, dust, and regional inflow. During the monsoon, rainfall scavenges particles, suppresses some open-burning activities, and increases ventilation, producing the most consistent seasonal minimum in both AOD and surface PM across many Nepalese sites (Regmi et al., 2020; Ramachandran & Rupakheti, 2021; Chalise et al., 2025; Ramachandran & Rupakheti, 2026).

Kathmandu's topography intensifies these seasonal controls. Pollutants emitted within the basin can accumulate overnight and during stagnant episodes, while daytime upslope and valley circulations partially ventilate the basin. Telee et al. (2026) show that meteorological variability remains strongly associated with observed air-quality changes even in recent years. The implication is

practical: emission control and forecasting should be meteorology aware. The same emission rate can produce very different exposure depending on boundary-layer depth, wind direction, precipitation, and inversion strength.

Land cover adds another spatial dimension. Shrestha et al. (2025) assessed 2023 summer AOD in relation to land-use/land-cover indicators across Kathmandu Valley and reported lower aerosol loading over more vegetated areas and higher loading associated with built-up and other non-vegetated surfaces. Although satellite AOD and land-cover correlations cannot by themselves establish causation, the result supports the broader evidence that urban form, vegetation, emission density, and surface characteristics jointly shape the spatial aerosol field.

Regional Transport, the Indo-Gangetic Plain, and Wildfire Smoke

Transport pathways operate across multiple scales. Gautam et al. (2011) documented pre-monsoon aerosol accumulation from the IGP toward the southern Himalayan slopes, and Duchi et al. (2011) demonstrated synoptic dust transport to the high Himalaya. Rupakheti et al. (2018) further compared optical properties at foothill sites, supporting strong source and elevation contrasts. Together with recent Kathmandu, Rara and regional analyses, these studies indicate that “transboundary” should not be treated as a single source category: Nepal receives anthropogenic haze, mineral dust, and fire smoke through different pathways and at different altitudes.

The supplied literature also includes cryosphere-focused and atmospheric-chemistry extensions. Bhattarai et al. (2019) developed an empirical approach for estimating AOD over the Nepalese cryosphere where satellite retrieval is difficult, while Shrestha et al. (2025b) examined aerosol–ozone relationships over Langtang National Park. These studies are not direct PM_{2.5} health assessments, but they demonstrate that aerosol pollution interacts with radiation, trace gases and high-elevation environments in ways that matter for Himalayan climate and ecosystem exposure.

A central conclusion of the combined literature is that Nepal's aerosol burden cannot be managed as a purely local problem. Regmi et al. (2020) used back trajectories and fire information to identify mixed transboundary aerosol over Pokhara. Kafle et al. (2025) combined Kathmandu PM_{2.5}, Indian monitoring data, AOD, fire information, HYSPLIT trajectories, PSCF, and CWT analyses and found evidence for important transboundary and regional source contributions. Ramachandran and Rupakheti (2026) place these findings in a broader IGP–Himalaya framework, showing that the foothills are embedded in a regional aerosol system with strong seasonal exchange.

Western Nepal provides particularly clear evidence of transported fire pollution. Maharjan et al. (2026) analyzed Rara National Park measurements and reported that regional forest-fire activity explained a large fraction of PM_{2.5} variability during polluted periods, with southern and southwesterly air masses linked to elevated concentrations. This finding is significant because Rara lacks the dense local urban sources of Kathmandu. Elevated PM_{2.5} there therefore provides a natural demonstration of how regional transport can degrade air quality far from major cities.

The public-health consequence of wildfire transport is illustrated by Kuikel et al. (2025), who identified hundreds of wildfire-smoke days in Kathmandu Valley over 2003–2023 and linked smoke episodes to persistent air-quality degradation. Their mortality analysis indicates that rapid population growth greatly increased the number of people exposed to the hazard over time. Thus, even without a strong long-term increase in measured PM_{2.5}, population expansion can sharply increase total health burden. This distinction between concentration trend and burden trend is crucial for policy evaluation.

EXPOSURE AND HEALTH CONSEQUENCES

Modeled Mortality and Burden

Tuladhar et al. (2021) coupled WRF-Chem PM_{2.5} fields with a health-impact model for Kathmandu Valley. Their December 2019 analysis estimated substantial mortality attributable to PM_{2.5} and showed that a hypothetical 50% concentration reduction would markedly reduce monthly mortality. Although model-based estimates depend on concentration fields, exposure assumptions, and concentration–response functions, the study provides a clear demonstration of the potential health benefit of emission reduction.

