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From Aerosol Columns to Breathing-Zone Exposure: Meteorological Controls, Vertical Mixing, and Measurement Uncertainty in Nepal's Mountain Valleys

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ABSTRACT

Aerosol optical depth (AOD) and ground-level particulate matter (PM) are frequently interpreted together in Himalayan air-pollution research, although they measure different atmospheric quantities. In Nepal, sharp elevation gradients, mountain–valley circulations, monsoon rainfall, combustion sources, and transboundary transport can decouple column-integrated optical loading from breathing-zone exposure. This critical integrative review asks how meteorological processes connect emissions, aerosol optics, surface PM2.5, and exposure, and which monitoring designs can test those links. Nepalese sun-photometer, surface, chemical, airborne, transport, and health evidence is synthesized across urban valleys, the Terai, and high-elevation sites. The analysis gives particular attention to multiyear optical measurements in Lumbini and draws methodological lessons from neighborhood-level mobile monitoring in Massachusetts and a 2026 review of remote-sensing technologies in the United States. Those international studies inform method selection rather than supply Nepal-specific effect estimates. The synthesis shows that vertical mixing, aerosol water uptake, particle composition, sampling gaps, and neighborhood heterogeneity can produce different trends in AOD and surface PM. It proposes a cross-platform validation strategy linking reference PM monitoring, calibrated mobile sensors, ground-based and satellite optical observations, vertical profiles, meteorology, and uncertainty-aware data fusion. This approach could improve exposure-relevant estimates and event-specific forecasting in complex Himalayan terrain.

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Nepal provides a demanding natural laboratory for aerosol research. Over relatively short horizontal distances, polluted urban basins, the rain-exposed central hills, the low-elevation Terai, and high Himalayan environments occupy sharply different meteorological and emission regimes. Motor vehicles, household fuels, road dust, brick kilns, open burning, and secondary atmospheric chemistry influence lower-atmosphere particles; seasonal fires and the IndoGangetic Plain contribute additional regional loading (Islam et al., 2020, 2022; Kafle et al., 2025; Zhong et al., 2019). Yet aerosol loading observed by a sun photometer is not the concentration inhaled at a bus stop, school, or residence. The methodological distinction matters because a column-integrated measurement may increase as aerosols are lofted above a valley even while the lowest few meters become cleaner—or the reverse may occur beneath a shallow, stagnant boundary layer.

Existing Nepalese studies provide increasingly detailed descriptions of aerosol optical climatology, compositional mixtures, radiation effects, regional transport, and human health consequences. For example, the broad national synthesis by Pandey et al. (2026) surveys AOD variability and associated evidence across observation domains. The question pursued here is different. Rather than repeating a countrywide catalog of seasons, sources, and impacts, this review examines the inferential chain: how emissions are transformed and mixed, how different instruments detect those processes, and under what conditions an observation can be used to estimate human exposure. The goal is to move from coexistence of datasets toward tests that distinguish competing explanations. The distinction is supported by fundamental measurement physics. AOD at wavelength λ is the vertical integral of atmospheric extinction, approximately $AOD(\lambda) = \int \beta ext(\lambda, z)\, dz$. In contrast, surface PM2.5 is a size-selective mass concentration measured near human activity. They are linked through particle size, composition, water uptake, optical efficiency, vertical distribution, and local

meteorology—not by a fixed conversion factor. Studies measuring optical properties over Pokhara, Lumbini, Kathmandu, and the high Himalaya describe the column dimension (Acharya et al., 2020; Jha et al., 2021; Ramachandran & Rupakheti, 2021). Ground monitors and personal samplers reveal partly different outcomes (Carson et al., 2026; Chalise et al., 2025; Dhital et al., 2014).

Three complementary studies clarify where cross-scale inference succeeds or fails. At Lumbini, Sapkota, Gautam, Pokhrel, et al. (2023) derived aerosol optical and microphysical properties from multiyear AERONET observations, providing strong evidence about the atmospheric column but not a direct measure of human inhalation. In Massachusetts, O'Leary et al. (2023) combined regulatory observations and GPS-linked mobile particle sensing, identifying the importance of time-varying pollution episodes and the limits of neighborhood snapshots. More recently, Sapkota et al. (2026) reviewed ground-based, airborne, and satellite remotesensing systems in the United States and emphasized calibration, data fusion, and differences in spatial and temporal resolution. Taken together, these studies motivate a testable distinction among (a) what sensors detect, (b) what atmospheric processes connect those observations, and (c) what people actually encounter near the ground.

