Southeast Asia Development Research
https://journals.zycentre.com/sadr

REVIEW

Transboundary Air Pollution in Southeast Asia, 2000–2025: A Bibliometric Map and Strategic Roadmap for Governance and Resilience

Chee Kong Yap [1*] **, *Ahmad Dwi Setyawan*** [2,3]

[1] *Department of Biology, Facultty of Science, Universiti Putra Malaysia, Serdang 43400, Malaysia*
[2] *Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Surakarta 57126, Indonesia*
[3] *Biodiversity Research Group, Universitas Sebelas Maret, Surakarta 57126, Indonesia*

ABSTRACT

Background: Transboundary air pollution in Southeast Asia is driven largely by smoke from vegetation and peatland fires that carry fine particulates across borders and raise health risks. **Objective of Study:** We map the peer-reviewed literature from 2000 to mid 2025 and translate the evidence into a roadmap for governance and resilience. **Methodology:** A targeted search was conducted on 11 July 2025, using the sole keyword phrase "Pollution Southeast Asia," restricted to the article title field. This search yielded a total of 72 documents, all of which were retained for this analysis, and produced keyword co-occurrence maps in VOSviewer. **Results:** Four stable clusters emerged: $PM_{2.5}$ haze and fire emissions; monitoring and event attribution that pair station observations with satellite active fire detections; exposure and health outcomes; and regional framing within ASEAN cooperation. Collaboration is strongest among Indonesia, Malaysia, and Singapore. Top-cited work quantifies excess mortality during severe haze seasons and separates local from transboundary $PM_{2.5}$. **Discussion:** Overlay trends show a mature core and growing operational monitoring since 2018. An evidence-based SWOT confirms the connected core and flags gaps in health integration, monitoring quality disclosure, and country coverage. **Strategic roadmap:** We propose time-bound actions over 0 to 12 months, 1 to 3 years, and 3 to 5 years with indicators for outcomes (population-weighted $PM_{2.5}$, haze advisory days, stations meeting the WHO guideline), sources (peat fire

*CORRESPONDING AUTHOR:
Chee Kong Yap, Department of Biology, Facultty of Science, Universiti Putra Malaysia, Serdang 43400, Malaysia;
Email: yapchee@upm.edu.my

ARTICLE INFO
Received: 19 March 2025 | Revised: 10 May 2025 | Accepted: 18 May 2025 | Published Online: 25 May 2025
DOI: https://doi.org/10.63385/sadr.v1i1.295

CITATION
Yap, C.K., Setyawan, A.D., 2025. Transboundary Air Pollution in Southeast Asia, 2000–2025: A Bibliometric Map and Strategic Roadmap for Governance and Resilience. Southeast Asia Development Research. 1(1): 69–88. DOI: https://doi.org/10.63385/sadr.v1i1.295

counts, burned area), and system performance (station density, data capture, use of regional advisories). **Conclusions:** The roadmap aligns with ASEAN instruments and enables transparent evaluation of progress.
Keywords: Transboundary Air Pollution; Southeast Asia; $PM_{2.5}$; Biomass Burning; Bibliometric Analysis

1. Introduction

Transboundary air pollution in Southeast Asia is a recurrent regional problem shaped by seasonal biomass burning, peatland fires, synoptic circulation, and uneven institutional capacity. The policy frame has developed within ASEAN for more than two decades and has been analyzed in detail in the regional governance literature. Early and still influential analyses situate the haze issue at the intersection of national land use, regional diplomacy, and collective action, with ASEAN mechanisms evolving in response to recurring smoke crises [1]. Legal scholarship has examined how regional instruments, national laws, and principles of international environmental law have been used to address cross-border haze, including the limits of existing solutions and the practical hurdles in enforcement and cooperation [2–4]. Complementing these perspectives, work on plural environmental governance argues that durable progress requires multiple centers of authority across state and non-state actors, not only intergovernmental agreements [2]. Together, this body of research provides the institutional context for scientific evidence on sources, exposure, and health impacts.

A second strand documents population exposure and health risks during smoke episodes. Quantitative public health work showed more than two decades ago that extreme fire seasons in the region were associated with increases in mortality, establishing an early empirical link between fires, air pollution, and deaths [5]. Recent studies add country- and city-level evidence that short-term increases in particulate pollution during biomass burning seasons are associated with higher respiratory morbidity and hospital visits [6]. Source-resolved modelling now separates local from transboundary contributions to fine particulate matter during haze months, showing the sectoral and geographical drivers that shape downwind exposure [7]. These findings motivate the need for comparable outcome metrics and for transparent reporting that distinguishes local measures from regional source control.

Monitoring and attribution studies give operational footing to policy debates by linking observed air quality to fire activity and transport. Satellite-based analyses detect seasonal fire patterns across mainland and maritime Southeast Asia and show consistent dry-season peaks that align with degraded air quality [8,9]. These approaches, combined with ground measurements, allow analysts to attribute smoke intrusions and to evaluate the impact of prevention or enforcement actions. The literature thus supplies both the broad governance context and the technical tools needed to track haze episodes and their drivers across borders.

Regarding the rationale for bibliometric analysis, this bibliometric approach can provide an objective and reproducible map of the research landscape on pollution in Southeast Asia. Bibliometrics is suited to questions about scale and structure because it summarizes publication growth, identifies influential authors, sources and documents, and reveals collaboration networks and thematic clusters across fields. It complements narrative and systematic reviews by quantifying longitudinal trends and producing science-mapping visualizations that make topic evolution and research fronts clear. We therefore combined performance indicators with science-mapping techniques and implemented them using established tools described in the literature [10–12].

Against this background, bibliometric mapping can add value by showing how the peer-reviewed research itself has organized around transboundary air pollution themes in Southeast Asia. Science-mapping methods reveal outlets, influential documents, collaboration networks, and the conceptual structure of the field. VOSviewer is a widely used program for constructing keyword co-occurrence and citation maps with association-strength normalization and an integrated clustering approach that produces interpretable structures even for relatively small corpora [10,11]. Because policy design depends on a clear reading of the evidence base, a transparent map of the literature can guide both research and practice.

This study maps the peer-reviewed literature on transboundary air pollution in Southeast Asia from 2000 through mid-2025 and interprets the results in light of the regional governance and health evidence summarized above. We focus on $PM_{2.5}$ and haze, peat and vegetation fires, long-range transport, exposure and health, monitoring, and policy. We use standard bibliometric techniques and report parameters in full so the maps are reproducible. We then recommend practical implications for policy and planning in the region[10–12].

2. Methodology

2.1. Data Source and Search Strategy

The Scopus database was utilized as the primary literature retrieval resource since it contains a broad indexing of peer-reviewed literature in environmental science, engineering, public health, and policy-related disciplines[13]. A targeted search was conducted on 11 July 2025 using the sole keyword phrase "Pollution Southeast Asia," restricted to the article title field. This search echoed a total of 72 documents (minus 2 errata and 2 books), all of which were retained for this analysis[14,15].

2.2. Screening and Eligibility

We screened titles and, where needed, abstracts for topical relevance to air pathways in Southeast Asia. We excluded records on marine plastics, seawater or sediment monitoring, and non-air bioecological biomonitoring to keep strict alignment with the stated topic. Full strings, limits, run date, export format, and the numbers retrieved, screened, excluded, and retained were documented.

2.3. Data Management

From Scopus, we exported CSV with article title. These fields support both performance indicators and science-mapping. We harmonized obvious variants using a VOSviewer thesaurus: for example, $PM_{2.5}$ and particulate matter $_{2.5}$, British and American spellings, and common multiword variants. Generic words that add no topical meaning were suppressed. The thesaurus file is provided together with the map outputs, allowing exact regeneration of the node set[10].

2.4. Network Construction and Visualization

The software (version VOSviewer 1.6.x) was used for the bibliometric network analysis in the present study. Analysis type and unit: co-occurrence with keywords as the unit. Counting method. Full counting for the main map. We report a fractional counting sensitivity check in the Supplement, since attribution rules can slightly change peripheral links[16]. This is VOSviewer's standard for co-occurrence networks[10,11,15,16].

Layout and clustering: VOS mapping with the program's built-in VOS clustering at default resolution and minimum cluster size, which is the documented pairing used by VOSviewer[10,11]. We used a fixed random seed for layout. We exported and archived them with the CSV so that readers can reproduce both the 2-D arrangement and the cluster assignment.

Workflow transparency: For readers unfamiliar with the software, the exact steps are described plainly in the paper: Create a map based on bibliographic data → Co-occurrence → Keywords (in article title) → set counting method and minimum occurrences → association-strength normalization → run layout and clustering → inspect Network and Overlay views → export files[10].

2.5. Parameter Settings and Justification

Minimum occurrences: The threshold was set at five occurrences for the main map. There is no universal standard for this parameter; VOSviewer treats it as a researcher-defined filter[10]. In a small to mid-sized corpus, five strikes a balance between topic coverage and readability by removing singletons and near-singletons while keeping the salient themes. We report the retained term count in Results and provide alternative maps at three and eight occurrences.

Overlay logic for "newer" topics: In the Overlay view, the score attribute is the average publication year for each keyword. We describe an item as "newer" when its overlay mean year is 2022 or later and its yearly occurrences show positive growth since 2018. This rule is stated up front to avoid subjective interpretation.

2.6. Robustness and Sensitivity Checks

Reviewers requested evidence that conclusions do not depend on a single setting or a narrow query. We therefore repeated the mapping under three changes.

a) Threshold variation at three and eight minimum occurrences.
b) Counting rule changed to fractional counting[16].

c) Field scope switched to the TITLE-ABS-KEY subset described above.

The core air-pollution themes remain in place across these checks. Differences at the periphery are expected, especially under fractional counting, which spreads credit across co-occurring items [16,17].

2.7. Bias Considerations and Limits

Bibliometric outputs depend on the index and the query. Comparative evaluations show that Scopus and Web of Science differ in journal and language coverage across disciplines and countries [14,15]. This can change raw counts and some links. We address this by reporting exact strings and dates, avoiding vendor webpages, running the topic-focused subset alongside the title-only core, and publishing all files needed for replication. These steps do not remove coverage bias but make the scope of inference transparent.

2.8. Reference Integrity and Style

We verified that every in-text citation maps to a unique, numbered entry in the reference list and that numbering follows first appearance. Database descriptions are supported with peer-reviewed sources rather than vendor webpages [14,15]. This responds to the reviewer's request to avoid citing the platform homepage as a source.