More recent burden-of-disease work broadens this picture. Adhikari et al. (2026) used government monitoring data and an environmental burden framework to estimate mortality, disability-adjusted life years, and economic costs attributable to long-term ambient PM_{2.5} in Kathmandu Valley. The study translates air pollution from an environmental indicator into a development and economic issue. Joshi et al. (2026), reviewing Nepal's health evidence, similarly emphasizes respiratory and cardiovascular impacts, vulnerable populations, and persistent gaps in policy implementation.

Personal Exposure and Vulnerable Groups

Ambient concentration is only one component of dose. Carson et al. (2026) assessed personal PM_{2.5} exposure among children in Kathmandu and Bandung, demonstrating the feasibility and importance of personal monitoring in settings where children move among home, school, travel, and outdoor microenvironments. Such measurements can reveal exposure patterns that fixed monitors cannot capture. In Kathmandu, this need is reinforced by the in-vehicle findings of Dhital et al. (2014), which show that commuters can encounter concentrated traffic-related pollution during daily travel.

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The evidence therefore supports a shift from a monitor-centered to an exposure-centered framework. Protecting health requires identifying where high concentrations overlap with large populations, susceptible groups, and high-exposure activities. Schools near traffic corridors, public-transport users, outdoor workers, households using solid fuels, and communities near brick kilns or waste-burning areas deserve targeted study and intervention. The supplied literature strongly establishes hazard and burden, but Nepal still lacks enough longitudinal epidemiology to quantify source-specific risks across diverse populations.

Integrated Synthesis: What the Studies Show Together

The expanded archive sharpens this conceptual model in three ways. First, the aerosol problem has a vertical structure: pollutants are concentrated in inhabited valleys but can be lofted and transported into the free troposphere and high Himalaya. Second, aerosol is both an air-quality and climate-forcing agent; optical absorption, scattering and radiative forcing link source control to regional climate cobenefits. Third, observational coverage remains geographically uneven. Kathmandu has the strongest chemical and health evidence, whereas the Terai, eastern Nepal and high mountains rely more heavily on optical, satellite or short-duration observations. These asymmetries should guide the next generation of monitoring and study design.

Taken together, the comprehensive body of literature reviewed here supports a coherent conceptual model. First, local combustion and dust sources establish a high aerosol baseline in urban valleys. Traffic, brick kilns, biomass burning, garbage burning, cooking, industrial activity, construction, and road dust appear repeatedly across independent methods. Second, atmospheric chemistry transforms a substantial portion of emitted gases and primary particles into secondary aerosol, so primary-emission inventories alone do not fully explain observed aerosol loading. Third, topography and meteorology determine whether these emissions disperse, remain trapped, absorb water, or are removed by precipitation. Fourth, regional transport adds pollution from the Indo-Gangetic Plain and seasonal fires, extending the problem into cleaner and remote regions. Together, these processes explain much of the observed spatial and seasonal variability of AOD over Nepal, while surface PM and exposure evidence clarifies the implications of this columnar aerosol burden for air quality and health.

The agreement among optical, surface, chemical, satellite, trajectory, and modeling studies is stronger than any single dataset. AERONET establishes robust seasonal column loading; surface monitors confirm that people experience corresponding fine-particle episodes; chemistry identifies source mixtures; trajectories and fire data demonstrate regional transport; and health models quantify consequences. Where findings differ—for example, the exact month of maximum AOD in Lumbini or the sign of simple humidity correlations—the differences are scientifically plausible because aerosol– meteorology relationships depend on rainfall timing, hygroscopic growth, source activity, vertical distribution, and the specific observation period. These differences should be interpreted as context dependence, not contradiction.

