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Research Article

Engineering Pathways for Clean-Air and Climate Resilience: Integrating Aerosol-Lightning Science, Emission-Control Technologies, and Early Warning in Eastern India

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ABSTRACT: This review presents a technology assessment and implementation-oriented decision-support framework for advancing clean-air management, industrial emission reduction, and clean-energy deployment in Eastern India, with particular emphasis on the Kolkata-Lower Gangetic region. It critically examines the applicability, technological performance, and implementation requirements of source-level emission prevention, industrial particulate-control systems, precursor-emission mitigation, energy-efficient processes, and integrated environmental monitoring infrastructures. Aerosol-cloud-convection-lightning interactions are considered primarily as relevant atmospheric constraints for environmental technology planning, monitoring-system integration, and weather-related risk assessment, rather than as the principal objective of technological intervention. Drawing upon recent scientific and engineering evidence, the review evaluates the complementary roles of electrostatic precipitators, fabric filtration, hybrid particulate-capture systems, cleaner energy pathways, calibrated air-quality sensors, satellite-based observations, and meteorological forecasting technologies. Particular attention is devoted to technology selection criteria, pollutant-removal efficiency, energy consumption, lifecycle expenditure, operational reliability, data quality, and institutional feasibility. In this context, a Kolkata Aerosol-Lightning Environmental Decision-Support Framework (KALEDSF) is proposed as a modular architecture integrating emissions inventories, ambient-air monitoring, meteorological observations, satellite-derived aerosol products, lightning detection, and aerosol-aware predictive modeling. The framework is conceptual and requires retrospective and prospective validation before operational deployment. Its implementation is envisaged through a phased approach encompassing technological assessment, data harmonization, performance verification, and stakeholder coordination. The proposed assessment establishes a practical basis for evaluating clean-technology deployment through measurable environmental and engineering indicators, including emissions avoided, energy penalties, cost-effectiveness, forecast skill, warning lead time, and equitable accessibility. By connecting emission-control engineering, clean-energy transitions, environmental monitoring, and climate-resilient decision support, this review advances an integrated technological perspective towards sustainable urban and industrial environmental management.

Keywords: Clean technology, Industrial emission control, Clean energy deployment, Environmental monitoring, Decision-support systems, Climate resilience, Eastern India.

1. INTRODUCTION: CLEAN-TECHNOLOGY ASSESSMENT AND ENVIRONMENTAL DECISION-SUPPORT

The transition to sustainable industrial development, improved ambient-air quality, and climate-resilient infrastructure increasingly requires integrating technologically feasible emission-control interventions, cleaner energy systems, and data-driven environmental management strategies. In rapidly urbanizing and

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industrializing regions, the effectiveness of environmental interventions depends not merely on the availability of individual pollution-control technologies but also on their engineering performance, economic viability, operational reliability, and compatibility with region-specific environmental conditions. Accordingly, assessing clean technologies must extend beyond isolated equipment-level performance to encompass integrated systems involving emission prevention, particulate and gaseous pollutant abatement, continuous environmental monitoring, predictive analytics, and evidence-based decision-making. From this perspective, developing an integrated technological framework for clean-air management is essential to translating environmental research into practical engineering and policy interventions.

Within this broader technological context, atmospheric processes, particularly aerosol variability, convective development, and lightning activity, constitute important environmental parameters influencing monitoring requirements and the interpretation of weather-related risks. Lightning is both a significant natural hazard and an atmospheric chemical process, contributing to upper-tropospheric nitrogen oxide production, influencing ozone chemistry, and indicating deep convection. Its occurrence is governed by interacting thermodynamic, microphysical, and dynamical conditions, including atmospheric instability, moisture availability, cloud development, and large-scale circulation. Consequently, variations in individual environmental parameters cannot be interpreted as deterministic indicators of lightning activity [1,3]. Across India, pronounced seasonal and regional variations in thunderstorm and lightning occurrence have been documented, particularly during pre-monsoon and monsoon periods [12,13]. For environmental technology assessment, these findings show the need to incorporate appropriate meteorological observations and hazard-monitoring capabilities into integrated environmental information systems, without treating atmospheric electrification as a direct performance indicator of emission-control interventions.

Aerosols constitute another important environmental variable because their atmospheric behavior involves radiative interactions, cloud-microphysical modifications, and region-dependent influences on convective development. Their interactions with incoming solar radiation can modify atmospheric heating and boundary-layer stability. In contrast, their roles as cloud condensation nuclei and ice-active particles can influence droplet populations, precipitation development, mixed-phase cloud processes, and charge separation. However, the resulting aerosol-convection-lightning relationship is nonlinear and dependent on particle size, chemical composition, humidity, cloud regime, and the prevailing thermodynamic environment. Recent numerical investigations over India have shown that aerosol concentrations associated with enhanced lightning activity vary across regions, precluding a universal aerosol optical depth threshold or an invariant aerosol-based operational criterion [5,13]. These scientific constraints inform the design of environmental monitoring networks, the selection of atmospheric predictors, and the development of regionally calibrated forecasting systems. Importantly, this review does not consider pollution control as a means of manipulating lightning occurrence. Rather, atmospheric aerosol-lightning interactions are incorporated as background scientific considerations for developing reliable environmental monitoring and decision-support technologies.

The principal engineering challenge, therefore, is identifying, assessing, and coordinating the implementation of technologies that reduce pollutant emissions, improve energy efficiency, strengthen environmental surveillance, and support climate-resilient management. Established intervention pathways include cleaner energy substitution, combustion optimization, industrial process efficiency, electrostatic precipitation, fabric filtration, hybrid particulate-capture systems, and the control of gaseous aerosol precursors. These technological interventions should be evaluated through measurable parameters, including pollutant-removal efficiency, energy consumption, capital and operational expenditure, equipment reliability, maintenance requirements, and lifecycle environmental performance. India-specific assessments have identified substantial opportunities to generate air-quality and climate-related co-benefits through the coordinated implementation of clean-energy and emission-reduction policies. However, the magnitude of these benefits depends on sectoral characteristics and implementation effectiveness [8,17]. Furthermore, recent evaluations of emission-control measures in India demonstrate that expenditure, pollutant reduction, ambient environmental improvement, and associated health outcomes must be assessed collectively rather than treating financial investment as an independent measure of technological effectiveness [18]. These considerations underscore the need for a comprehensive technology-assessment approach that links engineering performance to demonstrable environmental outcomes.