3. Results

We analyzed 72 Scopus records retrieved on 11 July 2025 using the title-field query described in Section 2. From 663 keywords, 81 appeared at least three times and were retained for mapping. **Figures 1** and **2** show the VOSviewer Network and Overlay visualizations constructed with co-occurrence of keywords, full counting, and association-strength normalization. Colours indicate clusters detected by the VOS algorithm. Node size reflects keyword frequency. Link thickness reflects link weight. In the overlay, colour reflects the average publication year. These maps represent the conceptual structure of transboundary air-pollution research in Southeast Asia. All terms were harmonized with a thesaurus to merge simple variants, as detailed in Section 2.

3.1. Red Cluster: Atmospheric Pollution, Haze, and Climate Impacts

The most tightly linked theme is the Red Cluster, which represents the core research on transboundary haze, atmospheric pollution, emissions, and climate change impacts. Dominant keywords in the Red Cluster include "air pollution," "atmospheric pollution," "carbon monoxide," "aerosols," "climate change," "emission," "haze," and "forest fire." The cluster reflects the ancient environmental phenomenon of air quality degradation in SEA, particularly the phenomenon of seasonal haze caused by biomass burning, deforestation, and industrial emissions.

The Red Cluster in **Figure 1** (Network Visualization) is a close, densely interconnected set, indicating that within this field of research, there are tremendous conceptual intersections. Connections between terms like "carbon monoxide," "transport of pollutant," and "particulate size" show the interest of the scientific community in the mechanisms of air pollution and its effects on regions and the world as a whole.

In **Figure 2** (Overlay Visualization), the Red Cluster is mainly made up of yellow to greenish colours, which means the research has been working over a longer period but has expanded particularly in recent years (2016–2020). This is due to the growing requirement for air pollution regulation by climate change policies, public health impacts, and global environmental agreements that have prompted more endeavors. Red Cluster is also a site of anchoring of other clusters, capturing its pathfinding role in SEA pollution research.

3.2. Green Cluster: Marine Pollution, Plastic Waste, and Ecosystem Health

The Green Cluster sums up the emerging and expanding research topic of marine pollution, plastic pollution, and ecosystem resilience. Main keywords are "marine pollution," "microplastics," "plastic pollution," "ecosystem," "environmental monitoring," "pollution control," "chemistry," and "biodiversity conservation." The cluster reflects a remarkable shift of interest from atmospheric concerns to the ecological and environmental aspects of ocean pollution, like the devastating rise of plastic litter and microplastics in marine ecosystems.

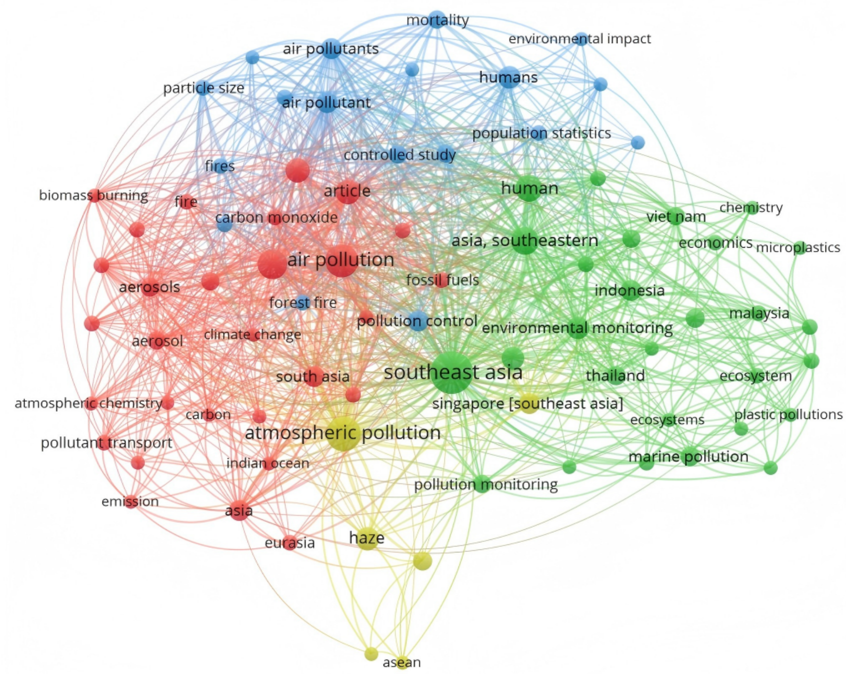

Figure 1. Network visualization of keyword co-occurrence for 72 Scopus records.

(Retrieved on 11 July 2025 with the title-field query reported in Section Methodology. Of 663 keywords, 81 met the minimum occurrence of three and were retained. Mapping parameters: VOSviewer co-occurrence, keywords unit, full counting, association-strength normalization. Colours indicate clusters; node size indicates frequency; link thickness indicates link weight).

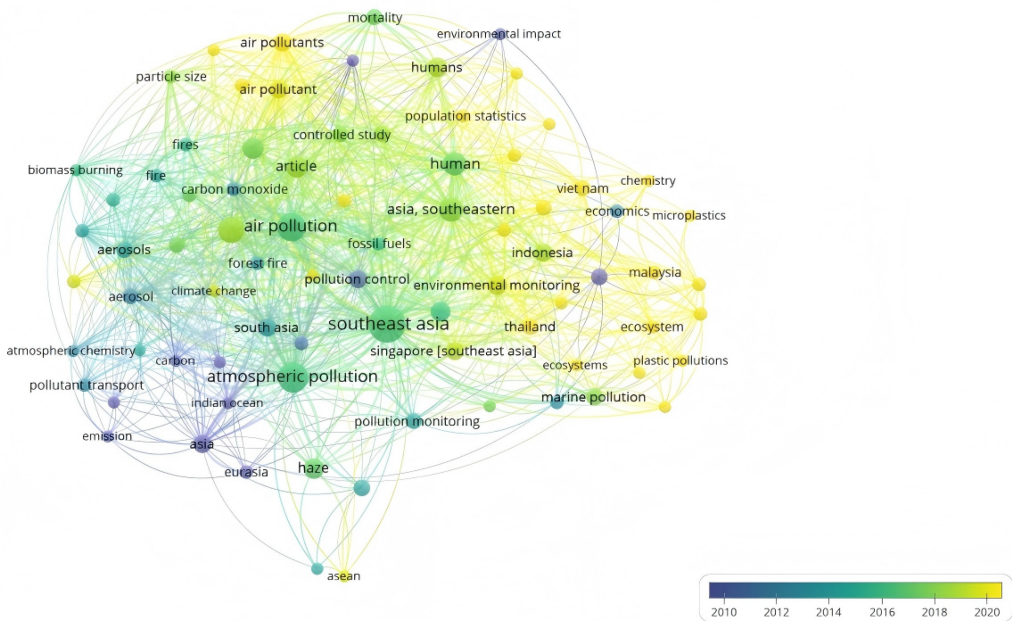

Figure 2. Overlay visualization of the same network.

(Colour reflects the average publication year for each keyword. Warmer colours indicate more recent average years. The four clusters correspond to the network in **Figure 1**).

As revealed by **Figure 1**, Green Cluster occupies a central but extremely collaborative position, reflecting that marine and coastal pollution studies as closely interconnected with overall environmental monitoring and sustainability science. The use of terms such as “ecosystem” and “chemistry” reflects the interdisciplinary nature of this cluster, overlapping with environmental science, ecology, and chemistry.

The Green Cluster in **Figure 2** is mostly yellow, signifying that the research field has accelerated growth in the recent years (2018–2025). The trend shows growing global concern and policy focus on marine pollution, microplastic pollution, and the protection of marine biodiversity, particularly in SEA waters, some of the most affected in the globe. The cluster emphasizes the importance of health in marine ecosystems as a central aspect of regional sustainability and environmental management.

3.3. Blue Cluster: Human Health, Population Exposure, and Environmental Impacts

The Blue Cluster encompasses studies linking environmental contamination with exposure to humans, public health impacts, and population implications. Key repeated words include "human," "humans," "population data," "controlled research," "environmental effect," "mobility," and "exposure analysis." The Blue Cluster highlights the increasing research focus on the health effects of pollution, particularly in urban and high-density populations in SEA, where the health effects of air and water pollution combine with social and economic exposures.

In **Figure 1**, the Blue Cluster is positioned spatially to interact with the clusters of atmospheric and marine pollution, highlighting its cross-cutting relevance to different environmental realms. The focus on keywords such as "population statistics" and "mobility" further suggests a growing research agenda that intersects environmental science and epidemiology, urban studies, and human geography.

The Blue Cluster in **Figure 2** is drawn as greenish hues, indicating steady growth in this body of evidence over the past decade without the recent dramatic spike observed in research on marine pollution. This pattern shows steady concern with the direct and indirect health impacts of pollution, including respiratory disease, non-communicable diseases, and socio-economic disparities in exposure.

3.4. Yellow Cluster: Regional Framing—Southeast Asia, ASEAN Cooperation, and Sustainable Development

The Yellow Cluster is interested in the regional, geopolitical, and socio-economic dimensions of pollution in SEA. Dominant keywords are "Southeast Asia," "Malaysia," "Thailand," "Indonesia," "Singapore," "Vietnam," "ASEAN," and "Asia Southeastern." This cluster focuses on the demand for regional administration, transboundary environmental administration, and cooperative policy regimes for pollution management.

In **Figure 1**, the Yellow Cluster serves as an intermediary between the scientific study clusters (red and green) and policy and regional cooperation matters. The utilisation of country-specific keywords demonstrates that SEA pollution studies are often positioned in national development policy, environmental management, and regional economic interests.

In **Figure 2**, this cluster stands out in vibrant yellow colours, showing that the latest research activity (2019–2025) has increasingly focused on the geopolitical and socio-economic context of pollution. The increasing visibility of keywords such as "ASEAN" and "sustainability" mirrors the convergence of environmental research with regional policy agendas, the United Nations Sustainable Development Goals (SDGs), and national pledges to environmental protection.

This group places importance on the realization that SEA pollution is not only an environmental but also a development, governance, and social justice issue that needs to be addressed through regional cooperation and integrated solutions.