This review addresses four questions. First, which atmospheric processes produce systematic differences between aerosol-column and surface signals? Second, how do topography, inversion structure, hydrometeorology, and seasonal sources alter those processes across Nepal?

Third, how should source chemistry, radiative feedback, and remote-sensing products be combined without claiming unsupported causal attribution? Fourth, what practical observational and validation strategy could improve exposure-relevant prediction and decision making?

REVIEW APPROACH AND SCOPE

A critical integrative narrative design was used because the supplied evidence spans optical climatology, aerosol chemistry, transport, remote sensing, exposure, and regional modeling rather than a single comparable effect measure.

The review does not claim to be a systematic literature search. No exhaustive database strategy, prospective protocol, risk-of-bias tool, or PRISMA screening sequence was undertaken, and no pooled meta-analytic effect is presented. Instead, studies were appraised for directness of measurement, physical interpretability, spatial and temporal scale, whether seasonal associations were distinguished from mechanistic tests, and whether source or health conclusions required assumptions not directly observed. We distinguish Nepal-specific results from external methodological analogs throughout.

A weight-of-evidence interpretation is particularly important for studies using related AERONET measurements or partly overlapping periods. Agreement among publications that reuse similar observations does not create fully independent replication. Conversely, discordant surface and column results need not imply measurement failure: they may reflect actual changes in mixing height, aerosol type, or cloud-filtered sampling. When the underlying records differ in season, location, wavelength, height, or sampling completeness, numerical values are intentionally not pooled.

The international comparison is deliberately bounded. The Lumbini optical study (Sapkota,

Gautam, Pokhrel, et al., 2023) is treated as Nepal-specific evidence; the Massachusetts mobilemonitoring study (O'Leary et al., 2023) and the United States sensing-technology review (Sapkota et al., 2026) are used to assess portability of measurement principles, not to transfer concentration statistics, seasonal cycles, or health risks.

METEOROLOGY AS THE LINK BETWEEN EMISSIONS AND OBSERVED POLLUTION

At a fixed emissions rate, breathing-zone PM can change markedly with the depth and stability of the air volume into which pollutants mix. Stable nocturnal conditions restrict turbulent exchange, and valley floors can accumulate emissions beneath cold pools. During daytime heating, mixed-layer growth may dilute near-surface concentrations while redistributing particles upward. Valley and slope winds may ventilate one location while transporting pollutants into another. The observed associations among rainfall, temperature, humidity, winds, and particles in Kathmandu (Telee et al., 2026) and Lumbini (Rijal et al., 2025) are consistent with this process picture, but their observational design alone cannot isolate a single driver from simultaneous changes in emissions and air-mass history.

It is useful to distinguish an inversion from a complete explanation of pollution. An inversion is a vertical temperature structure, whereas exposure depends on inversion height and persistence, emissions below and above it, exchange across layers, advection, and the time of measurement. The Birmingham study by Moustafa et al. (2026) illustrates the analytical payoff of separating surface-based, elevated, and lower-tropospheric inversions using surface observations and radiosondes. Reported inversion-type associations with PM2.5 were not uniform, and episodes involved multilayer conditions. Those numerical relationships belong to Birmingham, Alabama; they should not be transferred to Kathmandu or Pokhara. The transferable method is the need for inversion-type and mixing-height classification rather than a binary "inversion present" indicator.

Nepal-specific measurements provide complementary evidence. Airborne observations near Pokhara found changes in aerosol number, size, absorption, and meteorology with altitude (Singh et al., 2019), establishing that surface monitors cannot be assumed

to represent the full column. Historical high-Himalayan measurements documented transported mineral dust and carbonaceous aerosol (Carrico et al., 2003; Duchi et al., 2011). Together these studies favor models that resolve aerosol layers and dynamically varying mixing depths. In a mountain valley, a kilometer of altitude is not merely a proxy for distance from emissions: it can change which atmospheric layer the observing instrument samples.

Precipitation and relative humidity exert competing effects that must be disentangled.

Hygroscopic growth increases particle size and optical extinction in moist air, potentially raising AOD without a proportional increase in dry particle mass. Rain scavenges aerosols, changes source activities, and is correlated with cloudy conditions that eliminate many satellite and sunphotometer retrievals. Thus a lower monsoon AOD is partly a physically plausible wet-removal signature and partly a statement about observations obtainable between clouds. Long records from Pokhara show a pre-monsoon maximum and monsoon minimum (Ramachandran & Rupakheti, 2021); more recent Pokhara observations support similar seasonality while highlighting wavelength-dependent differences. Both mechanisms and sampling must be considered when turning seasonal comparisons into trend statements.