Eastern India, particularly the Kolkata metropolitan region and the adjoining Lower Gangetic environment, provides

a significant geographical context for examining the practical applicability of such integrated technological interventions. The region faces multiple, interacting environmental pressures from urban and industrial combustion, regional pollutant transport, marine atmospheric influences from the Bay of Bengal, elevated humidity, and pronounced seasonal meteorological variability. These characteristics necessitate an integrated environmental management approach in which source-level emission reduction, ambient-air surveillance, meteorological observation, and severe-weather preparedness operate as complementary but functionally distinct technological components. Integrating calibrated ground-based sensors, satellite-derived aerosol observations, meteorological datasets, and validated predictive systems can strengthen conventional pollution-control infrastructure. Such integration can improve environmental data availability, enable spatially resolved pollution assessment, and support timely communication of weather-related risks. Nevertheless, these technologies' operational feasibility must be established through region-specific validation, transparent performance indicators, and appropriate institutional coordination.

Against this background, this review adopts a technology-centered approach to examine the relationship between clean-technology deployment, environmental monitoring, and climate-resilient decision support in Eastern India. Its principal contribution is the proposed Kolkata Aerosol-Lightning Environmental Decision-Support Framework (KALEDSF), which integrates emissions information, air-quality measurements, meteorological observations, satellite-derived aerosol products, lightning detection, and predictive modeling within a coordinated environmental information architecture. The review pursues four interconnected objectives: (i) to examine aerosol-convection-lightning research relevant to India and identify its implications for environmental monitoring and technology-system design; (ii) to critically assess practical clean-energy, industrial emission-prevention, particulate-capture, and precursor-control technologies in terms of engineering performance and implementation feasibility; (iii) to propose an integrated, regionally adaptable environmental monitoring and decision-support architecture for the Kolkata metropolitan region; and (iv) to establish measurable technological, economic, environmental, and operational indicators for assessing implementation performance and identifying future validation requirements. Through this approach, the review seeks to bridge the gap between atmospheric environmental knowledge and its practical translation into clean-technology assessment, sustainable engineering applications, and accountable environmental decision-making.

2. REVIEW APPROACH AND EVIDENCE BOUNDARIES

This manuscript is a narrative, technology-oriented synthesis of the literature and datasets described in the source manuscript, supplemented by targeted literature verification for 2019-2026. It is not a new field experiment, a life-cycle assessment, or a validated numerical simulation. Existing satellite and reanalysis products mentioned in the source manuscript-including MODIS, CAMS, MERRA-2, TRMM-LIS, ISS-LIS, and meteorological reanalysis-are treated as potential evidence streams, not as a newly harmonized dataset analyzed here. Any quantitative statement attributed to an individual study is reported as that study's finding and should not be interpreted as a measurement generated by this review.

The review does not claim systematic-review exhaustiveness: no formal PRISMA screening, pooled effect-size estimate, or meta-analysis was undertaken. Consequently, the evidence synthesis is intended to support technology selection and research design, not to estimate a single global aerosol-lightning effect. Where a source reports model-derived thresholds, those values are treated as study-specific outcomes rather than operational cut-offs.

Evidence was organized into four engineering-relevant domains: (a) aerosol and lightning processes; (b) emission prevention and end-of-pipe control; (c) sensor, satellite, and model integration; and (d) operational governance and evaluation. Peer-reviewed sources from 2019-2026 were prioritized where available. Foundational references outside that window are retained only where necessary for context. Because the editorial assessment provided a scope-level requirement rather than numbered, line-specific reviewer queries, the change log at the end maps the substantive revisions to the numbered paragraphs in this revised file.

For transparency, the synthesis distinguishes three evidence classes: (i) observational associations, which establish co-variability but cannot by themselves identify causation; (ii) numerical sensitivity experiments, which can isolate mechanisms subject to model assumptions; and (iii) engineering-performance evidence, which is evaluated using source-specific emissions, energy demand, reliability, and lifecycle cost. The strength of inference is therefore not treated as uniform across these

classes. Studies are interpreted in the context of their spatial domain, temporal sampling, aerosol metric, lightning-detection method, and meteorological controls.

3. SCIENTIFIC CONSTRAINTS FOR ENVIRONMENTAL MONITORING AND EARLY-WARNING TECHNOLOGY ASSESSMENT

Atmospheric aerosol loading may be associated with convective and lightning variability, but the relationship is nonlinear and conditioned by meteorological state, aerosol characteristics, and regional climate. Satellite-derived aerosol optical depth (AOD) represents column-integrated aerosol loading and is not interchangeable with surface $PM_{2.5}$ concentration or cloud-condensation-nuclei abundance. $_5$ concentration or cloud-condensation-nuclei abundance. $_5$ concentration or cloud-condensation-nuclei abundance. $_5$ concentration or cloud-condensation-nuclei abundance. Observational and modeling studies over India report regionally variable aerosol-lightning associations, indicating that aerosol information should be interpreted alongside moisture, atmospheric instability, precipitation, and other relevant meteorological observations rather than as an independent or deterministic predictor [2,4,5,10,13].

For clean-technology assessment, the principal implication is therefore methodological: environmental monitoring and early-warning systems require multi-source observations, regional calibration, explicit uncertainty characterization, and independent validation. The available evidence does not support a universal aerosol threshold for lightning prediction, and lightning frequency must not be used as a direct performance indicator of pollution-control equipment [5,13,16]. The proposed KALEDSF should accordingly integrate satellite aerosol products with ground-based $PM_{2.5}$, meteorological and precipitation observations, atmospheric-instability indicators, and independent lightning-detection data. Pollution-control technologies should be evaluated separately on emissions reduction, removal efficiency, energy demand, reliability, and lifecycle cost. At the same time, assess early-warning capability based on forecast skill, detection probability, false-alarm characteristics, and warning lead time.

4. CLEAN-TECHNOLOGY PATHWAYS FOR EMISSION REDUCTION

4.1. Prevention Through Clean Energy and Process Efficiency

The first intervention tier is source prevention: reduce fuel consumption per unit of useful output, substitute lower-emission energy where technically feasible, electrify suitable end uses, improve combustion efficiency, and prevent uncontrolled biomass and waste burning. India-focused analysis indicates that coordinated air-quality and clean-energy policies can produce climate co-benefits, particularly when they include short-lived climate forcers alongside carbon dioxide [8,17]. These benefits vary across sectors, and local implementation should consider grid emissions, fuel supply chains, technology use, and affordability.

For industrial and institutional facilities, an engineering audit should identify thermal losses, inefficient motors and fans, leaks, poor combustion control, and avoidable process heat demand before selecting equipment. The energy baseline should be normalized by production or service output. Relevant indicators include energy intensity (kWh per unit output), fuel consumption, direct CO_2-equivalent emissions, and pollutant mass emitted per unit output. These indicators permit comparison before and after intervention and help prevent an apparent reduction in stack emissions from being offset by excessive electricity demand or increased upstream emissions.