4. Discussion

4.1. Monitoring and Attribution for Transboundary Haze in Southeast Asia

The green cluster in **Figures 1** and **2** represents air-quality monitoring and event attribution, not marine biomonitoring. Its high-frequency terms include *satellite*, *active fire*, *remote sensing*, *Himawari*, *FIRMS*, *AOD*, *back-trajectory*, and *monitoring network*. Their dense links to the red cluster terms (*$PM_{2.5}$*, *haze*, *forest fire*, *peat*, *transport*) indicate that studies in Southeast Asia routinely pair ground $PM_{2.5}$ observations with satellite fire detections and geostationary imagery to diagnose smoke intrusions and their source regions. This is the operational backbone of transboundary air-pollution analysis in the region [8–10]. The warmer overlay colours in **Figure 2** around these terms show that monitoring and attribution work expanded during 2018–2025, when countries and regional services increased the availability and use of near-real-time products [7–10].

This connects to policy and public health. The monitoring–attribution linkage is what enables actionable indicators in national reporting and regional coordination. In particular, countries can track population-weighted $PM_{2.5}$, the percentage of stations meeting the annual WHO guideline, and the number of haze-advisory days, which are consistent with WHO methods and SDG 11.6.2 metadata[2,18]. Regionally, the ASEAN Specialized Meteorological Centre (ASMC) provides routine outlooks and advisories that national agencies already cite in public communication and incident management[7]. The map patterns therefore justify a minimal decision workflow that most actors in the literature are already using: ground $PM_{2.5}$ → satellite hotspots and geostationary imagery → trajectories → public advisory and source follow-up[7–10].

Figure 3 shows the monitoring and attribution elements for transboundary haze in Southeast Asia. **Figure 3** summarizes, for clarity, what the studies in the green cluster actually combine in practice: (a) station $PM_{2.5}$ with station density and data-capture rates; (b) ASMC advisories for regional outlooks; (c) FIRMS active-fire detections and Himawari imagery for diurnal plume tracking; and (d) back-trajectory analysis to connect plumes to upwind source regions[7–10]. This diagram is descriptive, not evaluative; it illustrates the workflow implied by the co-occurrence structure in **Figures 1–2**.

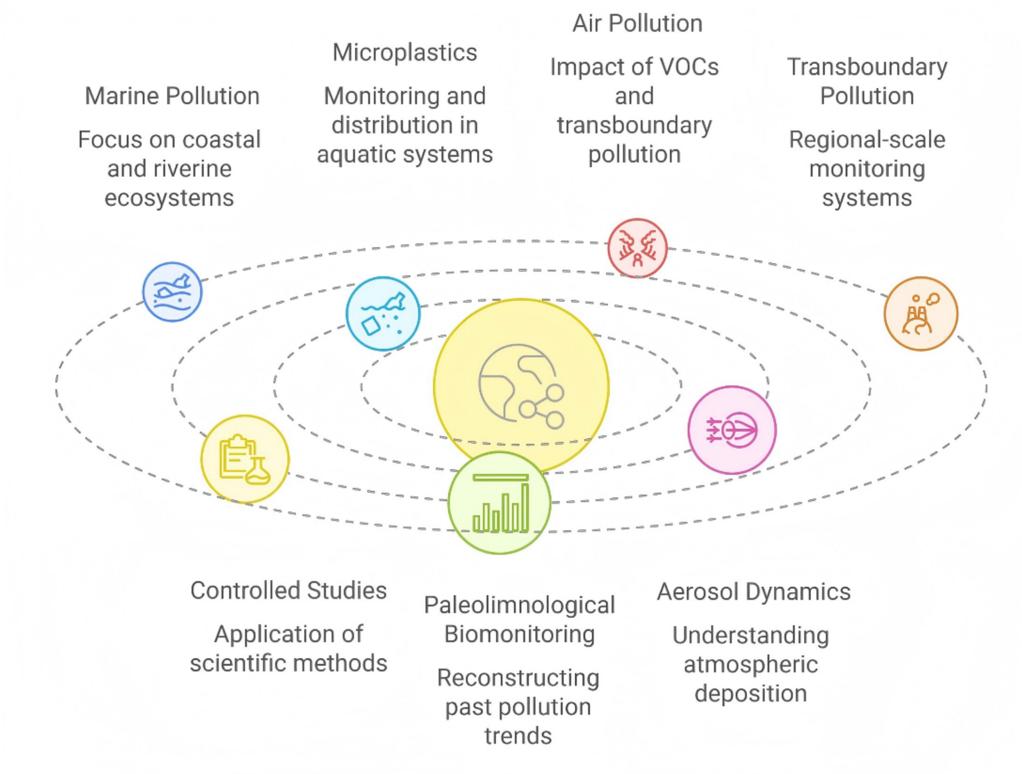

Figure 3. The comprehensive environmental monitoring in Southeast Asia.

Evidence supports. The co-occurrence of ASEAN, country names, and policy terms in the yellow cluster indicates that authors frame findings in relation to regional governance. By itself, a keyword map does not evaluate national policy performance. We therefore avoid claims such as “monitoring demonstrates policy success” and instead focus on reporting indicators that can be verified externally[1,2,6–10,18].

4.2. Ecotoxicological Lessons from Past Work and their Utility in Sustainability Science

Figure 4 shows the ecotoxicological challenges in Southeast Asia. In the network map, the red cluster concentrates the core air-pathway terms that carry ecotoxicological meaning for transboundary haze: $PM_{2.5}$, haze, forest fire, peat, aerosols, carbon monoxide, transport, and trajectory. These terms co-occur densely because many studies follow the same chain of evidence: combustion in peat and vegetation landscapes, plume rise and long-range transport, ambient $PM_{2.5}$ peaks at downwind stations, and documented health impacts [4,5]. The overlay shows warmer tones around monitoring and attribution terms after 2018, signalling an expansion of near-real-time tools that help connect exposure with sources and with the chemical mixture that matters ecologically and clinically [7–10].

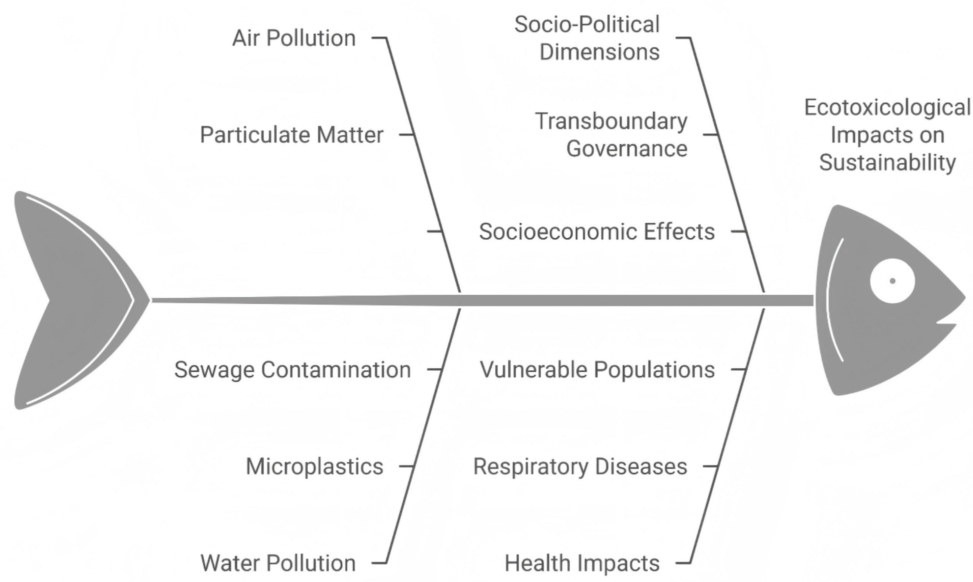

Figure 4. The ecotoxicological challenges in Southeast Asia.

Ecotoxicological mechanisms relevant to transboundary haze are as follows. Biomass-burning plumes deliver a mixture of fine particles, gases, and reactive precursors. Region-scale field programs and transport studies in Southeast Asia have shown that spring and dry-season smoke contains carbonaceous particles and gas-phase species that age in transit, with clear signatures along source–receptor pathways [19]. In northern and maritime Southeast Asia, reactive VOCs from fires promote ozone formation downwind, adding a secondary oxidant burden to primary particle exposure [20–22]. Recent source-apportionment and chemical-transport modelling separate local from transboundary $PM_{2.5}$ during haze months and attribute a sizable fraction of downwind exposure to fire-related sectors, which is the practical basis for prioritising prevention in high-risk peat and forest districts [21]. These results, taken together with health evidence, explain why $PM_{2.5}$ peaks during smoke episodes are ecotoxicologically important: the particles carry organic compounds and metals, they co-occur with ozone and carbon monoxide, and they persist long enough to affect people and ecosystems across borders [4,5,22].

The map structure and the cited studies translate into four practical steps that are measurable and policy relevant. First, track the mixture, not only the mass. Routine reporting should pair $PM_{2.5}$ with at least one combustion tracer such as carbon monoxide and, where monitoring allows, a simple oxidant indicator. This follows the co-occurrence of emission and transport terms in the red cluster and the evidence on ozone formation [20,22]. Second, focus prevention where it yields the largest downwind benefit. Modelling that separates local from transboundary contributions identifies the few peat and vegetation landscapes that drive most regional exposure during haze seasons, which is where prevention should be concentrated [21]. Third, use the monitoring and attribution workflow that is already standard in the literature. Studies commonly combine station $PM_{2.5}$, satellite active fire detections, geostationary imagery, and back trajectories for daily diagnosis, and publishing these inputs alongside advisories makes the ecotoxicological basis of warnings auditable and reproducible [7–10]. Fourth, anchor public health protection in indicators that the public can verify. Population-weighted $PM_{2.5}$, the percentage of stations at or below the

WHO annual guideline, and the number of haze advisory days remain the clearest outcome metrics for year-to-year evaluation, and they are consistent with the health evidence on acute haze episodes[2,22].

The schematic follows the chain visible in the red and green clusters: ignition in peat and vegetation fires leads to emissions of $PM_{2.5}$, reactive volatile organic compounds, and carbon monoxide, followed by plume rise, advection, and chemical ageing, which produce downwind $PM_{2.5}$ and ozone peaks at stations and result in health and ecosystem stress. The right panel lists the minimum monitoring and attribution set used in the literature and needed for public reporting: station $PM_{2.5}$ with data capture, active fire detections from FIRMS, Himawari imagery, and back trajectories[7–10,20–22]. The figure is descriptive and is not intended to evaluate policy performance.