Columnar water vapor is not interchangeable with precipitation, relative humidity, or liquid water inside aerosol particles. Sapkota, Gautam, Gautam, and Ale (2023) compared AOD– precipitable-water relationships across international AERONET sites and emphasized context dependence. In an independent Lumbini analysis using 2013–2019 AERONET observations, Sapkota, Gautam, Pokhrel, et al. (2023) examined spectral AOD, Ångström parameters, singlescattering albedo, refractive index, asymmetry, and visibility. The authors reported mean AOD at 675 nm of 0.18 ± 0.12 for the monsoon and 0.61 ± 0.38 for the higher-loading post-monsoon period, as summarized in their abstract; they also estimated mean visibility of 8.76 ± 4.95 km. Their wavelength-specific linear fits between AOD and precipitable water showed low explanatory power (reported R^2 values of approximately 0.01–0.04). These are optical and statistical observations, not direct measurements of rainfall washout or source-specific PM mass. Spectral studies in Nepal and the Himalayan foothills (Acharya et al., 2020; Rijal et al., 2025; Rupakheti et al., 2018) further show why Ångström exponent, wavelength, aerosol type, and the sampling window need to accompany AOD magnitude when interpreting meteorological associations.

SPATIAL CONTRASTS AS PROCESS TESTS

Kathmandu is the best-studied basin but should not be treated as a national template. During the NAMaSTE pre-monsoon campaign, Islam et al. (2020) documented multiple particulate and trace-gas sources as well as meteorology-sensitive aerosol chemistry. Winter PM observations across Ratnapark, Lalitpur, and Dhulikhel subsequently revealed substantial differences in fine and coarse particle mass and composition over short distances (Islam et al., 2022). These contrasts are consistent with heterogeneous source proximity and ventilation; neither an urban average nor a single optical station captures all population microenvironments. The winter optical and radiative measurements reported by Cho et al. (2017) provide additional column properties but do not independently determine the surface exposure of commuters or children.

Pokhara offers an important test of whether the same pathway operates in a wetter Himalayan basin. Ramachandran and Rupakheti (2021) described interannual and seasonal optical changes influenced by combustion, dust, fires, and transport, whereas Kuikel and Pandey (2026) examined a newer multiyear optical window. Surface observations in three Pokhara locations were compared by Pandey et al. (2024), helping reveal spatial differences that a single city-center monitor might conceal. Comparisons of Lumbini, Pokhara, and Langtang Base Camp (Sapkota, Gautam, Gautam, Poudel, et al., 2023), along with cross-regional Ångström exponent analysis in a master's dissertation (Pokhrel, 2023), provide useful particle-size context; however, dissimilar site elevations and sampling intervals prevent interpreting raw intersite AOD differences as proportional differences in inhaled fine-particle dose.

The lowland Terai and Lumbini are strongly influenced by the regional aerosol background. Jha et al. (2021) compared optical properties at several Nepalese locations, and Rijal et al. (2025) specifically examined meteorological associations at Lumbini. The relationship among observed AOD, industrial and traffic emissions, relative humidity, and regional inflow changes across seasons. New satellite–reanalysis fusion in southern Nepal (Lamichhane et al., 2026) is a promising advance for areas without dense ground monitoring, but its scientific value is conditional on spatially independent testing and validation across meteorological regimes. A model that reproduces the average dry-season signal may still miss acute exposure beneath locally shallow mixing layers.

The Lumbini work provides a useful lowland anchor for the present review because its observables address different parts of the optical mechanism. The Ångström exponent constrains the spectral signature of particle size, single-scattering albedo distinguishes the relative contributions of scattering and absorption, and visibility responds to extinction near the observer; none independently identifies a unique combustion source or the surface PM2.5 concentration. Sapkota, Gautam, Pokhrel, et al. (2023) interpreted seasonal contrasts in terms of mixed anthropogenic and biomass-burning aerosols, but source contributions were not quantitatively separated by chemical receptor modeling. Juxtaposing that study with Kathmandu's chemically resolved campaigns (Islam et al., 2020, 2022) and with satellite–reanalysis fusion in southern Nepal (Lamichhane et al., 2026) therefore suggests a concrete validation

experiment: colocate optical measurements, dry-mass PM2.5, aerosol speciation, and meteorological profiles in Lumbini before attributing optical change to ground-level exposure or a particular source.