4.2. Particulate Capture and Precursor Control

End-of-pipe particulate controls remain necessary where source prevention and process optimization are insufficient to achieve the applicable emission limits. Select technology based on the complete gas-cleaning train and the characteristics of the untreated stream, including volumetric flow, temperature, moisture, particle-size distribution, dust resistivity, inlet loading, corrosivity, and required outlet concentration. Electrostatic precipitators (ESPs), fabric filters (baghouses), wet electrostatic precipitators (WESPs), and ESP-fabric-filter hybrids provide technically distinct options. Although each can achieve high overall particulate removal under suitable design and operating conditions, their fractional performance for fine and submicrometre particles, auxiliary energy demand, maintenance burden, and retrofit requirements differ substantially [7,9,11,24,30].

Table **1** synthesizes representative engineering and cost benchmarks for preliminary technology screening. The efficiency values are indicative ranges reported for appropriately designed systems, not guaranteed plant-specific outcomes. Pressure-drop and energy figures are kept distinct because high-voltage power supplies and gas handling mainly drive ESP electrical consumption. In contrast, fabric filters impose a fan-power penalty that rises with filter-cake resistance and system pressure drop.

Table 1: Indicative techno-economic comparison of industrial particulate-control technologies

Technology	Indicative PM removal	Particle-size applicability	Pressure drop/energy demand	Capital-cost benchmark	Maintenance and principal constraints
Dry ESP (wire-plate)	Typically, 99-99.9% design efficiency; actual performance is dust- and operating-condition-dependent.	Broad size spectrum (approximately 0.1 to >100 μm); fractional efficiency may be lower in the submicrometre range.	Very low gas-side pressure drop; electrical demand for corona generation and rapping. Typical industrial benchmark: 0.05-2 kWh per 1,000 m³ [20].	US$10-33/scfm (EPA historical estimate; 2002 dollars; equipment-specific and excluding some auxiliaries).	Periodic electrode/rapping-system inspection, hopper evacuation, transformer-rectifier maintenance and control of dust resistivity, back-corona and re-entrainment.
Fabric filter/ baghouse	Typically, 99-99.9% for new systems; operating efficiencies reported at approximately 95-99.9%.	Effective for PM2.5, PM2.5 and fine particles; membrane media can improve submicrometre capture.	Higher than ESP because of filter-cake resistance; EPA guidance discusses maximum values of about 5-10 in. H_2O across the baghouse (≈1.2-2.5 kPa). Fan power and pulse-jet compressed air are material loads.	US$6-26/scfm (EPA historical estimate; 2002 dollars; excludes auxiliary fans and ductwork).	Bag and cage inspection/replacement, pulse-valve and compressed-air maintenance, differential-pressure monitoring; sensitive to temperature, condensation, abrasion, and sticky dust.
Wet ESP (WESP)	High-efficiency polishing; often >90% for fine particulate/aerosol fractions under suitable conditions; performance is stream-specific.	Particularly useful for submicrometre particles, acid mist, condensable aerosols, and fine residual dust downstream of upstream controls.	Low gas-side pressure drop; electrical demand plus water circulation, washing and effluent treatment. A 158-dataset assessment reported specific power consumption of 0.5-2.5 × 10^{-4} kWh/m³ [22].	US$40-200/scfm (EPA historical wire-pipe WESP estimate; 2002 dollars).	Requires corrosion-resistant materials, wash-water management, wastewater/slurry treatment and inspection of electrodes/nozzles; corrosion and water treatment influence lifecycle cost.
ESP-fabric-filter hybrid (EF/EFF)	Generally designed for very high overall removal; performance depends on ESP pre-collection, filter media and operating regime. No single transferable efficiency range is defensible across configurations.	Broad size spectrum; electrostatic preconditioning/pre-collection can reduce bag loading and improve capture of fine fractions.	Combined electrical and filtration demand; pressure drop is generally governed by the fabric-filter stage and its dust cake. Site-specific energy measurement is required.	No robust, universally comparable public cost range; normally higher integration/controls complexity than a stand-alone unit. Obtain vendor quotations on a common capacity and scope basis.	More complex controls and maintenance; potential benefits include reduced filter loading, but electrode, rapping, bag, pulse-cleaning, and bypass systems all require coordinated maintenance.

Note: PM = particulate matter; scfm = standard cubic feet per minute. The historical EPA cost values are screening benchmarks in 2002 US dollars, not updated 2026 prices. They are not directly comparable across device types unless gas flow, inlet loading, outlet target, operating hours, auxiliary equipment, installation scope, and cost year are harmonized. The cited energy and efficiency values are drawn from different process applications and should therefore be treated as indicative ranges rather than a head-to-head trial.

Published capital-cost benchmarks are retained in their original 2002 US-dollar basis where the underlying EPA fact sheets report that basis; they must not be interpreted as current quotations or compared without currency-year escalation, capacity normalization and consistent system boundaries [20,25-27].

Recent field evidence reinforces the need to evaluate energy performance alongside outlet emissions. A 2025 investigation of 22 fabric-filter and 21 electrostatic-fabric systems before ultra-low-emission upgrades, together with additional post-upgrade units, reported increased specific energy consumption after tighter particulate-control requirements; the authors observed a general energy-demand ordering of ESP > electrostatic-fabric integrated precipitator > fabric filter for the configurations assessed [23]. This result should not be generalized to every installation, but it demonstrates that achieving a lower outlet concentration may impose a measurable electricity and indirect CO_2 penalty. Similarly, WESP performance datasets show that the operating boundary should include auxiliary power, water, and alkali consumption [22].

Accordingly, procurement should compare annualized total cost rather than purchase price alone. At a minimum, the assessment should report installed capital expenditure; annual electricity, water, compressed air, and reagent costs; bag/electrode/catalyst replacement; labor and planned downtime; residuals treatment; and annual mass of PM removed. Calculate cost-effectiveness as the annualized system cost divided by the measured annual mass of pollutant avoided, and state the currency year, discount rate, plant lifetime,

capacity factor, and system boundary. Where site-specific quotations are unavailable, the cost column should explicitly remain a benchmark or qualitative category rather than an invented current price. Lifecycle accounting should also include indirect greenhouse-gas emissions from auxiliary electricity used by air-pollution-control devices. At the same time, hybrid filtration studies underline the importance of matching filter design to the particle-size distribution and process stream [29,30].

Particulate capture must also be integrated with gaseous-precursor control, as SO_2, NO_x, and volatile organic compounds (VOCs) contribute to secondary particulate formation. For SO_2, wet flue-gas desulfurization (FGD) is commonly selected for high removal requirements. In contrast, dry sorbent injection (DSI) can provide a lower-capital retrofit option, but its performance depends on sorbent chemistry and the downstream particulate collector. EPA cost-development guidance reports approximately 40-50% SO_2 removal for trona injection with an ESP and approximately 70-90% for sodium-based sorbent injection with a baghouse [28]. For NO_x, selective catalytic reduction (SCR) generally provides higher removal than selective non-catalytic reduction (SNCR), although catalyst cost, temperature window, ammonia slip, and pressure-drop effects must be considered; a recent comparative review reports typical SCR removal of 60-95% and SNCR removal of 25-75% [21]. Select VOC control based on volatility, concentration, recovery potential, and stream composition, using adsorption, condensation, solvent recovery, or thermal/catalytic oxidation as appropriate. These precursor-control processes complement, rather than substitute for, particulate collection.