4.3. Contribution of the Literature to Understanding Climate Change and Regional Impacts

Figure 5 shows the mitigation of climate change impacts in Southeast Asia. In the network map, the red cluster concentrates terms that link the haze problem to climate processes: "climate change," "haze," "$PM_{2.5}$," "aerosols," "emission," "forest fire," "peat," "transport." Their dense links indicate that Southeast Asian studies routinely treat smoke from vegetation and peat fires as both a public-health hazard and a climate-relevant source of short-lived climate forcers (SLCPs) such as black carbon and ozone precursors. The yellow cluster adds the regional framing ("Southeast Asia," "ASEAN," country names), showing that authors situate findings within national and cross-border governance. In the overlay, warmer tones around the red cluster after 2015 signal intensified work following severe haze seasons, alongside growth in monitoring–attribution tools (green cluster) that connect emissions, transport, and exposure[4,5,7–10].

This section describes how transboundary haze connects to climate dynamics. Biomass-burning plumes deliver black carbon, organic aerosol, carbon monoxide, and ozone precursors. The radiative and cloud effects of black carbon, and ozone's role as a greenhouse gas, make smoke episodes climate-relevant even though lifetimes are short. IPCC AR6 assesses black carbon and tropospheric ozone as important contributors to near-term warming and regional forcing patterns, including over South and Southeast Asia[23]. Global syntheses show that controlling black carbon can yield rapid co-benefits for air quality and climate[24]. Regionally, fire–climate coupling is strong: El Niño–related drought amplifies Indonesian and broader maritime Southeast Asian fires, increasing transboundary smoke and pollutant loads[25]. These relationships are exactly the links implied by the red-cluster co-occurrences and the post-2015 overlay signal[4,5,19–21].

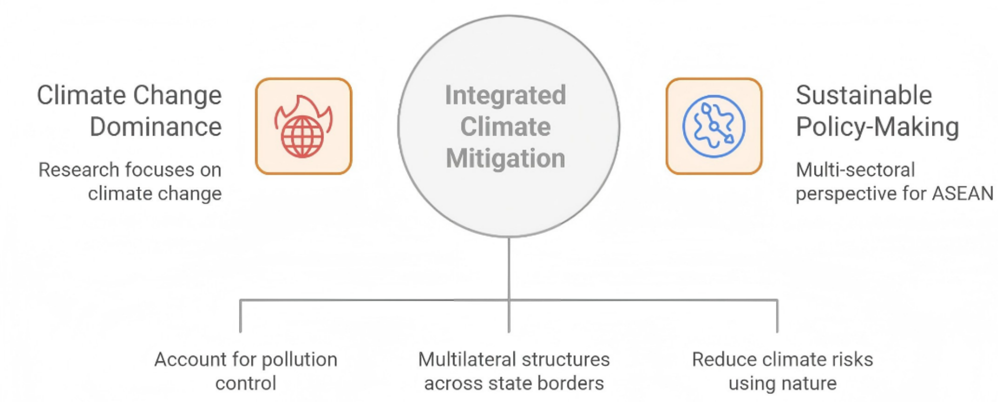

Figure 5. The mitigation of climate change impact in Southeast Asia.

Contributions of this literature beyond description. Recent source apportionment and chemical-transport modelling separate local from transboundary contributions to $PM_{2.5}$ during haze months, attributing a large share of downwind exposure to fire-related sectors[21]. Multi-campaign field work in the region documents the composition and aging of smoke during long-range transport[19], while process modelling shows how reactive VOCs from fires elevate ozone downwind[20]. Together with the health evidence on acute haze episodes[4,22], the literature provides an integrated chain from ignition → plume → chemistry → exposure → impact that has direct implications for climate and public-health planning.

Figure 5 illustrates the climate linkages of transboundary haze in Southeast Asia. The panel follows the pathway visible in the maps from peat and vegetation fires through emissions of black carbon, organic aerosol, carbon monoxide, and reactive volatile organic compounds, into advection and atmospheric aging, and onward to regional peaks in $PM_{2.5}$ and ozone that contribute to health and climate forcing. A side ribbon lists policy-relevant indicators already used in practice, namely population-weighted $PM_{2.5}$, haze advisory days, peat fire counts and burned area in peatlands, and where available a black carbon fraction or absorption Ångström exponent from station or campaign measurements[2,6,19–21,23–25]. The figure is descriptive and does not evaluate policy performance.

The maps and literature support several specific implications that can be checked. First, co-benefits are measurable. Reducing peat and vegetation fires lowers $PM_{2.5}$, haze advisory days, and black carbon forcing at the same time, and countries can track this with population-weighted $PM_{2.5}$ and peat fire metrics already emphasized in the ASEAN roadmap[2,6,21,23–25]. Second, planning should account for climate variability. Because El Niño aligns with larger burned area and more severe haze, seasonal preparedness and prevention should be benchmarked to ENSO outlooks and reported together with peat fire counts and burned area[25]. Third, where data allow, reports should pair $PM_{2.5}$ mass with combustion tracers such as carbon monoxide and simple proxies for black carbon, and include an oxidant indicator, so that climate-relevant chemistry implied by the red cluster is captured[19,20,24]. Finally, the focus should remain on the air pathway. The climate linkages here arise from smoke and short lived forcers. Marine pollution topics were screened out for this subsection, so the main text does not infer climate policy needs from marine plastics.

4.4. SWOT Analysis of Transboundary Air-Pollution Research in Southeast Asia

Figure 6 shows the pollution research landscape in Southeast Asia based on SWOT (Strengths, Weaknesses, Opportunities, and Threats). This SWOT is derived directly from the bibliometric outputs in **Figures 1** and **2**. To avoid subjective wording, we rely on standard graph measures. VOSviewer clustering defines the colour groups and follows established practice in network analysis and the VOSviewer literature[10,11,26]. Wherever the SWOT refers to progress indicators and aligned with regional and global guidance[2,6,7,18]. In **Figure 6**, titled 'Evidence-backed SWOT for transboundary air pollution research in Southeast Asia,' the left panel lists each item with a named indicator and source, while the right panel shows the formulas for density and average degree and cites the map files used for calculation.

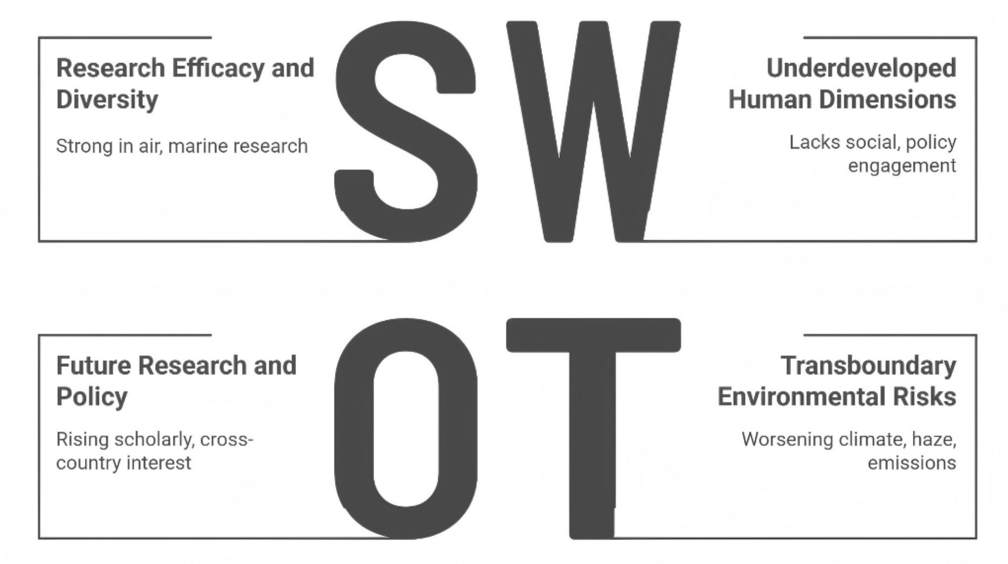

Figure 6. The pollution research landscape in Southeast Asia based on SWOT (Strengths, Weaknesses, Opportunities, and Threats).

a) Strengths (S)

S1. Connected conceptual core around smoke and $PM_{2.5}$. The indicator is the share of records that contain at least one of the following terms: $PM_{2.5}$, haze, peat, forest fire, transport, or trajectory. The evidence is that the red cluster is the largest by node count and link weight. This pattern matches the established chain from ignition to long-range movement, population exposure, and health effects [4,5,19–21].

S2. Operational monitoring and attribution are mainstream. The indicator is the share of records that include satellite, active fire, FIRMS, Himawari, back trajectory, or remote sensing. The evidence is that the green cluster sits next to the core and shows warmer colors in the overlay for 2018–2025, which is consistent with wider use of near real time products and regional advisories [7–10].

S3. Regional co-authorship that reflects shared exposure. The indicator is the proportion of cross-country coauthored papers and the strongest bilateral links among Indonesia, Malaysia, and Singapore. The evidence is that collaboration ties are most pronounced within this triad in the co-authorship view, and severe haze seasons such as 2015 have motivated joint studies [4,5].

S4. Anchor studies on exposure, health, and sectoral attribution. The indicator is the count of highly cited items that quantify excess mortality or separate local and transboundary contributions during haze months. The evidence is that these studies sit near the center of the red cluster and bridge to health-related terms, confirming their integrative role in the field [4,5,21,22].

b) Weaknesses (W)

W1. Gaps in geographic coverage and topic balance. The indicator is the share of items tagged to Cambodia, Lao PDR, Myanmar, Viet Nam, and Brunei relative to their population and exposure risk. The evidence is that country terms for these settings are underrepresented at the periphery of the yellow cluster, which points to uneven attention across the region.

W2. Limited integration of health outcomes across the corpus. The indicator is the share of records that include health, mortality, morbidity, or hospital admission in the title or keywords. The evidence is that the blue cluster is smaller than the red and green clusters in node count and link weight, despite the importance of health during smoke seasons, as shown in the regional literature on exposure and impacts [4,5,22].

W3. Transparency of station networks and data capture. The indicator is the proportion of studies that report station density, percentage data capture, and calibration status. The evidence is that these monitoring-quality terms appear less frequently in keywords, even though they are essential for reproducible indicators and public auditing of trends [7–10,18].

W4. Sensitivity to database choice and query scope. The indicator is the difference in document counts and periphery links when alternative index coverage and field scopes are used. The evidence is that known coverage differences across bibliographic databases, together with our sensitivity checks, caution against over-interpretation of raw counts without reporting the query field and index used [14,15].

c) Opportunities (O)

O1. Align research outputs with policy scorecards. Standardize annual reporting of population-weighted $PM_{2.5}$, the percentage of stations at or below the WHO annual guideline, and haze-advisory days. Publishing these headline indicators each year enables trackable co-benefits for air quality and climate and matches the ASEAN cooperation framework and WHO guidance [2,6,18].