Eastern and western Nepal provide deliberately different checks on a Kathmandu-centered account. Festival-associated perturbations in eastern Nepal (Dahal, Bhattarai, et al., 2022) suggest that emissions can change over short timescales, while an eastern-foothill optical investigation

(Dahal, Rupakheti, et al., 2022) points to mixed local and regional influences. In western Nepal, Maharjan et al. (2026) linked elevated PM2.5 around Rara to forest-fire episodes, air-mass transport, and meteorological conditions. Comparison of urban Ratnapark with remote Rara (Chalise et al., 2025) further supports a contrast in source and exposure setting. These places are especially valuable for testing transported-plume mechanisms because they do not share Kathmandu's density of local urban emissions.

High-altitude observations should be retained even when the chief policy outcome is health at lower elevations. Jomsom observations described aerosol spectral variability in a high-mountain setting (Shrestha et al., 2015). In Langtang National Park, Shrestha, Gupta, et al. (2025) investigated aerosol–ozone associations; this provides an atmospheric-composition perspective without establishing a causal aerosol effect on ozone. High-altitude optical and forcing studies at or near Yala Glacier (Rai et al., 2019) and empirical AOD estimation across the Nepalese cryosphere (Bhattarai et al., 2019) show where satellite retrieval and vertical transport become challenging. An aerosol layer that produces significant radiative effects above populated valleys could contribute little immediate surface mass at that location; conversely, a surface accumulation event can create very high exposure without exceptional total-column optical loading.

WHAT MEASUREMENT SYSTEMS CAN—AND CANNOT—ESTABLISH

AERONET and related sun-photometer observations offer calibrated spectral column information under suitable sky conditions. They can constrain aerosol loading, particle-size indicators, and selected optical properties, yet cannot by themselves identify a vertical aerosol distribution or an individual's inhaled mass. Satellite AOD expands spatial coverage but introduces retrieval uncertainty over complex surfaces and in cloud-affected scenes. Empirical cryospheric

AOD reconstruction (Bhattarai et al., 2019) and land-use/AOD analyses in Kathmandu (Shrestha, Chand, et al., 2025) therefore have different inferential strengths: the former addresses observational coverage, whereas the latter offers spatial associations that may be confounded by emission density, surface reflectance, elevation, and meteorology.

The wider sensor landscape is described by Sapkota et al. (2026) in Environmental Monitoring and Assessment. Their United States review covers ground instruments, aircraft and other airborne platforms, satellite imagers, multispectral and hyperspectral techniques, and datafusion workflows applied to natural and human-related emission sources. Its principal contribution here is a technology-selection and comparability framework: a satellite provides regional coverage but not uninterrupted cloud-free sampling or intrinsic ground-level specificity; a ground station can establish local accuracy but cannot alone recover three-dimensional transport; airborne profiling supplies vertical information but at limited sampling times. Crossplatform calibration, consistent units and averaging windows, spatial support, and independent validation are prerequisites before fusing these different measurements. These recommendations are particularly relevant to Nepal, where terrain changes both satellite retrieval conditions and the atmospheric layer sampled by a valley-floor monitor.

Dry gravimetric PM, reference-grade continuous measurements, and calibrated low-cost sensors provide more direct surface evidence, but each samples a specific location, size fraction, humidity environment, and time interval. Particularly for low-cost optical PM sensors, relative humidity and aerosol composition can change measurement response. Thus apparent spatial differences should be tested against collocated reference measurements and meteorological variables rather than treated as definitive source contrasts. The urban–remote measurements by Chalise et al. (2025), site comparisons in Pokhara by Pandey et al. (2024), and meteorological time series in Kathmandu by Telee et al. (2026) demonstrate the value of repeated surface observations while exposing gaps in vertical and personal representativeness.

O'Leary et al. (2023) illustrate the practical design and limitations of mobile neighborhood sensing. Their Massachusetts investigation combined United States Environmental Protection Agency monitoring records with GPS-referenced, car-mounted AirBeam 3 measurements of PM1, PM2.5, and PM10, alongside relative humidity and route location, during repeated sessions in 2023. They mapped readings against the Social Vulnerability Index and reported that temporal differences between sampling days, including Canadian wildfire-smoke episodes, were more conspicuous than the smaller neighborhood contrasts in their sampled routes. A brief comparison of the portable sensor with regulatory information also revealed a mismatch associated with non-equivalent sampling windows and possible sensor-response factors; it was not a full field calibration across concentration and humidity ranges. For a Nepalese adaptation, repeated fixed-route measurements and reference collocation would be necessary to distinguish neighborhood hotspots from time-of-day, meteorological, traffic, and instrument effects.