Characterize captured fly ash, filter dust, scrubber sludge, and spent sorbents for chemical composition and leachability before reuse or disposal. Material recovery is appropriate only where the recovered material meets applicable product specifications and does not transfer hazardous constituents to another environmental compartment. The final technology decision should therefore be based on multi-criteria assessment of outlet compliance, size-resolved removal, energy and water demand, reliability, residuals management and lifecycle cost [9,11,24].

Figure **1** shows the hierarchy of prevention, capture, precursor control, and verification. This hierarchy is deliberately technology-neutral: it prioritizes avoiding emissions at the source where feasible, while retaining end-of-pipe systems for residual emissions that process redesign cannot eliminate. Support all performance claims with inlet-outlet measurements, operating logs, and clearly defined system boundaries.

4.3. Cost-Effectiveness and Accountability

The economics of control should be expressed transparently. At minimum, report capital expenditure, annual operating and maintenance cost, energy penalty, annual pollutant mass removed, cost per kilogram or tonne avoided, and expected equipment availability. Assess cost-effectiveness against measured emissions

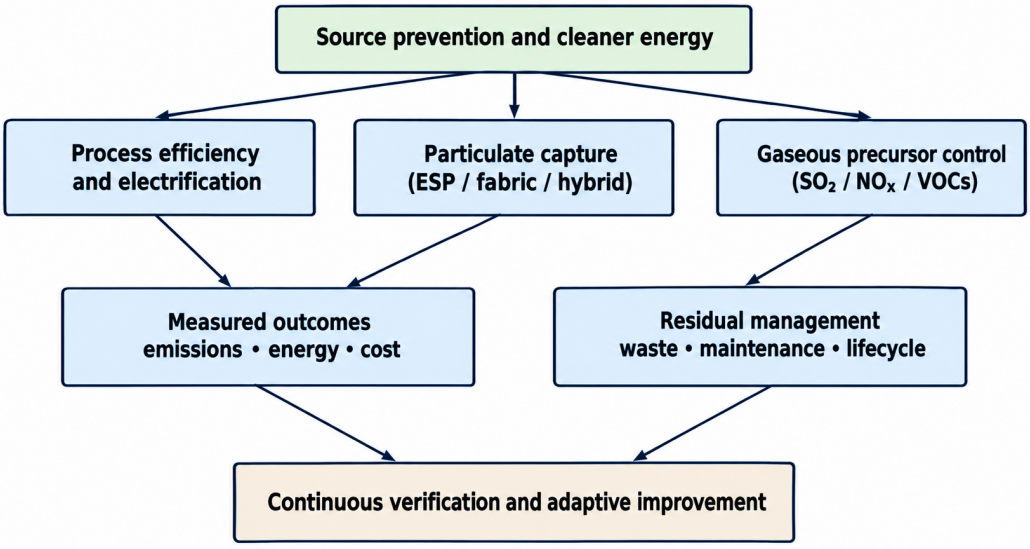


Figure 1: Engineering hierarchy for emission prevention and control, including performance verification and residual-material management.

and ambient outcomes, not just installed capacity or expenditure. A recent national modeling assessment found that the cost and health benefits of Indian emission-control measures varied over 2017-2022, illustrating the need for integrated pollutant-specific evaluation [18]. Experimental evidence from an industrial particulate-emissions market in Gujarat also indicates that regulatory design can affect compliance and abatement costs. However, the results should not be generalized without accounting for local institutional conditions [6].

To compare facilities, cost per unit emission avoided should use a stated currency year, operating lifetime, discount rate, and pollutant-specific mass basis. If health benefits are monetized, the exposure-response function and valuation assumptions should be reported separately from the engineering cost calculation. A technology that achieves high nominal removal but has low uptime, poor maintenance support, or unsafe residual handling may underperform a less complex system in real-world conditions.

5. MONITORING AND FORECASTING AS ENVIRONMENTAL TECHNOLOGY

5.1. A Tiered Observation Architecture

A practical urban system should combine reference-grade ambient monitors, calibrated lower-cost sensors, meteorological instruments, lightning detection, satellite retrievals, and model output. Reference instruments provide traceability; lower-cost sensor nodes can improve spatial coverage when their performance is characterized against reference measurements. A sensor-based wireless air-quality monitoring network has been demonstrated as an urban-management tool in India. At the same time, work in the Delhi region has evaluated low-cost sensors for real-time particulate monitoring [14,15]. Sensor readings should not be treated as regulatory-grade observations without calibration, humidity correction where appropriate, quality flags, and periodic collocation.

Network design should use a stratified deployment logic rather than uniform sensor spacing alone. Roadside, industrial-influence, residential, peri-urban and background locations represent different source mixtures and exposure settings; meteorological and lightning instruments should be sited to capture spatially varying storm environments while accounting for access, power, communications and instrument security. Data stewardship should specify ownership, retention, audit trails, version control, access permissions, and procedures for correcting or flagging suspect observations.

The proposed network for Kolkata would include: (i) $PM_{2.5}$ measurements at representative urban, roadside, industrial-influence, and background sites; (ii) meteorological observations including temperature, relative humidity, wind, pressure, and rainfall; (iii) lightning data from a validated ground network and/or satellite products; (iv) satellite/reanalysis aerosol products such as MODIS AOD, CAMS, or MERRA-2; and (v) upper-air or model-derived instability indicators such as CAPE and vertical wind profiles. Each stream should retain its native spatial and temporal resolution. Data fusion must document sampling differences, retrieval uncertainty, sensor downtime, detection efficiency, and version changes.

5.2. Proposed Kolkata Aerosol-Lightning Environmental Decision-Support Framework (KALEDSF)

KALEDSF is proposed here as a modular decision-support architecture, not as an existing or validated operational product. Its modules would comprise (1) data ingestion and quality assurance; (2) emissions and ambient-air monitoring; (3) meteorological and aerosol-aware analysis; (4) lightning and severe-convection nowcasting; (5) threshold-based alert dissemination; and (6) post-event evaluation. The system should separate pollution advisories from lightning warnings: the former are based on air-quality standards and exposure considerations. At the same time, the latter require calibrated severe-weather indicators and an authorized warning protocol.

A minimum viable pilot could be developed in stages. Stage 1 would inventory available monitoring sites, lightning feeds, satellite products, data rights, and agency responsibilities. Stage 2 would establish quality-control rules, synchronized timestamps, geospatial metadata, and a shared event database. Stage 3 would retrospectively validate against documented thunderstorm cases and independent observations. Stage 4 would run a shadow-mode trial in which forecasts are evaluated but do not independently trigger public warnings. Only after documented skill, reliability, and institutional approval should the system support operational decisions.