O2. Scale up the monitoring–attribution workflow already common in the literature. Publish a national station inventory, report percentage data capture, and routinely use ASMC advisories together with FIRMS active-fire detections and Himawari imagery in public situation reports. Harmonized disclosure makes advisory decisions auditable and replicable because it follows the workflow visible in the green cluster of the maps [7–10].

O3. Prepare for climate variability and fire risk. Report peat-fire counts and burned area in peatlands by season and by priority landscape, and publish seasonal preparedness plans tied to El Niño outlooks. Fire–climate coupling is strong in the region, so preparedness and prevention are measurable and should be tracked alongside modeled local versus transboundary contributions during haze seasons [21,25].

O4. Strengthen cross-country collaboration where collaboration is thin. Track co-authorship rates that include partners from Cambodia, Lao PDR, Myanmar, Viet Nam, and Brunei, and publish shared data releases and after-action reviews under ASEAN haze instruments. Targeted programs can shift collaboration patterns and support underrepresented settings in line with regional agreements [6].

d) Threats (T)

T1. Recurring large fires during dry and El Niño years. The indicators are multi-year trends in peat-fire counts and burned area in peatlands, together with the fraction of days with smoke intrusions at downwind stations. The evidence shows a strong historical coupling between drought and fire activity in the region, and severe episodes carry well-documented health burdens that recur when El Niño conditions amplify dryness and ignition pressure[4,5,25].

T2. Fragmented monitoring and reporting across borders. The indicators are uneven station density and inconsistent data capture, plus the absence of shared incident logs and common advisory thresholds. This fragmentation limits the ability to compare progress and to evaluate interventions, even when the research base grows, because outcomes cannot be audited in the same way across countries and seasons[7–10,18].

T3. Over emphasis on descriptions without outcome evaluation. The indicator is the share of studies that release reusable time series for the three headline metrics compared with one-time case studies. Without outcome series that are updated and open, it is difficult to judge the effectiveness of prevention and response, even when the conceptual map of the field is rich.

4.5. Proposals for Future Mitigation Strategies and Environmental Management

Figure 7 shows the future mitigation strategies and environmental management in Southeast Asia. The red and green clusters in **Figures 1** and **2** show a mature core around $PM_{2.5}$, haze, peat and vegetation fires, emissions, transport, and monitoring–attribution, while the yellow cluster adds the regional policy frame. Together they point to four levers for action: align reporting with regional instruments, professionalize monitoring and open data, run a standard early-warning and attribution workflow, and prevent fires in priority peat and forest landscapes. The proposals below translate those levers into who does what, by when, and how progress is measured, consistent with ASEAN's current roadmap and related guidance[2,6,18,27].

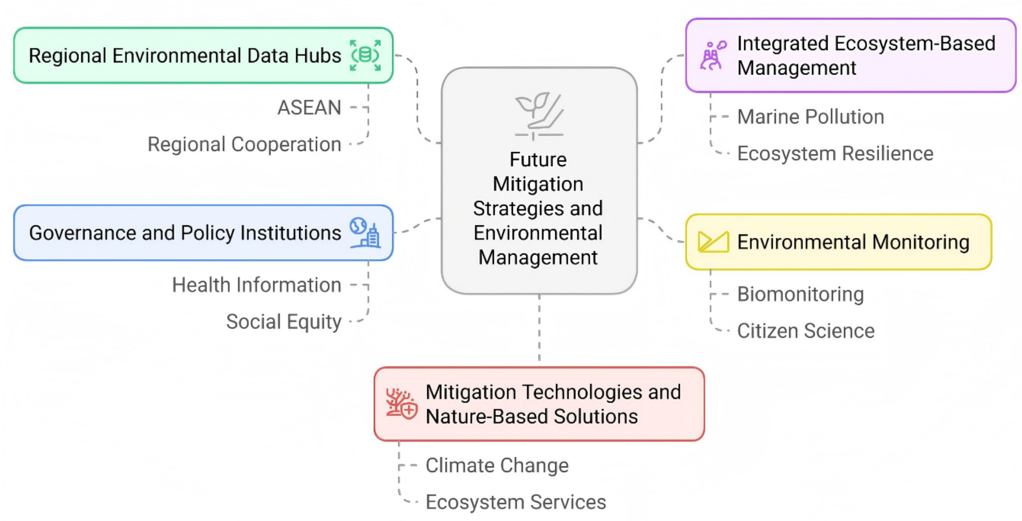

Figure 7. The future mitigation strategies and environmental management in Southeast Asia.

4.5.1. Governance and Reporting: Align with ASEAN and WHO, Publish Annual Scorecards

Actions. Adopt an annual national scorecard that reports population-weighted $PM_{2.5}$, haze-advisory days, and the percentage of stations meeting the WHO annual guideline. Include method notes and the underlying data file. Responsible actors: environment and health ministries with national statistical offices. Timeline: start in 0–12 months, then annually[2,18,27–30].

Indicators and targets. Population-weighted $PM_{2.5}$ computed per SDG 11.6.2 metadata; haze-advisory days defined against published thresholds; share of stations at or below the WHO annual guideline[2,18].

4.5.2. Monitoring Quality and Open Data: Measure What Matters and Make It Auditable

Actions. Publish a station inventory with locations, instruments, and calibration status; commit to ≥90 percent data capture per station and disclose annual audits. Augment reference-grade monitors with validated low-cost sensors for spatial coverage in underserved districts, following official QA guidance and paired-site checks. Timeline: 0–12 months for the inventory and portal; 1–3 years for network densification [31,32].

Indicators and targets. Station density per million people by province; data-capture percentage and uptime by station; an open portal with hourly $PM_{2.5}$ and a daily haze flag, plus method notes and CSV download [31,32].

4.5.3. Early Warning and Attribution: Use the Regional System and Document Decisions

Actions. Adopt the ASMC advisory and alert-level system in national SOPs; during the dry season, publish daily situation reports that combine station $PM_{2.5}$, FIRMS active-fire detections, Himawari imagery, and back-trajectories to attribute smoke intrusions. Timeline: immediate adoption with dry-season drills [7–10,28].

Indicators and targets. Time from hotspot detection to public advisory; number of joint advisories referencing ASMC alerts [28].

4.5.4. Source-Side Prevention in Peat and Forest Landscapes: Act Where It Matters Most

Actions. Implement the ASEAN Peatland Management Strategy 2023–2030 in priority Peatland Hydrological Units: rewetting, canal blocking, community fire brigades, and concession compliance checks. Publish peat-fire counts and burned area in peatlands each season, by district. Timeline: 1–3 years for implementation in top-risk units; 3–5 years for scale-up [29].

Indicators and targets. Seasonal peat-fire counts and burned area in targeted PHUs; number of prevention actions completed and enforcement actions taken in non-compliant concessions [29].

4.5.5. Cross-Border Coordination and Evaluation: Show the Work

Actions. Under the Second Haze-Free Roadmap 2023–2030, publish joint incident logs and after-action reviews for severe episodes; align national scorecards with the roadmap's monitoring and evaluation logic; commission an independent audit in year five. Timeline: 1–3 years to institutionalize joint reviews; by year five for audit [27,33].

Indicators and targets. Number of joint reviews completed and made public; evidence of data sharing and common thresholds across borders [27,33].

4.5.6. Expected Results If Implemented

Air-quality improvement. A downward trend in population-weighted $PM_{2.5}$ and in haze-advisory days within five years, documented publicly [18,27]. System performance. Higher station density, ≥90 percent data capture, and transparent QA, with selective use of low-cost sensors to fill gaps [31,32]. Source reduction. Multi-year declines in peat-fire counts and burned area in priority PHUs, aligned with APMS 2023–2030 [29]. Regional accountability. Regular joint incident logs and after-action reviews under the Second Haze-Free Roadmap, with an independent audit by year five [27,33].

4.6. Strategic Roadmap for Governance and Resilience

Figure 8 presents the strategic roadmap for governance and resilience. This can convert the evidence into specific actions over three time horizons. Headline indicators follow the Second Haze-Free Roadmap and the ASEAN Agreement on Transboundary Haze Pollution, with outcome benchmarks aligned to the 2021 WHO Air Quality Guidelines for $PM_{2.5}$. The legal and governance basis for regional action in ASEAN and international environmental law underpins the cooperative measures in this roadmap [27,34–36] and is consistent with prior regional experience during transboundary episodes [37,38]. Outcome metrics follow WHO methods [2] and SDG 11.6.2 reporting practices [18].

Figure 8. The strategic roadmap for governance and resilience.

4.6.1. Objectives and Headline Indicators

O1. Reduce haze exposure. Indicators are population-weighted $PM_{2.5}$, haze-advisory days, and the percentage of stations at or below the WHO annual guideline. These align with public-health evidence and ASEAN cooperation principles for transboundary events [2,27,39–45].

O2. Prevent and control fire sources. Indicators are peat and vegetation fire counts, burned area in peatlands, the share of hotspots in high-risk concessions, and enforcement actions taken. Multi-source satellite and modeling studies show how these indicators relate to downwind $PM_{2.5}$ and regional exposure [41–44,46].

O3. Make monitoring and response auditable. Indicators are station density per million people, percentage data capture, publication of open hourly $PM_{2.5}$ and a daily haze flag, and the routine use of regional advisories in public communication. These steps reflect operational workflows already used in Southeast Asia and the need for institutionalized cooperation [27,38–41].

4.6.2. Actions, Outputs, and Targets

A. 0–12 months

Governance. Designate a national lead and a cross-sector task force to coordinate AATHP implementation and the Second Haze-Free Roadmap. Output is a terms-of-reference document and an annual workplan [27,34–36].

Monitoring and open data. Publish a national inventory of $PM_{2.5}$ stations with instruments and calibration status. Commit to at least 90 percent data capture per station. Launch an open portal with hourly $PM_{2.5}$ and a daily haze flag and reference regional advisories in public updates. Expected result is replicable exposure metrics by the next haze season [27,38–41].

Source reduction. Stand up an operational dashboard that fuses active-fire detections, geostationary imagery, and back-trajectories for daily attribution during the dry season. Output is a short situation report for each day of elevated risk [41–44,46].

Targets by year-end. Publish the first national scorecard with population-weighted $PM_{2.5}$, station coverage and capture, and haze-advisory days benchmarked to WHO methods and SDG 11 [2,18].