Particle composition substantially improves mechanism identification. The pre-monsoon NAMaSTE dataset resolved combustion-related gases and aerosol chemistry (Islam et al., 2020), while high-time-resolution mass spectrometry identified organic-aerosol factors and secondary material (Werden et al., 2022). Winter observations across three Kathmandu sites identified varied organic, black-carbon, and inorganic contributions (Werden et al., 2023), with related fine/coarse mass analysis from Islam et al. (2022). Werden's (2021) doctoral synthesis offers deeper sourceapportionment context. These data support mixed primary and secondary sources rather than a single homogeneous haze. Chemical factors, however, are inferred from tracer patterns and modeling assumptions; they should be interpreted with uncertainty and compared against local emissions inventories and meteorology.

Source testing provides a complementary constraint. Zhong et al. (2019) measured emissions from Kathmandu vehicles and brick kilns and evaluated effects on chemical transport model simulations. If source-specific emissions are incorrect, fitted meteorological relationships may absorb inventory error and appear more predictive than they are physically. Chemical source profiles collected during a short campaign can also change with season, fuel, technology, and operating practices. A robust system therefore cross-checks receptor factors, bottom-up inventories, transported background concentrations, and atmospheric transformation rather than choosing one as authoritative.

Neither surface PM nor AOD alone constitutes a personal health-exposure study. Dhital et al. (2014) documented pollution within Kathmandu public transport, and Carson et al. (2026) examined personal PM2.5 exposure among children in Kathmandu and Bandung. These sources show why microenvironments, travel patterns, and indoor–outdoor time matter. O'Leary et al.
(2023) add an international monitoring analogy: mobile sensing can reveal where fixed stations may lack spatial detail, but measurements taken from a moving vehicle still reflect a sampled route and period rather than every resident's dose. Their finding that sampling-day variation was larger than many within-route differences is a reminder that mobile campaigns must be temporally repeated and meteorologically matched. For Nepal, the defensible next step is to integrate fixedsite, mobile, and personal sampling rather than treating any one as a complete exposure measure.

LINKING NEPALESE OBSERVATIONS WITH INTERNATIONAL MULTIPLATFORM RESEARCH

These studies are complementary precisely because their observational targets differ. The
Lumbini paper measures column extinction and wavelength-dependent optical behavior (Sapkota, Gautam, Pokhrel, et al., 2023); the Massachusetts paper evaluates near-surface particle observations at neighborhood and event timescales (O'Leary et al., 2023); and the 2026 Environmental Monitoring and Assessment review catalogues cross-platform remote-sensing capabilities and integration constraints (Sapkota et al., 2026). The methodological question is not which platform is superior in isolation, but whether observations from distinct atmospheric volumes, time windows, and error processes can jointly explain exposure-related variability. A practical synthesis has four ordered stages. First, define a common space–time unit and flag clear-sky selection, route coverage, and missing records. Second, calibrate surface sensors against reference PM instruments and evaluate the dependence of optical sensor response on humidity and aerosol composition. Third, introduce vertical or boundary-layer information to determine whether observed AOD lies near the breathing zone or primarily aloft. Fourth, train and test satellite–surface estimates using geographically and temporally independent folds, reporting errors by season, aerosol type, elevation, inversion regime, and fire-smoke status. The international evidence supports this study design, while its success in Nepal remains an empirical question requiring new collocated measurements.

This cross-scale view also makes publication-to-publication comparisons more defensible. The seven-year Lumbini AERONET series cannot be compared numerically with brief mobile sensing routes in Massachusetts, because the studies use different physical quantities, heights, averaging periods, climates, and source environments. Nor does a U.S.-focused catalogue of sensing platforms establish that a particular sensor is accurate in Nepal's rainy valleys or bright high-altitude terrain. What can transfer is the transparent logic of measurement validation: common reference scales, explicit uncertainty, representative sampling, and assessment of whether added instruments improve prediction at the endpoint that matters.

Table 1. **Interpretive reach and limitations of major aerosol evidence types**

Observable	Typical instrument or platform	Can support	Cannot alone support
Column AOD / spectral optical	AERONET sun photometer, satellite imager	Spectral extinction, Ångström exponent, optical properties	Surface concentration, individual dose, causal source fraction

Surface PM2.5 and PM10	Reference monitors, calibrated lowcost and mobile PM sensors	Near-surface mass and sampled streetlevel variation	Personal dose, complete neighborhood or seasonal representation
Vertical layer structure	Aircraft, lidar, radiosonde or balloon profiles	Layering, stability and mixing depth	Surface mass or health burden without concurrent PM data
Aerosol chemistry	Filter analysis, mass spectrometry	Source markers, secondary components	Unique source percentages without model uncertainty
Transport and events	Trajectories, fire products, emission inventories	Candidate pathways, plume timing	Definitive national attribution from trajectories alone
Personal exposure and burden	Portable samplers, health modeling	Microenvironmental exposure or modeled burden	Direct causality without epidemiological assumptions

Note. AOD = aerosol optical depth; PM = particulate matter. "Cannot alone support" denotes missing inferential links, not lack of scientific value.