The proposed end-to-end data and decision pathway is presented in Figure **2**. The architecture maintains two separate output channels-air-quality advisories and lightning warnings-because they use different thresholds,

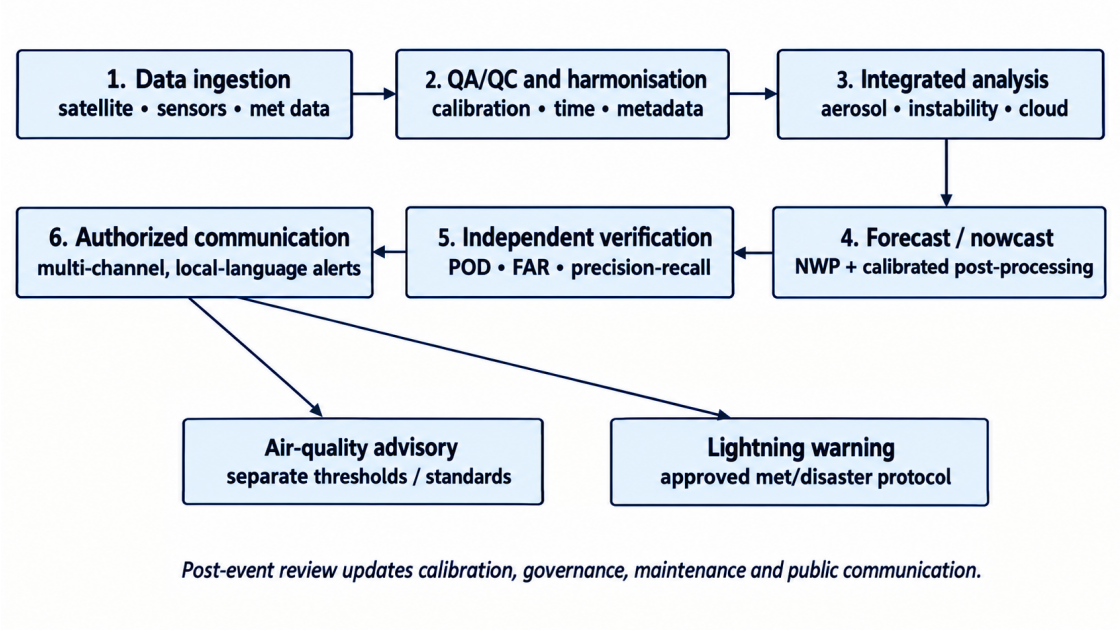


Figure 2: Proposed Kolkata Aerosol-Lightning Environmental Decision-Support Framework (KALEDSF), from data ingestion and quality control to separate air-quality and lightning communication pathways.

evidence requirements, and authorization pathways. This separation reduces the risk of conflating long-term pollution mitigation with short-lead-time severe-weather preparedness.

The framework should not claim that AOD alone predicts lightning. Candidate predictors may include aerosol indicators, humidity, CAPE, convective inhibition, vertical wind, cloud-top properties, rainfall, and recent lightning activity. Model options may include physically based numerical weather prediction with aerosol-aware microphysics and statistical or machine-learning post-processing. Training and evaluation must use temporally separated samples, independent event testing, and region-specific calibration to reduce leakage and overfitting. Explainability, missing-data handling, model drift monitoring, and human oversight are essential for public-sector use.

5.3. Operational Logic and Validation

The proposed Kolkata Aerosol-Lightning Environmental Decision-Support Framework (KALEDSF) is conceptualized as an integrated, modular decision-support architecture that synthesizes heterogeneous environmental observations through systematic data harmonization, quality assurance and quality control (QA/QC), aerosol-aware meteorological analysis, and independent forecast verification. Its operational design encompasses two functionally distinct yet complementary decision pathways: (i) air-quality advisories informed by pollutant concentrations, exposure considerations, and applicable environmental standards; and (ii) lightning-risk warnings derived from validated convective indicators, lightning observations, forecast uncertainty, and authorized warning protocols. Goenka *et al*. [19] support the scientific rationale for integrating satellite-derived meteorological parameters with lightning observations, demonstrating the potential of INSAT-3D observations to identify precursory signatures of lightning activity over India. Furthermore, the region-dependent nature of aerosol-cloud-lightning interactions documented by Ghoshal Chowdhury *et al*. [5] underscores the need to incorporate aerosol characteristics and prevailing thermodynamic conditions without assuming a universal or deterministic aerosol-lightning relationship. Accordingly, the proposed architecture, illustrated in Figure **2**, constitutes a research-oriented blueprint for integrating environmental monitoring, atmospheric analysis, and risk communication within an urban decision-support system. Nevertheless, its operational feasibility, predictive skill, reliability, and societal utility must be established through retrospective case-based evaluation, independent out-of-sample testing, and prospective validation under Kolkata-specific environmental conditions before deployment in operational decision-making.

Figure **3** presents the conceptual architecture of the proposed Kolkata Aerosol-Lightning Environmental Decision-Support Framework (KALEDSF). The framework integrates environmental observations, data-