Evidence Gaps and Methodological Limitations

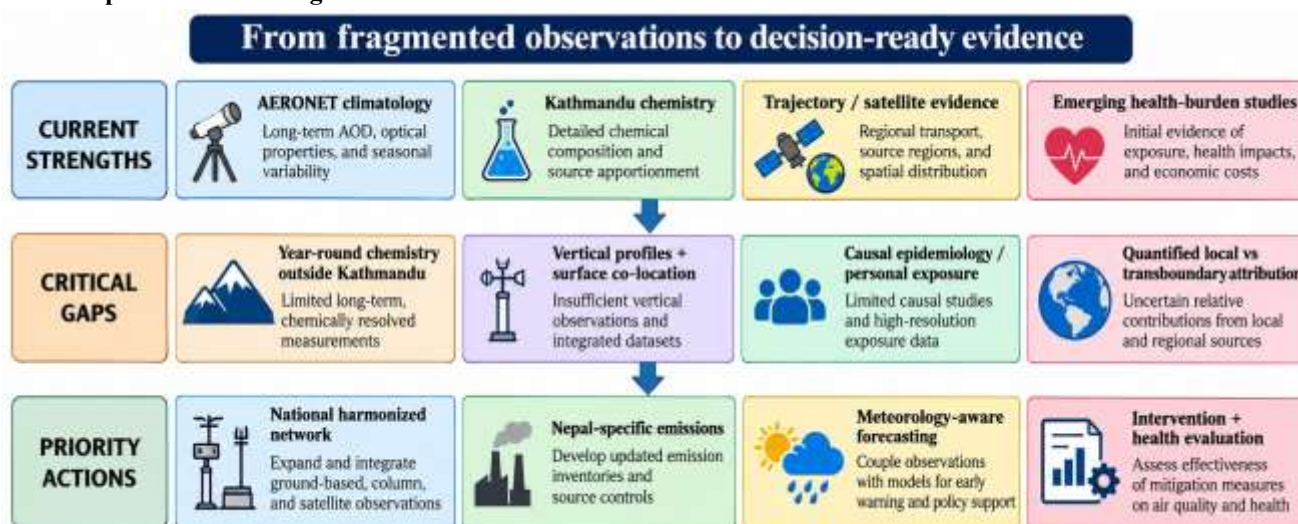


Figure 4. | Evidence-to-action roadmap. Strong observational foundations now need to be connected through harmonized monitoring, year-round chemistry, vertical profiling, causal health studies and intervention evaluation.

The largest geographic limitation is the concentration of chemically detailed research in Kathmandu Valley. Pokhara and Lumbini have valuable optical and routine PM observations, but far fewer longterm measurements of composition, black carbon, secondary inorganic aerosol, organic aerosol factors, and source-specific tracers. Remote Himalayan evidence is also sparse relative to the importance of cryosphere and ecosystem exposure.

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A second limitation is cross-study comparability. The literature uses AOD, PM₁, PM_{2.5}, PM₁₀, optical parameters, satellite products, low-cost sensors, reference monitors, filter chemistry, and models across different periods. These metrics describe related but nonidentical parts of the aerosol system. Future work should colocate surface PM, AERONET, lidar or vertical-profile measurements, meteorology, and chemical speciation so that column-to-surface relationships can be quantified rather than assumed. Third, source apportionment is strongest during intensive campaigns rather than across full annual cycles. Kathmandu source contributions measured during pre-monsoon or winter cannot automatically be generalized to monsoon and post-monsoon conditions. Year-round chemically resolved monitoring is needed to distinguish persistent sources from seasonal sources and to evaluate policy changes.

Fourth, health evidence is developing but remains less mature than the atmospheric evidence. Burden models demonstrate substantial impacts, yet Nepal needs more cohort, time-series, birth-outcome, childhealth, cardiovascular, respiratory, and source-specific epidemiological studies. Personal exposure, indoor–outdoor exchange, occupation, transport mode, socioeconomic vulnerability, and household energy use should be integrated into future health designs.

Finally, transboundary attribution remains inherently uncertain. Back trajectories, PSCF/CWT, satellite AOD, and fire detections identify likely source regions, but quantitative separation of local versus imported PM requires chemically constrained regional modeling, receptor modeling, and coordinated measurements across Nepal and neighboring countries. **Research Priorities**

- Establish a harmonized national aerosol network linking reference PM_{2.5}/PM₁₀ monitors with calibrated low-cost sensors, AERONET, meteorology, and periodic chemical speciation.
- Expand year-round source-apportionment measurements beyond Kathmandu to Pokhara, Lumbini, the Terai, and remote Himalayan sites.
- Develop Nepal-specific, frequently updated emission inventories for vehicles, brick kilns, industry, open waste burning, household combustion, road dust, and fires.
- Integrate boundary-layer observations and meteorological forecasting into operational air-quality alerts, especially for winter stagnation and pre-monsoon fire episodes.
- Quantify transboundary contributions with coordinated regional observations and chemically evaluated transport models.
- Prioritize personal-exposure and epidemiological studies in children, commuters, outdoor workers, kiln-adjacent communities, and other high-exposure groups.
- Evaluate interventions with before–after designs so that changes in emissions, concentrations, exposure, and health outcomes can be linked directly.