RADIATIVE FEEDBACKS, TRANSPORT, AND THE INTERPRETATION OF POLLUTED EVENTS

The aerosol–meteorology connection is bidirectional. Absorbing particles change solar radiation and atmospheric heating; altered heating can then influence stratification and mixing.

Kathmandu radiative studies (Cho et al., 2017; Thapa et al., 2017) and high-altitude work near Yala Glacier (Rai et al., 2019) establish the need to consider radiative effects alongside visibility and PM. Ramachandran et al. (2023) evaluated Himalayan aerosol atmospheric heating, and Ramachandran and Rupakheti (2026b) synthesized aerosol composition and radiative forcing across the Indo-Gangetic Plain–Himalaya system. The existence of radiative interactions should not be overread as proof that any particular observed stagnation episode was aerosol-caused. Testing feedback requires time-resolved radiation, stability, and aerosol profiles or paired numerical experiments.

Regional transport adds a second reason why local pollution can diverge from local emissions. During the pre-monsoon, Gautam et al. (2011) documented aerosol accumulation toward Himalayan slopes. Duchi et al. (2011) described high-altitude dust transport at the Nepal Climate Observatory–Pyramid, while Rupakheti et al. (2018) investigated optical properties at foothill locations. Kafle et al. (2025) combined observations and trajectory-based methods for Kathmandu regional influences. These independent modes of evidence support transport as a real process, although backward trajectories are probabilistic indicators of source pathways rather than direct measurements of the fraction of a ground-level PM sample attributable to another country.

Wildfire smoke provides an especially relevant stress test. Fire activity can alter particle concentrations, size distributions, absorption, and population exposure over hours to days, while the same transport event may be detected by optical instruments aloft before it reaches ground sensors. Kuikel et al. (2025) evaluated wildfire-smoke-related mortality in Kathmandu, and Maharjan et al. (2026) documented the interaction of transport, fires, and meteorology in western Nepal. Regional interpretation in Ramachandran and Rupakheti (2026a) reinforces the difference between long-term background and episodic intrusions. Proper event attribution requires simultaneous fire detections, wind and layer heights, chemical markers where feasible, and sensitivity analysis of trajectories.

Related international case studies illustrate what to test rather than what quantitative result to import. In Florida's Everglades Agricultural Area, El Afandi et al. (2026) combined particle source characterization with trajectory modeling, illustrating multimethod attribution in an agricultural setting. The Birmingham study of Moustafa et al. (2026) points to inversion-type classification as a meteorological design choice. O'Leary et al. (2023) further show that mobile PM sensors can supplement regulatory stations while introducing route and temporal-sampling biases. At the systems level, Sapkota et al. (2026) explain why airborne, satellite, and ground technologies must be compared and calibrated before data fusion. For Nepal, the common lesson is to triangulate optical, vertical, chemical, and mobile surface evidence; the U.S. studies do not establish Nepalese emission fractions, inversion coefficients, or health effects.

FROM AMBIENT LEVELS TO EXPOSURE AND HEALTH DECISIONS

The final link in the inference chain is health. Modeled ambient concentrations have been used to estimate PM2.5-attributable mortality in Kathmandu (Tuladhar et al., 2021), and more recent government-monitoring-based work estimated health and economic burdens (Adhikari et al., 2026). A Nepal-focused health review summarized respiratory, cardiovascular, and policy concerns (Joshi et al., 2026). These investigations make clear that pollution is a public-health issue, but each burden estimate is conditional on the exposure surface, concentration–response relationship, baseline rates, counterfactual, and population distribution assumed. AOD maps by themselves cannot resolve those assumptions.

Interpretation should further distinguish concentration, exposure, dose, and attributable burden. Concentration describes pollutant in an environment; exposure incorporates human location and time; inhaled dose also depends on breathing and deposition; attributable burden incorporates epidemiological relationships and baseline risk. Dhital et al. (2014) and Carson et al. (2026) address a part of the ambient-to-personal gap. Meanwhile, population growth during recurring smoke episodes can raise numbers exposed even if the monitored long-term PM trend is stable (Kuikel et al., 2025). Consequently, policy evaluation should report both changes in hazard and changes in the distribution of exposure, rather than relying solely on an annual AOD or station-average PM decline.