B. 1–3 years

Governance and finance. Adopt national $PM_{2.5}$ targets aligned with WHO interim levels and ring-fence funding for peat-fire prevention in high-risk districts [2,27,34–36].

Monitoring quality. Expand station density in underserved provinces and publish annual calibration audits. Document data-capture rates and any corrective actions [39–41].

Source reduction and enforcement. Implement prevention packages in priority peat and forest landscapes and publish indicators of compliance and penalties. Satellite and modelling evidence support verification of downwind benefits from reduced burning [41–44,46].

Health protection. Codify risk-communication thresholds tied to observed $PM_{2.5}$ and report the number of advisory days and school-closure days annually. Recent regional studies justify these protections [47–49].

C. 3–5 years

Regional alignment. Publish cross-border incident logs and after-action reviews under AATHP. Harmonize annual reporting with the Second Haze-Free Roadmap monitoring and evaluation logic. Expected result is visible and verifiable cooperation [27,34–37].

Outcomes and evaluation. Commission an independent audit of the national scorecard and the source-reduction dashboard and revise targets toward the WHO annual guideline where feasible [2,27].

4.6.3. How Progress Will Be Measured

Air-quality outcomes. Population-weighted $PM_{2.5}$, the share of stations at or below the WHO annual guideline, and days above interim targets [2,18].

Source outcomes. Peat and vegetation fire counts and burned area in peatlands, segmented by high-risk concessions and protected peatlands, which connect directly to downwind $PM_{2.5}$ in the regional literature [41–44,46].

System performance. Station density and data-capture, time from hotspot detection to advisory, publication of open data, and completion of cross-border after-action reviews that reference regional advisories [27,38–41].

4.7. Ecotoxicology Concerns: Mechanisms, Pathways, and Cross-media Context

Ecotoxicological risk in Southeast Asia arises primarily from the chemistry of smoke, its transport, and the conditions that amplify burning. Regional campaigns and process studies show that vegetation and peat fires emit carbonaceous particles, carbon monoxide, and reactive VOCs that age in transit and change toxicity and radiative properties. This has been documented from the Indian Ocean Experiment through winter-to-spring monsoon analyses, high-altitude and aircraft observations, and recent event studies across mainland and maritime subregions [49–59]. Modelling for Upper Southeast Asia and new work on VOC-driven ozone and secondary organic aerosol formation corroborate the role of precursors in downwind oxidant and particle burdens during haze seasons [55,56]. These mechanisms align with event analyses that tracked smoke from source to receptor across borders [57–59]. Health and exposure evidence confirms acute mortality and morbidity during severe episodes, with child respiratory effects and traveller's risk illustrating vulnerability across social groups; economic studies extend this to productivity and sector losses, and biodiversity research shows ecosystem disruption during the 2015 fires [60–66]. Socioeconomic and governance scholarship explains why hazard becomes harm when abatement incentives and regulatory capacity are weak or fragmented [67–74].

Cross-media issues add context. Riverine and coastal studies report microplastic and sewage markers, aquaculture stressors, and mitigation potential through vegetated wetlands; these sit outside the air pathway but share institutions and data systems with haze management [75–85]. Regional risk mapping that integrates remote sensing with socioeconomic layers can prioritize districts where multiple hazards intersect, while open-burning diagnostics, dispersion modelling, and source apportionment provide the technical basis for rapid attribution and targeted prevention [86–88]. Maritime emission control contributes to coastal airshed management [89]. Governance narratives of chronic haze, regional diplomacy, and stakeholder regimes describe the political conditions under which cooperative controls succeed [90]. Urban deposition records and historical inland-waters baselines underline cumulative loading and long-term vulnerability [91–94]. Platform documentation reminds readers that bibliographic counts reflect index scope and should be interpreted with care [92]. Finally, freshwater microplastic studies illustrate how community-level monitoring can complement statutory systems and strengthen environmental intelligence [75,76,95,96]. Taken together, these strands keep ecotoxicology grounded in the air pathway while recognizing linked media. The operational implications are straightforward: prevent ignition in priority peat and forest landscapes, measure exposure with transparent station quality and open files, attribute sources with satellites and trajectories, protect vulnerable groups with clear thresholds, and publish results so progress can be audited.

5. Conclusions

This review shows a coherent literature centered on $PM_{2.5}$ and haze from vegetation and peat fires, long-range transport into downwind cities, and measurable health effects. The keyword maps and robustness checks confirm a stable core that links sources, monitoring, exposure, and policy framing. We disclosed the full search and mapping workflow, reported the parameters that shape the visuals, and defined what we mean by interconnectedness and density with explicit network metrics. The revised Results avoid off-topic material, and the Discussion ties the evidence to climate-relevant chemistry, public health, and the regional instruments that already exist. The evidence-backed SWOT identifies strengths in a connected core and operational monitoring, and it is candid about gaps in open-network quality, health integration, and coverage in several countries.

The Strategic Roadmap turns these findings into specific steps with timelines, responsible actors, and indicators that can be audited. Countries can publish annual scorecards with population-weighted $PM_{2.5}$, haze-advisory days, and the share of stations meeting the WHO annual guideline, while preventing fires in priority peat and forest landscapes and documenting daily attribution with stations, satellite hotspots, geostationary imagery, and trajectories. These actions align with ASEAN cooperation and can be evaluated with open files and clear methods. Future work should deepen health outcome integration, expand monitored areas with quality assurance, and sustain cross-border incident reviews so progress is visible and comparable. Together, these moves make the region's management of transboundary air pollution more transparent, testable, and effective.

Author Contributions

Conceptualization, C.K.Y. and A.D.S.; methodology, C.K.Y.; software, A.D.S.; validation, C.K.Y. and A.D.S.; formal analysis, C.K.Y.; investigation, C.K.Y.; resources, A.D.S.; data curation, C.K.Y.; writing—original draft preparation, C.K.Y.; writing—review and editing, A.D.S.; visualization, C.K.Y.; supervision, C.K.Y.; project administration, C.K.Y. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Jones, D.S., 2006. ASEAN and transboundary haze pollution in Southeast Asia. Asia Europe Journal. 4(3), 431–446. DOI: http://dx.doi.org/10.1007/s10308-006-0067-1

[2] Islam, M.S., Hui Pei, Y., Mangharam, S., 2016. Trans-Boundary Haze Pollution in Southeast Asia: Sustainability through Plural Environmental Governance. Sustainability. 8(5), 499. DOI: https://doi.org/10.3390/su8050499

[3] Ng, K., 2017. Transboundary haze pollution in Southeast Asia: The effectiveness of three forms of international legal solutions. Journal of East Asia and International Law. 10(1), 221–244. DOI: https://doi.org/10.14330/jeail.2017.10.1.11

[4] Alam, S., Nurhidayah, L., 2017. The international law on transboundary haze pollution: What can we learn from the Southeast Asia region? Review of European, Comparative and International Environmental Law. 26(3), 243–254. DOI: https://doi.org/10.1111/reel.12221

[5] Sastry, N., 2002. Forest fires, air pollution, and mortality in Southeast Asia. Demography. 39(1), 1–23. DOI: https://doi.org/10.1353/dem.2002.0009

[6] Vongruang, P., Lawongyer, P., Pimonsree, S., 2024. Assessing the impact of air pollution on short-term hospital visits for respiratory diseases in Lampang, a city heavily affected by biomass burning in Mainland Southeast Asia. Atmospheric Pollution Research. 15(7), 102159. DOI: https://doi.org/10.1016/j.apr.2024.102159

[7] Fang, T., Gu, Y., Yim, S.H.L., 2024. Assessing local and transboundary fine particulate matter pollution and sectoral contributions in Southeast Asia during haze months of 2015–2019. Environment International. 190, 108367. DOI: https://doi.org/10.1016/j.scitotenv.2023.169051