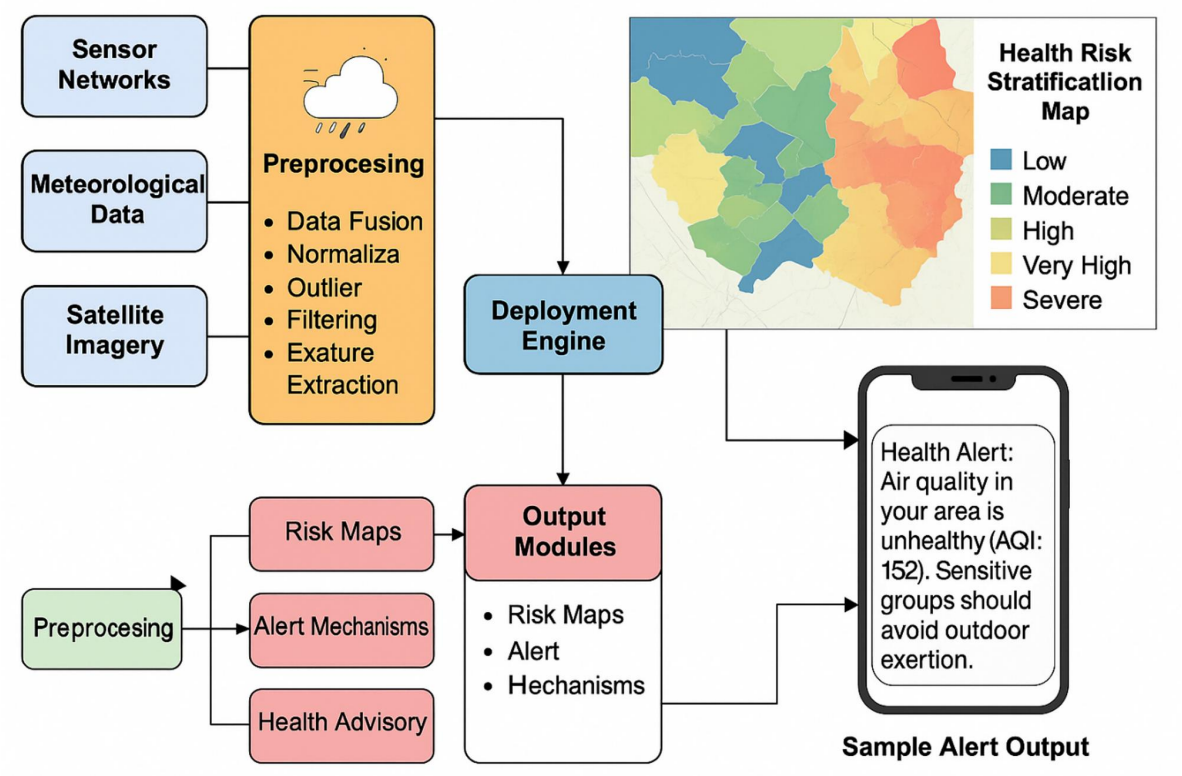


Figure 3: Proposed operational architecture of the Kolkata Aerosol-Lightning Environmental Decision-Support Framework.

quality management, aerosol-aware meteorological analysis, and independent forecast verification to support two distinct decision pathways: air-quality advisories and lightning-risk warnings. The architecture is an original conceptual synthesis informed by published research on aerosol-cloud-lightning interactions and satellite-based lightning detection [5,19]. It is a proposed framework requiring Kolkata-specific validation, not an established operational system.

6. PROPOSED IMPLEMENTATION AND EVALUATION MATRIX

A phased implementation strategy should begin with a comprehensive stakeholder assessment and data audit rather than immediately deploying a new technological platform. Potential collaborating institutions include environmental regulatory authorities, municipal agencies, meteorological services, research institutions, utilities, and industrial operators. Clearly defined institutional responsibilities should encompass sensor maintenance and calibration, data stewardship, cybersecurity, alert authorization, and public communication. Where feasible, adopt interoperable data formats and documented application programming interfaces (APIs), subject to applicable data-licensing requirements, privacy safeguards, and critical-infrastructure security protocols. Table **2** summarizes the proposed performance indicators and implementation constraints for the associated technological and monitoring interventions.

The monitoring dashboard should communicate measurement uncertainty and operational status alongside quantitative estimates. For air-quality monitoring, the relevant indicators should include instrument status, calibration dates, data completeness, and comparisons with applicable regulatory standards. For lightning monitoring, the dashboard should report detection coverage, update intervals, and forecast-verification results. Model performance metrics should not be presented in isolation; rather, they should be accompanied by the verification period, event definition, reference baseline, and sample size. Furthermore, given the class imbalance commonly encountered in severe-weather datasets, the probability of detection and false-alarm ratio should be supplemented with precision-recall metrics and appropriate skill scores, supported by event-based validation. These requirements provide an operational basis for evaluating the feasibility, reliability, and accountability of the proposed KALEDSF decision-support framework.

Table **3** provides a proposed data-governance matrix for integrating heterogeneous observation streams. It specifies the principal role of each data source, the

Table 2: Technology options and evaluation indicators proposed for a Kolkata pilot

Intervention	Primary Purpose	Core Performance Indicators	Principal Caveat
Clean Energy and Process Efficiency	Prevent emissions and reduce energy demand.	Energy consumption (kWh per unit of output); fuel use; CO_2-equivalent (CO_2e) and pollutant emissions per unit of output.	Upstream impacts associated with electricity generation and fuel production must be included.
ESP, Fabric, or Hybrid Filtration	Reduce particulate emissions from eligible sources.	Inlet and outlet particulate matter (PM) concentrations; removal efficiency; energy consumption (kWh per tonne treated); downtime; lifecycle cost.	Performance depends on particle characteristics and process-specific operating conditions.
Precursor Emission Controls	Reduce SO_2, NO_x, and VOC emissions and secondary aerosol formation.	Stack pollutant concentrations and mass emission rates; regulatory compliance; cost per tonne of emissions avoided.	Control strategies require source-specific engineering, implementation, and monitoring.
Calibrated Air-Quality Sensor Network	Improve the spatial and temporal characterization of air pollution and exposure.	Data completeness; bias and root mean square error (RMSE) against reference instruments; operational uptime; cost per valid observation.	Low-cost sensor measurements require calibration, quality assurance, and quality control (QA/QC).
Lightning and Weather Data Integration	Strengthen convective hazard monitoring and early-warning capabilities.	Probability of detection; false-alarm ratio; warning lead time; spatial error.	Account for lightning-network detection efficiency and satellite sampling limitations.
KALEDSF Decision-Support Framework	Translate validated environmental and meteorological data into actionable operational information.	Forecast skill; processing latency; warning reach; usability; equitable access.	The framework is proposed and requires prospective validation under operational conditions.

Table 3: Proposed data streams, quality-assurance requirements and interpretive limitations for a Kolkata aerosol-lightning monitoring pilot

Evidence stream	Primary role	Minimum QA/QC and metadata	Interpretive limitation
Reference-grade $PM_{2.5}$/PM2.5	Quantify near-surface exposure and evaluate source controls	Calibration/collocation records; uptime; units; site type; humidity correction where needed	Represents the sampling point, not the full urban airshed
Low-cost air-quality sensors	Increase spatial density and identify local gradients	Co-location against reference instruments; drift checks; QA flags; maintenance log	Uncorrected readings may be biased by humidity, aging, and aerosol composition
Satellite AOD / aerosol products	Characterize column-integrated aerosol loading and regional transport	Product version; retrieval QA; cloud screening; overpass time; spatial resolution	AOD is not equivalent to surface $PM_{2.5}$ or CCN concentration
Meteorology / upper-air profiles	Describe instability, moisture, wind, and storm environment	Timestamp alignment; vertical-level metadata; missingness; station/reanalysis provenance	Spatial smoothing and temporal mismatch can obscure local storm evolution
Ground/satellite lightning	Detect flashes and verify warning performance.	Detection efficiency; event definition; coverage; sampling interval; sensor version	Detection systems differ in sensitivity, polarity, and spatial/temporal sampling.
Forecast and warning records	Evaluate operational value and public communication	Forecast issue time; lead time; baseline; event labels; audience reach; verification window	Skill scores are not comparable unless event definitions and reference baselines match

quality-control requirement, and the principal limitation that should accompany downstream interpretation.