Equity-relevant priorities follow directly. Outdoor workers, public-transport users, households near combustion sources, children at schools near traffic, and remote communities receiving transported smoke may differ substantially in exposure. These categories should not be assigned numerical risks without local data, but they can guide stratified sampling. A defensible study would compare personal and fixed-site PM, record activity and indoor–outdoor time, and assess how predictive errors vary by neighborhood, season, and meteorological regime. The goal is not just a more accurate satellite-to-PM regression, but a demonstrably more useful representation of where exposure occurs.

A PROCESS-BASED RESEARCH AND VALIDATION FRAMEWORK

The literature supports a hierarchical observational design rather than a single universal
AOD-to-PM model. First, define the endpoint—column extinction, surface mass, personal exposure, or a health outcome—before selecting predictors. Second, colocate reference PM instruments, calibrated low-cost sensors, AERONET measurements where available, precipitation and humidity sensors, wind observations, and representative vertical measurements of aerosol or mixing height. Third, classify shallow stable layers, well-mixed afternoons, wet scavenging, transported smoke, and dust-dominated events. Fourth, test whether estimates remain valid across new sites and years, rather than random observations from the same time series. The optical variables characterized for Lumbini (Sapkota, Gautam, Pokhrel, et al., 2023), repeated route sampling demonstrated in Massachusetts (O'Leary et al., 2023), and multisensor fusion issues reviewed by Sapkota et al. (2026) provide complementary starting points for this protocol.

For empirical surface estimation, a conceptual model may be written $PM_{2.5,surface} = f(AOD_{\lambda}$, aerosol-type indicators, boundary-layer height, RH, precipitation, temperature, wind, transported-background indicators, elevation, and season). This expression is a hypothesis about covariate roles, not a fitted formula or evidence that every factor improves prediction. Satellite AOD retrieval quality, temporal matching, missingness, and spatial support should be represented explicitly. Site-blocked and year-blocked validation can expose overoptimistic skill from spatial or temporal leakage. Comparisons should include simple season-only and persistence baselines as well as models with vertical information; the incremental skill of each data stream is the scientifically meaningful result.

Source attribution should be evaluated as a distinct task. Trajectories identify candidate origins; aerosol optical features suggest size or absorbing behavior; receptor chemistry constrains source categories; and emission inventories estimate activities. No one component supplies a complete causal estimate. A coordinated campaign could compare receptor-derived source factors with modeled local and transboundary contributions under multiple meteorological states.

Sensitivity runs that alter emissions while holding meteorology fixed—and conversely alter meteorological inputs while retaining emissions—would better separate drivers than ordinary correlations. The chemistry-oriented Kathmandu studies provide candidate tracers and factor structures, while Rara and eastern-foothill observations provide contrasts with very different local emission patterns.

A health-facing validation step should follow atmospheric validation rather than be assumed to arise automatically from it. Personal or microenvironmental monitors can quantify whether improvements in predicted outdoor concentrations meaningfully reduce exposure error for relevant groups. Uncertainty should be reported in physical units, at episode thresholds, and by season and location. Public warnings should be evaluated on event detection, lead time, and false alarms, not just annual average prediction scores. Policy evaluation should explicitly compare emission-reduction periods with suitable meteorological controls to avoid crediting cleaner weather to an intervention.

The implementation priorities are feasible in stages. An initial network could prioritize one contrasting lowland site, two urban valleys, an eastern or western transport corridor, and one highaltitude background location. A nested intensive campaign could

obtain chemistry and vertical profiles in winter stagnation and pre-monsoon fire periods, with continuing lower-cost surface measurements in other months. Protocols should record sensor calibration, cloud-screened optical sampling, reference-site representativeness, trajectory uncertainty, and missing values. The value of network expansion should be judged by the reduction in predictive and attribution uncertainty rather than sensor count alone.

One pilot design could pair dry-season and monsoon measurements in Lumbini with selected Kathmandu and Pokhara sites. AERONET retrievals would be matched to surface PM2.5 only within defined observation windows; mobile routes would be repeated at fixed times and across contrasting meteorological regimes; occasional lidar or balloon/radiosonde profiles would identify aloft aerosol layers and mixing depth. Optical descriptors such as Ångström exponent and single-scattering albedo would be evaluated as aerosol-type information, not presumed ground-level source fractions. The key outcome would be an out-of-site, out-of-season improvement in PM estimation over a meteorology-only baseline, together with transparent uncertainty and event detection metrics. This adapts the validation logic of Sapkota et al. (2026) and O'Leary et al. (2023) to the geographic and optical constraints illustrated by Sapkota,
Gautam, Pokhrel, et al. (2023).