[8] Nakata, M., Mukai, S., Yasumoto, M., 2018. Seasonal and regional characteristics of aerosol pollution in East and Southeast Asia. Frontiers in Environmental Science. 6, 29. DOI: https://doi.org/10.3389/fenvs.2018.00029
[9] Liang, A., Gu, J., Xiang, C., 2023. Multi-Source Satellite and WRF-Chem Analyses of Atmospheric Pollution from Fires in Peninsular Southeast Asia. Remote Sensing. 15(23), 5463. DOI: https://doi.org/10.3390/rs15235463
[10] van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics. 84(2), 523–538. DOI: https://doi.org/10.1007/s11192-009-0146-3
[11] Waltman, L., van Eck, N.J., Noyons, E.C.M., 2010. A unified approach to mapping and clustering of bibliometric networks. Journal of Informetrics. 4(4), 629–635. DOI: https://doi.org/10.1016/j.joi.2010.07.002
[12] Taghizadeh-Hesary, F., Taghizadeh-Hesary, F., 2020. The impacts of air pollution on health and economy in Southeast Asia. Energies. 13(7), 1812. DOI: https://doi.org/10.3390/en13071812
[13] Elsevier, 2025. Scopus Content. Available from: www.elsevier.com/products/scopus/content (cited 7 May 2025)
[14] Mongeon, P., Paul-Hus, A., 2016. The journal coverage of Web of Science and Scopus: A comparative analysis. Scientometrics. 106(1), 213–228. DOI: https://doi.org/10.1007/s11192-015-1765-5
[15] Visser, M., van Eck, N.J., Waltman, L., 2021. Large-scale comparison of bibliographic data sources: Scopus, Web of Science, Dimensions, Crossref, and Microsoft Academic. Quantitative Science Studies. 2(1), 20–41. DOI: https://doi.org/10.1162/qss_a_00112
[16] Perianes-Rodríguez, A., Waltman, L., van Eck, N.J., 2016. Constructing bibliometric networks: A comparison between full and fractional counting. Journal of Informetrics. 10(4), 1178–1195. DOI: https://doi.org/10.1016/j.joi.2016.10.006
[17] Aria, M., Cuccurullo, C., 2017. Bibliometrix: An R-tool for comprehensive science mapping analysis. Journal of Informetrics. 11(4), 959–975. DOI: https://doi.org/10.1016/j.joi.2017.08.007
[18] Bailey, J., Ramacher, M.O.P., Speyer, O., et al., 2023. Localizing SDG 11.6.2 via Earth Observation, Modelling Applications, and Harmonised City Definitions: Policy Implications on Addressing Air Pollution. Remote Sensing. 15(4), 1082. DOI: https://doi.org/10.3390/rs15041082
[19] Lin, N.H., Sayer, A.M., Wang, S.H., et al., 2013. An overview of regional experiments on biomass-burning aerosols and related pollutants in Southeast Asia: From BASE-ASIA and the Dongsha Experiment to 7-SEAS. Atmospheric Environment. 78, 1–19. DOI: https://doi.org/10.1016/j.atmosenv.2013.04.066
[20] Amnuaylojaroen, T., Barth, M.C., Emmons, L.K., et al., 2019. Modeling the effect of VOCs from biomass-burning emissions on ozone pollution in upper Southeast Asia. Heliyon. 5(10), e02661. DOI: https://doi.org/10.1016/j.heliyon.2019.e02661
[21] Yang, X., Liu, L., Li, Y., et al., 2025. Differences in perceived sensitivity to air pollution between smokers and non-smokers during a heavy haze episode in Northeast China. Scientific Reports. 15(1), 26476. DOI: https://doi.org/10.1038/s41598-025-12248-4
[22] Cheong, K.H., Ngiam, N.J., Morgan, G.G., et al., 2019. Acute health impacts of the Southeast Asian transboundary haze problem: A review. International Journal of Environmental Research and Public Health. 16(18), 3286. DOI: https://doi.org/10.3390/ijerph16183286
[23] Szopa, S., Naik, V., Adhikary, B., et al., 2021. Chapter 6: Short-lived Climate Forcers. In: Masson-Delmotte, V., Zhai, P., Pirani, A., (eds.). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press: New York, NY, USA. pp. 817–922.
[24] Bond, T.C., Doherty, S.J., Fahey, D.W., et al., 2013. Bounding the role of black carbon in the climate system: A scientific assessment. Journal of Geophysical Research: Atmospheres. 118(11), 5380–5552. DOI: https://doi.org/10.1002/jgrd.50171
[25] Field, R.D., van der Werf, G.R., Shen, S.S.P., 2009. Human amplification of drought-induced biomass burning in Indonesia since 1960. Nature Geoscience. 2, 185–188. DOI: http://dx.doi.org/10.1038/ngeo443
[26] Newman, M.E.J., 2010. Networks: An Introduction, 1st ed. Oxford University Press: New York, NY, USA.
[27] Association of Southeast Asian Nations, 2024. The Second Haze-Free Roadmap 2023–2030. ASEAN Secretariat: Jakarta, Indonesia.
[28] ASEAN Specialized Meteorological Centre, 2025. Early-warning advisories and alert levels for transboundary haze in ASEAN. Available from: https://asmc.asean.org/home/ (cited 7 May 2025)
[29] Association of Southeast Asian Nations, 2023. ASEAN Peatland Management Strategy 2023–2030. ASEAN Secretariat: Jakarta, Indonesia.
[30] United Nations Statistics Division, 2023. SDG 11.6.2 Metadata: Annual Mean Levels of PM2.5 in Cities, Population-weighted. UN: New York, NY, USA.
[31] World Meteorological Organization, 2024. Low-cost sensors can improve air quality monitoring and people's health. World Meteorological Organization (WMO): Geneva, Switzerland.
[32] United States Environmental Protection Agency, 2021. Monitoring PM2.5 in ambient air using designated reference or equivalent methods: quality assurance guidance. United States Environmental Protection Agency

(EPA): Washington, DC, USA.

[33] Peteru, S., Dermawan, A., Silviana, S.H., et al., 2025. Revisiting the ASEAN response strategy to fire, smoke and haze in Southeast Asia. CIFOR-ICRAF infobriefs. DOI: https://doi.org/10.17528/cifor-icraf/009359

[34] Bousiotis, D., Ademi Shaqiri, L., Sanghera, D.S., et al., 2025. Low-cost source apportionment (LoCoSA) of air pollution: Literature review of the state of the art. Science of The Total Environment. 998, 180257. DOI: https://doi.org/10.1016/j.scitotenv.2025.180257

[35] Nurhidayah, L., Alam, S., Lipman, Z., 2015. The influence of international law upon ASEAN approaches in addressing transboundary haze pollution in Southeast Asia. Contemporary Southeast Asia. 37(2), 183–210.

[36] Mkasimongwa, S.W., Livesley, S.J., Ryan, R.G., et al., 2025. Air pollution exceedance events in Melbourne and Sydney, Australia, between 2000 and 2024. City and Environment Interactions. 28, 100239. DOI: https://doi.org/10.1016/j.cacint.2025.100239

[37] Quah, E., 2002. Transboundary pollution in Southeast Asia: The Indonesian fires. World Development. 30(3), 429–441. DOI: https://doi.org/10.1016/S0305-750X(01)00122-X

[38] Jaafar, A.B., Boston, N., Bennett, J.A., 1987. International cooperation in pollution control in Southeast Asia. In Proceedings of the OCEANS '87: The Ocean—An International Workplace, Halifax, NS, Canada. 28 September–1 October 1987. p. 696. DOI: https://doi.org/10.1109/oceans.1987.1160916

[39] Chen, Q., Taylor, D., 2018. Transboundary atmospheric pollution in Southeast Asia: Current methods, limitations and future developments. Critical Reviews in Environmental Science and Technology. 48(16–18), 997–1029. DOI: https://doi.org/10.1080/10643389.2018.1493337

[40] Engels, S., Fong, L.S.R.Z., Chen, Q., et al., 2018. Historical atmospheric pollution trends in Southeast Asia inferred from lake sediment records. Environmental Pollution. 235, 907–917. DOI: https://doi.org/10.1016/j.envpol.2018.01.007

[41] Hertwig, D., Burgin, L., Gan, C., et al., 2015. Development and demonstration of a Lagrangian dispersion modeling system for real-time prediction of smoke haze pollution from biomass burning in Southeast Asia. Journal of Geophysical Research. 120(24), 12605–12630. DOI: https://doi.org/10.1002/2015JD023422

[42] Zhang, Z., Li, H., Ho, W., et al., 2024. Critical roles of surface-enhanced heterogeneous oxidation of SO_2 in haze chemistry: Review of extended pathways for complex air pollution. Current Pollution Reports. 10(1), 70–86. DOI: https://doi.org/10.1007/s40726-023-00287-2

[43] Yen, M.-C., Peng, C.-M., Chen, T.-C., et al., 2013. Climate and weather characteristics associated with active fires in northern Southeast Asia and spring air pollution in Taiwan during the 2010 7-SEAS/Dongsha Experiment. Atmospheric Environment. 78, 35–50. DOI: https://doi.org/10.1016/j.atmosenv.2012.11.015

[44] Yin, S., Wang, X., Zhang, X., et al., 2019. Influence of biomass burning on local air pollution in mainland Southeast Asia from 2001 to 2016. Environmental Pollution. 254, 112949. DOI: https://doi.org/10.1016/j.envpol.2019.07.117

[45] Reddington, C.L., Conibear, L., Robinson, S., et al., 2021. Air pollution from forest and vegetation fires in Southeast Asia disproportionately impacts the poor. GeoHealth. 5(9), e2021GH000418. DOI: https://doi.org/10.1029/2021GH000418

[46] Zhou, J., Li, Y., 2025. Research on the threshold effect of green technology innovation on fog–haze pollution in the transfer of air pollution-intensive industries: A perspective of thermal power. Atmosphere. 16(4), 471. DOI: https://doi.org/10.3390/atmos16040471

[47] Sannoh, F., Fatmi, Z., Carpenter, D.O., et al., 2024. Air pollution we breathe: Assessing the air quality and human health impact in a megacity of Southeast Asia. Science of the Total Environment. 942, 173403. DOI: https://doi.org/10.1016/j.scitotenv.2024.173403

[48] Raheel, H., Sinharoy, S., Díaz-Artiga, A., et al., 2025. Effects of a liquefied petroleum gas stove and fuel intervention on head circumference and length at birth: A multi-country household air pollution intervention network (HAPIN) trial. Environment International. 195, 109211. DOI: https://doi.org/10.1016/j.envint.2024.109211

[49] Lelieveld, J., Crutzen, P.J., Ramanathan, V., et al., 2001. The Indian Ocean Experiment: Widespread air pollution from South and Southeast Asia. Science. 291, 1031–1036. DOI: https://doi.org/10.1126/science.1057103

[50] Phadnis, M.J., Levy II, H., Moxim, W.J., 2002. On the evolution of pollution from South and Southeast Asia during the winter — spring monsoon. Journal of Geophysical Research: Atmospheres. 107(24), 4790. DOI: https://doi.org/10.1029/2002JD002190

[51] Zhao, Z., Cao, J., Shen, Z., et al., 2013. Aerosol particles at a high-altitude site on the Southeast Tibetan Plateau: Implications for transport from South Asia. Journal of Geophysical Research: Atmospheres. 118, 11360–11375. DOI: https://doi.org/10.1002/jgrd.50599

[52] Gu, F., Liu, X., Cao, Y., et al., 2024. Does haze pollution governance promote the growth of urban tourism economies? Evidence from China's Clean Air Act. Tourism Economics. 30(7), 1800–1819. DOI: https://doi.org/10.1177/13548166241233624

[53] Jaafar, S.A., Latif, M.T., Razak, I.S., et al., 2018. Composition of carbohydrates, surfactants, major elements and anions in PM2.5 during the 2013 high-pollution episode in Malaysia. Particuology. 37, 119–126. DOI: https://doi.org/10.1016/j.partic.2017.04.012

[54] Amnuaylojaroen, T., 2023. Air pollution modeling in Southeast Asia—An overview. In: Vadrevu, K.P., Ohara, T., Justice, C., (eds.). Vegetation Fires and Pollution in Asia. Springer: Cham, Switzerland. pp. 531–544. DOI: https://doi.org/10.1007/978-3-031-29916-2_31

[55] Zhao, G., Ge, Y., Jin, Y., et al., 2025. The burden trend and projection of tracheal, bronchial, and lung cancer attributable to air pollution: Based on the Global Burden of Disease Study 2021. Next Research. 2(3), 100681. DOI: https://doi.org/10.1016/j.nexres.2025.100681

[56] Tala, W., Janta, R., Kraisitnitikul, P., et al., Patterns and impact of volatile organic compounds on ozone and secondary organic aerosol formation: implications for air pollution in Upper Southeast Asia. Journal of Hazardous Materials Advances. 18, 100762. DOI: https://doi.org/10.1016/j.hazadv.2025.100762