6.1. Technology Readiness Level (TRL) assessment

TRL is used here as a structured maturity descriptor rather than a certification or a claim of local operational validation. The nine-level scale progresses from observed principles and formulated concepts (TRL 1-2), through proof-of-concept and laboratory/relevant-environment validation (TRL 3-6), to operational prototype demonstration, qualification and proven operation (TRL 7-9) [31]. The ratings below distinguish the maturity of commercially available component technologies from the maturity of their proposed Kolkata-

specific configuration. These are provisional desk estimates based on the evidence reviewed; they are not supplier-certified ratings or the result of a formal technology-readiness audit.

Clean-energy substitution and industrial process-efficiency measures are generally commercially mature (component-level TRL 8-9), but their site-specific integration in Kolkata facilities is assessed at TRL 5-6 until energy audits, grid/fuel boundary analysis and monitored demonstrations establish performance under local operating conditions. Conventional ESPs, fabric filters, WESPs and established SO_2/NO_x/VOC controls are mature technologies (typically TRL 8-9); a particular retrofit configuration should be treated as TRL 6-7 until its performance, energy penalty, reliability and residuals handling are demonstrated at the target plant. Commercial reference-grade monitors and individual low-cost sensor products are likewise mature components (TRL 8-9), whereas a quality-assured, multi-source Kolkata network with harmonized data and lightning integration is estimated at TRL 4-5. KALEDSF, as an integrated, Kolkata-specific decision-support system, remains at TRL 2-3: the architecture and intended functions have been formulated, but a functioning integrated prototype and proof-of-concept validation have not yet been reported.

The TRL pathway is not a promise that every intervention must reach the same endpoint: established pollution-control equipment may already be commercially mature, while the main development gap lies in site-specific integration, independent performance verification, and institutional qualification. In particular, KALEDSF should not be described as TRL 7-8 until an operational prototype has been demonstrated and qualified under Kolkata conditions. The milestones in Table **4** define the evidence needed to make that progression auditable.

6.2. Pathway to Implementation: First Three Steps for Kolkata

A practical transition from the present conceptual design to pilot validation should be organized as three sequential work packages. The institutional entities listed below are potential collaborators, not confirmed partners; formal

Table 4: Provisional TRL assessment and evidence required for progression of proposed interventions

Intervention/system boundary	Provisional current TRL	Basis for estimate	Evidence and milestones to reach TRL 7-8
Clean energy and process efficiency	TRL 5-6 (Kolkata deployment); underlying technologies TRL 8-9	Mature technologies are commercially available; this review does not include Kolkata-specific facility audits or integrated performance evidence.	TRL 5: complete facility energy/emissions baseline and engineering design; TRL 6: demonstrate an integrated retrofit at a representative facility with normalized energy intensity and emissions; TRL 7: operate through seasonal/production cycles with independent metering; TRL 8: qualify performance, safety, maintenance and lifecycle-cost documentation.
ESP, fabric filter, WESP and hybrid particulate control	TRL 6-7 for a selected site-specific retrofit; equipment families TRL 8-9	Established industrial technologies, but performance is stream-, dust-, and plant-specific; no Kolkata installation trial is documented.	TRL 6: vendor design plus site-specific pilot or validated retrofit engineering; TRL 7: full-scale demonstration under actual inlet loading and operating conditions; TRL 8: independent stack testing, energy and uptime verification, maintenance and residuals-management qualification.
SO_2, NO_x and VOC precursor controls	TRL 6-7 for site-specific integration; technology families TRL 8-9	FGD, sorbent injection, SCR/SNCR, adsorption and oxidation are established processes; local process compatibility and cost remain facility-specific.	TRL 6: characterize flue-gas composition and select a process; TRL 7: demonstrate removal, reagent use, by-products, and compliance at operating scale; TRL 8: qualify long-duration performance, reagent supply, safety, waste handling, and cost per tonne avoided.
Calibrated air-quality and meteorological sensor network	TRL 4-5 for integrated Kolkata network; commercial sensor components TRL 8-9	Reference instruments and sensor products are available, but a stratified, collocated, quality-controlled Kolkata network is not yet demonstrated.	TRL 5: laboratory and collocation testing across humidity/temperature ranges; TRL 6: multi-site prototype with telemetry and QA/QC; TRL 7: operational demonstration across roadside, industrial, residential and background sites; TRL 8: independent data-quality audit, uptime and maintenance qualification.
KALEDSF integrated decision-support system	TRL 2-3	The system architecture and modules are formulated in Figures 4-5; no integrated prototype, retrospective benchmark or prospective shadow-mode trial is reported.	TRL 3: executable proof-of-concept joining sample data streams; TRL 4: module integration and software verification in a controlled environment; TRL 5-6: retrospective case validation and relevant-environment prototype; TRL 7: shadow-mode operation with authorized agency users; TRL 8: independent qualification of reliability, forecast skill, cybersecurity, governance and warning workflows.

roles would require agreements, data permissions, and project approval. The roadmap is designed to establish a minimum viable pilot before considering any public-facing operational warning function.

Progression beyond the pilot should be conditional on the exit criteria in Table **5**, not on completion of the calendar alone. Any public warning function must remain under the authority of the designated meteorological and disaster-management agencies. The emission-control workstream should proceed through plant-specific engineering and regulatory approvals independently of the lightning-warning workstream. This staged approach converts the review's principal evidence gaps into funded, verifiable activities without implying that the proposed integrated system is already operational.

The existing visual elements are retained: Figure **3** presents the emission-prevention and control hierarchy; Figure **3** depicts the KALEDSF data-to-decision pathway. Tables **1** and **2** define the intervention and data-governance matrices, while Table **5** provides indicative particulate-control benchmarks. Tables **4** and **5** add the provisional readiness assessment and the Kolkata implementation roadmap.

7. ENVIRONMENTAL, RESOURCE, AND PUBLIC-SAFETY IMPLICATIONS

The most direct environmental benefit of clean-energy and emission-control technologies is reduced pollutant emissions and exposure, with potential co-benefits for climate mitigation when short-lived climate forcers and greenhouse gases are considered jointly [8,17]. Particulate capture also creates a residual material stream that must be managed safely. Include resource recovery only where the captured material has verified composition, meets product specifications, and can be reused without transferring contaminants to another environmental compartment.