Table 2.Meteorological states and process-oriented validation checks

State	Plausible measurement contrast	Required check
Stable valley / shallow mixing	High near-surface accumulation can coexist with moderate column AOD	Record layer depth, time of day, valley winds, local emissions
Daytime mixed layer	Surface mass may fall as aerosols redistribute vertically	Synchronize ground and column retrievals; profile layers
Humid non-rain interval	Optical extinction may change through water uptake	Measure RH, aerosol size/composition, sensor response
Monsoon rain/cloud	Wet removal occurs; clear-sky retrieval samples also change	Log rainfall and cloud-driven missingness separately
Fire / dust transport	Aloft plume may precede or miss local surface maximum	Combine satellite, profiles, chemistry and trajectories

Note. Contrasts are conceptual hypotheses for field testing, not uniform empirical effects across Nepal.

LIMITATIONS OF THE EVIDENCE AND OF THIS REVIEW

Several constraints prevent stronger quantitative claims. The Nepalese optical investigations use different years, wavelengths, observation completeness, and elevations; the
Lumbini study also contains differences in seasonal maximum (Sapkota, Gautam, Pokhrel, et al., 2023). Chemical campaigns cluster in Kathmandu, while remote mountainous locations and the
Terai have fewer sustained collocated records. Mobile sampling from Massachusetts and broad United States remote-sensing evidence help identify methodological risks, but neither offers direct validation for Nepal's meteorological and geographic regimes (O'Leary et al., 2023; Sapkota et al., 2026). Available personal-exposure studies are sparse relative to diverse occupations and home environments. A harmonized national dataset with simultaneous column, vertical, chemical, surface, and personal observations does not yet emerge from these sources; consequently, national conversion factors, source fractions, or pooled exposure-effect coefficients cannot be justified.

This is a purposively assembled critical review, not a systematic review or quantitative meta-analysis. The input set comprises journal papers, conference research, dissertations, partly overlapping records, and studies from outside Nepal, so evidence strength is heterogeneous.
Several older or geographically remote studies function only as methodological comparators. The United States remote-sensing review by Sapkota et al. (2026) was accessible through its publisher abstract and publication metadata, not its subscription-only full text; its specific assertions are therefore limited to those public materials. Some papers were available principally as scanned pages or bibliographic records, and individually linked Google Scholar citation metadata could not be reliably retrieved. These limitations are reported openly rather than obscured by unsupported quantitative synthesis.

Interpretation is also vulnerable to causal ambiguity. Meteorological predictors are correlated with one another and with seasonal emissions, and similar aerosol observations can be generated by different mixtures of sources and atmospheric histories. Therefore a study relating

AOD to humidity or PM to inversion frequency should not automatically be described as measuring the causal effect of that predictor. The proposed framework provides testable designs; it does not imply that the required comparisons have already been performed.

CONCLUSION

Understanding air pollution in Nepal requires more than knowing where aerosol columns are optically thick. Column extinction, breathing-zone particle mass, personal exposure, and health burden are linked but non-equivalent endpoints. Across Kathmandu, Pokhara, Lumbini, the Terai, western Nepal, and high Himalayan locations, the evidence demonstrates that emissions interact with atmospheric stability, vertical mixing, precipitation, secondary chemistry, and long-range transport in ways that change what each instrument observes. The strongest mechanistic opportunity is to measure these interacting processes together rather than to seek a constant conversion between satellite AOD and surface PM2.5.

A differentiated research agenda emerges: classify atmospheric layers, validate satelliteto-surface estimates in physically distinct weather states, connect chemical source profiles to transport pathways, and assess whether better ambient estimates improve personal-exposure predictions. Lumbini's spectral optical evidence (Sapkota, Gautam, Pokhrel, et al., 2023) can be paired with the repeated mobile-monitoring approach of O'Leary et al. (2023) and the crossplatform standardization and fusion principles outlined by Sapkota et al. (2026). These studies are not substitutes for new Nepalese measurements; rather, their combination offers a credible, internationally informed roadmap for collecting and evaluating those measurements. Moving from descriptive agreement among datasets to tested cross-scale inference would strengthen airquality warnings, emission-control assessment, and health decision making across the highly heterogeneous Himalayan environment.

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