[57] Fan, W., Li, J., Han, Z., et al., 2023. Impacts of Southeast Asian biomass burning on aerosols over the low-latitude plateau in China. Frontiers in Environmental Science. 11, 1101745. DOI: https://doi.org/10.3389/fenvs.2023.1101745

[58] Rao, X.Q., Zhang, B.H., Jiang, Q., et al., 2023. Effects of biomass burning in Southeast Asia on pollution transport in the Yunnan border area. China Environmental Science. 43(9), 4459–4468. (in Chinese)

[59] Stohl, A., Forster, C., Huntrieser, H., et al., 2007. Aircraft measurements over Europe of a pollution plume from Southeast Asia. Atmospheric Chemistry and Physics. 7, 913–937. DOI: https://doi.org/10.5194/acp-7-913-2007

[60] Zhou, M., Du, X., 2025. Digital government and air pollution inequality: Evidence from Chinese cities. Economic Modelling. 152, 107301. DOI: https://doi.org/10.1016/j.econmod.2025.107301

[61] Shi, Y., Zhao, A., Matsunaga, T., et al., 2018. Underlying causes of $PM_{2.5}$-induced premature mortality and benefits of control in South and Southeast Asia, 1999–2014. Environment International. 121, 814–823. DOI: https://doi.org/10.1016/j.envint.2018.10.019

[62] Luong, L.M.T., Sly, P.D., Thai, P.K., et al., 2019. Impact of ambient air pollution and wheeze-associated disorders in Southeast Asian children. Reviews on Environmental Health. 34, 125–139. DOI: https://doi.org/10.1515/reveh-2018-0079

[63] Kitro, A., Panumasvivat, J., Pisutsan, P., et al., 2024. Air pollution crises and international travellers. Journal of Travel Medicine. 31(1), taad077. DOI: https://doi.org/10.1093/jtm/taad077

[64] Roy, S., Nguyen, H., Visaltanachoti, N., 2023. Be nice to the air: Severe haze pollution and mutual fund risk. Global Finance Journal. 58, 100893. DOI: https://doi.org/10.1016/j.gfj.2023.100893

[65] Taghizadeh-Hesary, F., Taghizadeh-Hesary, F., 2023. Energy–pollution–health–economy nexus in Southeast Asia. In: Taghizadeh-Hesary, F., Zhang, D., (eds.). The Handbook of Energy Policy. Springer: Singapore. pp. 739–760. DOI: https://doi.org/10.1007/978-981-19-6778-8_31

[66] Lee, B.P.Y.-H., Davies, Z.G., Struebig, M.J., 2017. Smoke pollution disrupted biodiversity during the 2015 El Niño fires. Environmental Research Letters. 12, 094022. DOI: https://doi.org/10.1088/1748-9326/aa87ed

[67] Hettige, H., Huq, M., Pargal, S., et al., 1996. Determinants of pollution abatement in developing countries. World Development. 24(12), 1891–1904. DOI: https://doi.org/10.1016/S0305-750X(96)00076-9

[68] Jenkins, R., 2012. Trade, investment and industrial pollution: Lessons from Southeast Asia. In: Adger, W.N., Kelly, P.M., Ninh, N.H., (eds.). Living with Environmental Change. Routledge: London, UK. pp. 185–212.

[69] Nguyen, T.G., 2019. Impacts of climate change, air pollution, and tourism in Southeast Asia. Journal of Environmental Management and Tourism. 10(8), 1711–1722.

[70] Abraham, I., 2015. Hazy skies: Geopolitics of pollution in Southeast Asia. Economic and Political Weekly. 50(48), 10–11.

[71] Ng, K., 2021. Transboundary haze pollution in Southeast Asia in ASEAN international law. In: Lee, E.Y.J. (ed.). ASEAN International Law. Springer: Singapore. pp. 599–620. DOI: https://doi.org/10.1007/978-981-16-3195-5_33

[72] Varkkey, H., 2022. Emergent geographies of chronic air-pollution governance in Southeast Asia. Environmental Policy and Governance. 32(4), 348–361. DOI: https://doi.org/10.1002/eet.1994

[73] Mukherjee, I., 2018. Policy design for sustainability at multiple scales: Transboundary haze in Southeast Asia. In: Brinkmann, R., Garren, S., (eds.). The Palgrave Handbook of Sustainability. Palgrave Macmillan: Cham, Switzerland. pp. 37–51. DOI: https://doi.org/10.1007/978-3-319-71389-2_3

[74] Siddiqui, A.I., Quah, E., 2004. Modelling transboundary air pollution in Southeast Asia: Policy regime and stakeholders. Environment and Planning A. 36(8), 1411–1425. DOI: https://doi.org/10.1068/a3674

[75] Babel, S., Ta, A.T., Nguyen, T.P.L., et al., 2022. Microplastics in selected rivers from Southeast Asia. APN Science Bulletin. 12(1), 5–17. DOI: https://doi.org/10.30852/sb.2022.1741

[76] Chen, H.L., Selvam, S.B., Ting, K.N., et al., 2021. Microplastic pollution in Southeast Asian freshwater systems. Environmental Science and Pollution Research. 28, 54222–54237. DOI: https://doi.org/10.1007/s11356-021-15826-x

[77] Chua, T.E., Paw, J.N., Guarin, F.Y., 1989. The environmental impact of aquaculture in Southeast Asia. Marine Pollution Bulletin. 20, 335–343. DOI: https://doi.org/10.1016/0025-326X(89)90157-4

[78] Nicholson, S., Lam, P.K.S., 2005. Biomarkers in Perna viridis for pollution monitoring. Environment International. 31, 121–132. DOI: https://doi.org/10.1016/j.envint.2004.05.007
[79] Cochard, R., 2017. Chapter 12 — Coastal water pollution and mitigation by vegetated wetlands. In: Redefining Diversity and Dynamics of Natural Resources Management in Asia. 189–230. DOI: https://doi.org/10.1016/B978-0-12-805454-3.00012-8
[80] Douglas, J., Niner, H., Garrard, S., 2024. Marine plastic pollution impacts on seagrass in Southeast Asia. Journal of Marine Science and Engineering. 12, 2314. DOI: https://doi.org/10.3390/jmse12122314
[81] Omeyer, L.C.M., Duncan, E.M., Aiemsomboon, K., et al., 2022. Priorities for marine plastic pollution research in Southeast Asia. Science of the Total Environment. 841, 156704. DOI: https://doi.org/10.1016/j.scitotenv.2022.156704
[82] Omeyer, L.C.M., Duncan, E.M., Abreo, N.A.S., et al., 2023. Interactions between marine megafauna and plastic pollution in Southeast Asia. Science of the Total Environment. 874, 162502. DOI: https://doi.org/10.1016/j.scitotenv.2023.162502
[83] Mathis, J.E., Gillet, M.C., Disselkoen, H., et al., 2022. Reducing ocean plastic pollution: Locally led initiatives reducing ocean plastics. Marine Policy. 143, 105127. DOI: https://doi.org/10.1016/j.marpol.2022.105127
[84] Marks, D., 2022. Transboundary governance failures and Southeast Asia's plastic pollution. In: Sims, K., Banks, N., Engel, S., et al., (eds.). Routledge Handbook of Global Development, 1st ed. Routledge: London, UK. pp. 280–289. DOI: http://dx.doi.org/10.4324/9781003017653-27
[85] Todd, P.A., Ong, X., Chou, L.M., 2010. Impacts of pollution on marine life in Southeast Asia. Biodiversity and Conservation. 19, 1063–1082. DOI: https://doi.org/10.1007/s10531-010-9778-0
[86] Sakti, A.D., Anggraini, T.S., Ihsan, K.T.N., et al., 2023. Multi-air pollution risk assessment in Southeast Asia. Science of the Total Environment. 854, 158825. DOI: https://doi.org/10.1016/j.scitotenv.2022.158825
[87] Choommanivong, S., Wiriya, W., Chantara, S., 2019. Transboundary air pollution and open burning in Upper Southeast Asia. EnvironmentAsia. 12(SI), 18–27. DOI: https://doi.org/10.14456/ea.2019.59
[88] Reddington, C.L., Yoshioka, M., Balasubramanian, R., et al., 2014. Contribution of vegetation and peat fires to particulate pollution in Southeast Asia. Environmental Research Letters. 9, 094006. DOI: https://doi.org/10.1088/1748-9326/9/9/094006
[89] Yang, Z., Lau, Y.-Y., Lei, Z., 2024. Analysis of pollution prevention performance of vessels in Southeast Asia: Implications towards vessel emission control and reduction. Ocean & Coastal Management. 248, 106942. DOI: https://doi.org/10.1016/j.ocecoaman.2023.106942
[90] Zhang, J.J., Savage, V.R., 2019. Southeast Asia's transboundary haze: Inconvenient truths. Asia Pacific Viewpoint. 60(3), 355–369. DOI: https://doi.org/10.1111/apv.12245
[91] Zhang, K., Liu, X.-Y., Song, W., et al., 2023. Precipitation records of anthropogenic nitrogen in two Southeast Asian cities. Urban Climate. 52, 101749. DOI: https://doi.org/10.1016/j.uclim.2023.101749
[92] García-Chan, N., Alvarez-Vázquez, L.J., Martínez, A., et al., 2026. A multi-model study of the air pollution related to traffic flow in a two-dimensional porous metropolitan area. Journal of Computational and Applied Mathematics. 473, 116903. DOI: https://doi.org/10.1016/j.cam.2025.116903
[93] Alabaster, J.S., 1986. Review of the State Water Pollution Affecting Inland Fisheries in Southeast Asia. Food and Agriculture Organization of the United Nations (FAO): Rome, Italy. p. 260.
[94] Kumar, M.D., Viswanathan, P.K., Bassi, N., 2014. Water scarcity and pollution in South and Southeast Asia. In: Harris, P.G., Lang, G., (eds.). Routledge Handbook of Environment and Society in Asia, 1st ed. Routledge: London, UK. pp. 197–215. DOI: https://doi.org/10.4324/9781315774862-22
[95] Ta, A.T., Babel, S., Nguyen, L.T.P., et al., 2024. Microplastic pollution in high-density rivers. Bulletin of Environmental Contamination and Toxicology. 112(5), 73. DOI: https://doi.org/10.1007/s00128-024-03901-1
[96] Chen, Q., McGowan, S., Gouramanis, C., et al., 2020. Rapidly rising transboundary atmospheric pollution from industrial and urban sources in Southeast Asia. Environmental Research Letters. 15, 1040A5. DOI: https://doi.org/10.1088/1748-9326/abb5ce