Lightning monitoring provides a complementary adaptation benefit by supporting timely risk communication and emergency preparedness. It should not be conflated with pollution mitigation: clean-air

Table 5: Three-step implementation roadmap from current status to pilot validation in Kolkata

Step and indicative period	Technical activities and deliverable	Potential institutional roles	Minimum resources	Exit criteria/validation evidence
1. Baseline, governance and site selection (0-6 months)	Create a joint data and infrastructure inventory; map reference monitors, CPCB/WBPCB stations, meteorological and lightning feeds, industrial sources and existing control equipment; agree event definitions, data standards, access rights and governance.	WBPCB and CPCB regional offices; Kolkata Municipal Corporation; IMD; West Bengal Disaster Management and Civil Defense Department; universities/research institutes; participating industrial operators.	Project coordinator; air-quality and meteorological data specialists; GIS/database support; stakeholder workshops; data-sharing and cybersecurity protocols; modest field-audit budget.	Approved site-selection protocol; data inventory with provenance and licensing; baseline emissions/energy information for at least one candidate facility; signed or formally approved data-access and responsibility matrix.
2. Minimum viable field network and facility audit (6-18 months)	Install or co-locate a small stratified network at roadside, industrial-influence, residential, and background sites; co-locate low-cost PM sensors with reference-grade instruments; deploy meteorological measurements; undertake one or more facility energy/emissions audits and select an appropriate control retrofit for pilot design.	WBPCB/CPCB monitoring teams; KMC; IMD; academic laboratories; accredited stack-monitoring laboratories; industrial plant owners and technology vendors; electricity utility where electrification is assessed.	Reference-grade $PM_{2.5}$ instrument access; calibrated sensor nodes; meteorological station(s); lightning data feed; telemetry, power and enclosures; stack sampling/CEMS access; engineering and LCA/techno-economic expertise.	Predefined data completeness, bias/RMSE and uptime criteria met during collocation; documented site-specific control design; verified baseline stack measurements and energy intensity; approved health, safety and maintenance plans.
3. Integrated retrospective and shadow-mode pilot validation (18-30 months)	Integrate timestamped data streams and QA/QC; develop baseline and candidate forecast models; perform temporally independent retrospective event testing; run a shadow-mode trial in which alerts are evaluated but do not independently trigger public warnings; evaluate emission and warning outcomes separately.	IMD and authorized disaster-management agencies for warning protocols; WBPCB/CPCB for air-quality compliance; KMC for local dissemination; universities for independent model evaluation; community representatives and participating facilities.	Secure server/cloud environment; data engineer and forecaster; model-validation protocol; independent evaluation team; user-interface and multilingual message testing; maintenance and operating budget.	Independent report on sensor quality, forecast skill, false alarms, lead time, system uptime and warning reach; verified stack/energy performance for any installed control measure; documented corrective actions and institutional decision on progression to operational demonstration.

technologies reduce source emissions, while lightning observation and forecasting manage residual weather risk. A well-designed system may help agencies plan outdoor work, school and transport advisories, and community outreach, but operational warnings must follow authorized meteorological and disaster-management procedures. The review does not infer that lowering aerosols will necessarily reduce lightning frequency or lightning-related fatalities.

Equity and accessibility are implementation requirements. Rural and peri-urban communities, outdoor workers, agricultural populations, and residents with limited access to digital alerts may face elevated exposure to lightning hazards. Multi-channel communication-mobile alerts, local-language messaging, community networks, and public-address systems-should be evaluated alongside technical forecast skill. Performance assessment should disaggregate warning reach and response by geography and user group where ethically and practically feasible. Equity assessment should distinguish technical alert delivery from effective protective action. Relevant measures include the proportion of at-risk users reached before impact; message comprehension; accessibility for people with disabilities; language coverage; network connectivity; and whether recommended actions are feasible for outdoor workers or households with limited shelter options. Co-design these indicators with local agencies and community representatives, and minimize and protect personal data collection.

8. RESEARCH GAPS AND VALIDATION PRIORITIES

Four gaps constrain translation into practice. First, aerosol products and surface PM measurements are not equivalent, and regional vertical profiles and aerosol composition are often sparse. Second, satellite lightning sensors have sampling limitations, while ground networks differ in detection efficiency and event classification. Third, correlations between aerosol indicators and lightning do not isolate aerosol effects from humidity, CAPE, circulation, land-sea breeze, or urban heat-island effects. Fourth, many proposed decision-support systems lack prospective evaluation, cost accounting, and evidence of whether warnings change behavior or reduce losses.

A future Kolkata pilot should therefore pre-register its event definitions, predictors, validation period, and primary metrics. Aerosol-aware numerical experiments should compare control and sensitivity simulations while documenting boundary conditions and microphysics assumptions. Observational analysis should use matched meteorological conditions, lagged predictors where physically justified, uncertainty propagation, and sensitivity tests for data resolution. Model evaluation should include out-of-sample events and comparisons with persistence and operational baselines. Technology assessment should include lifecycle energy, cost, maintenance, waste handling, and displaced or avoided emissions.

A useful validation design would report both discrimination and calibration. For rare severe-weather events, accuracy alone can be misleading because a model that predicts no event may appear accurate when non-events dominate. Therefore, select probability of detection, false-alarm ratio, critical success index, precision-recall performance, Brier score, or reliability diagrams based on the forecast target and operational use. Comparisons should include persistence and an established operational baseline, and uncertainty should be estimated across independent storm cases rather than randomly splitting adjacent time steps.

9. CONCLUSIONS

Three measurable contributions to clean-technology practice emerge from this review. First, the technology-assessment matrix (Tables **1** and **3**), extended by the readiness appraisal in Table **5**, provides a transparent basis for screening source-prevention, particulate-capture and precursor-control options under Indian operating conditions. It requires decision-makers to compare outlet-emission performance with energy and water demand, annualized lifecycle cost, reliability, residuals management and the mass of pollutant avoided, rather than selecting equipment on nominal removal efficiency or purchase price alone.

Second, the review specifies a minimum viable architecture and validation metrics for a Kolkata air-quality-lightning integrated decision-support system. Tables **2** and **5** identify the required data streams, QA/QC procedures, institutional interfaces, and staged pilot activities. The minimum validation set includes data completeness and bias relative to reference instruments; event-based probability of detection, false-alarm ratio, critical success index, and probability calibration; processing latency; warning lead time; system uptime; and the proportion of target users reached. Aerosol indicators are contextual predictors, not deterministic lightning triggers.

Third, the proposed evaluation framework explicitly separates emission-reduction benefits from lightning-risk-management benefits. Emission-control performance is to be quantified using inlet-outlet mass rates, pollutant

mass avoided, energy and water penalties, annualized cost per unit mass avoided, and lifecycle greenhouse-gas implications. Lightning-risk performance will be assessed independently through forecast skill, lead time, warning reach, accessibility, and evidence of protective response. No causal reduction in lightning is assumed to follow from pollution control.

Taken together, these contributions provide an actionable route from technology screening to a monitored Kolkata pilot while retaining the evidential distinction between commercially established equipment and the locally unvalidated integration proposed here. The review is a narrative synthesis and conceptual design; it does not report a newly collected dataset, a Kolkata field trial, a validated operational forecast, or a site-specific life-cycle assessment. The TRL values are preliminary, evidence-informed desk assessments and must be confirmed by a formal, independent technology-readiness assessment before procurement or deployment.

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This study does not involve human participants or animals and therefore does not require ethical approval.

Consent to Participate

Not applicable.

Consent for Publication

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Competing Interest

The authors state that none of the work described in this publication appears to have been influenced by any known competing financial interests or personal ties.

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