Policy Implications

The literature points toward a multi-source strategy rather than a single intervention. Cleaner and bettermaintained vehicle fleets, inspection and maintenance, public transport modernization, road-dust control, construction management, cleaner brick-kiln technologies and fuels, elimination of open garbage burning, improved household energy, and fire prevention all have defensible roles. Because secondary aerosol is substantial, controls on gaseous precursors must accompany direct particle controls. Because regional transport is important, Nepal also benefits from South Asian cooperation on agricultural burning, wildfire smoke, industrial emissions, and shared forecasting.

Policy timing matters. Winter stagnation and pre-monsoon fire periods should trigger stronger shortterm protection measures, while the monsoon provides a useful natural contrast for evaluating source strength. Public advisories should be linked to health-relevant PM_{2.5} rather than visibility alone, and vulnerable groups should receive specific guidance during high-pollution episodes. Monitoring should be designed not merely to report AQI but to evaluate whether policies reduce population-weighted exposure.

Cross-domain evidence synthesis

Table 1. | Cross-domain synthesis of the supplied evidence base. The table emphasizes convergence across methods and the most important unresolved gaps.

Evidence domain	Strongest locations	Main signal	Key methods	Priority gap
Optical climatology	Pokhara, Lumbini, Kathmandu, high Himalaya	Premonsoon/winter enhancement; monsoon minimum	AERONET, sun photometry, satellite AOD	Long, harmonized multi-site records
Surface PM	Kathmandu, Pokhara, Rara	Strong urban– remote and seasonal contrasts	Reference/lowcost PM sensors	National calibration and coverage

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Chemical sources	Kathmandu Valley	Traffic, biomass/trash burning, kilns, dust, secondary aerosol	AMS, chemistry, PMF/CMB filter	Year-round chemistry outside Kathmandu
Vertical/radiative	Pokhara, Kathmandu, Yala/high Himalaya	Strong lower-atmosphere gradients; absorption and forcing	Aircraft, radiometers, optical retrievals	Co-located vertical profiles and chemistry
Regional transport	IGP–foothills, Kathmandu, Rara, NCO-P	Anthropogenic haze, fires and dust reach remote/elevated sites	HYSPLIT, PSCF/CWT, satellite/fire data	Quantitative local-vs-imported attribution
Exposure/health	Kathmandu Valley	High personal exposure; mortality, DALY and economic burden	Personal monitors, WRFChem, burden models	Cohort/timeseries and sourcespecific epidemiology

CONCLUSION

The complete body of supplied literature shows that aerosol pollution in Nepal is a coupled local– regional atmospheric and public-health problem. Kathmandu Valley experiences the most intensively documented burden, driven by traffic, brick kilns, biomass and garbage burning, dust, and secondary aerosol formation under meteorological conditions that often suppress dispersion. Pokhara and Lumbini show strong seasonal aerosol loading and clear influence from fires, anthropogenic emissions, rainfall, and regional transport. Remote and high-elevation sites are cleaner on average but remain vulnerable to transported pollution, particularly during regional fire episodes.

The strongest scientific conclusion is not a single concentration value or source percentage, but the convergence of multiple methods. Optical observations, surface PM measurements, chemical source apportionment, satellite data, trajectory analysis, atmospheric modeling, personal monitoring, and health-burden studies all point toward the same need: integrated control of local emissions, improved regional cooperation, meteorology-aware management, and a stronger exposure and health surveillance system. Future research should move from isolated campaigns toward coordinated long-term observations that connect emissions to atmospheric transformation, population exposure, and measurable health benefits. Such an approach would provide Nepal with the evidence needed to shift from describing severe air pollution to demonstrating which interventions deliver the largest and most equitable improvements.

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