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SYSTEMATIC LITERATURE REVIEW OF SULFUR DIOXIDE SOURCES, IMPACTS, AND CONTROL STRATEGIES

Andriadi[1], Sayida Nafisa[1], Elma Asvira Vardhani[1], Suranto[1,2], Rahmawaty[1,3*]

[1]Natural Resources and Environment Management Study Program, Postgraduate School, Universitas Sumatera Utara, Medan 20155, North Sumatra, Indonesia
[2]Faculty of Engineering and Computer Science, Department of Civil Engineering, Universitas Pembinaan Masyarakat Indonesia, Medan 20214, North Sumatra, Indonesia
[3]Faculty of Forestry, Universitas Sumatera Utara, Kampus 2 USU Kuala Bekala, Pancur Batu, Deli Serdang 20353, North Sumatra, Indonesia

**Email: rahmawaty@usu.ac.id*

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ABSTRACT

Sulfur dioxide (SO_2) remains an important ambient air pollutant in Indonesia because it is emitted by fossil-fuel combustion, industrial processes, vehicular activities, and open burning at waste-disposal and commercial areas. This systematic literature review synthesizes empirical evidence on SO_2 emission sources, ambient concentrations, health and ecological impacts, monitoring approaches, and control strategies in Indonesia. Literature published between 2018 and 2025 was identified from Scopus, ScienceDirect, PubMed/MEDLINE, Google Scholar, and WHO-related databases, and the review process was reported in accordance with PRISMA 2020. After duplicate removal, title and abstract screening, full-text eligibility assessment, and methodological appraisal, 55 studies were included in the synthesis. The evidence shows that elevated SO_2 concentrations are repeatedly reported in traditional markets, landfills, industrial zones, transport corridors, and public facilities, although the spatial coverage and monitoring duration remain uneven. Health-related studies indicate respiratory irritation, non-carcinogenic exposure risks among high-exposure workers, and potential exacerbation of chronic respiratory disease, while ecological impacts remain comparatively under-investigated. Bibliometric mapping using VOSviewer identified air pollution, sulfur dioxide, ambient air, air quality, public health, and health impact as the dominant thematic clusters. This review contributes by integrating source-exposure-impact-control evidence and by identifying the main methodological and policy gaps for SO_2 management in Indonesia.

***Keywords**: Air Pollution; Control Strategies; Sulfur Dioxide; Systematic Literature Review; Quality of Life.*

INTRODUCTION

Ambient air pollution remains a major environmental health challenge because its adverse effects occur through multiple exposure pathways, affect both urban and rural populations, and require coordinated interventions across the energy, transport, industrial, and public health sectors. Sulfur dioxide (SO_2) is one of the key gaseous pollutants addressed in the WHO global air quality guidelines, together with particulate matter, ozone, nitrogen dioxide, and carbon monoxide (World Health Organization, 2021). Although SO_2 is often discussed alongside other criteria pollutants, it warrants specific attention because it is directly linked to the combustion of sulfur-containing fuels, industrial stacks, high-density transport activities, and secondary atmospheric transformation into sulfate aerosols. In Indonesia, the relevance of SO_2 control is amplified by the coexistence of fossil-fuel-based energy use, industrial development, dense urban transport, open burning practices, and highly localized exposure settings such as traditional markets and municipal landfills.

The main sources of SO_2 in Indonesia are predominantly anthropogenic, although natural emissions from volcanic activity may also contribute episodically in certain regions. Empirical studies reviewed in this paper indicate that SO_2 is commonly associated with vehicular traffic, market activities, landfill burning, petrochemical operations, boiler emissions, and other industrial combustion processes (Prastian et al., 2024; Andriani et al., 2025; Wijayanti et al., 2020). These sources are not distributed uniformly; rather, they are shaped by local land use, emission intensity, waste-management practices, meteorological conditions, and the availability of monitoring infrastructure. Consequently, a national understanding of SO_2 pollution cannot be inferred from a single measurement site or sector alone, because the pollutant profile differs substantially across transport corridors, waste-disposal areas, industrial zones, and indoor-adjacent microenvironments.

The health relevance of SO_2 has been established internationally and is increasingly reflected in Indonesian environmental-health studies. SO_2 can irritate the respiratory tract, aggravate asthma and bronchitis, and contribute to acute respiratory symptoms, particularly among children, older adults, and individuals with pre-existing respiratory conditions (World Health Organization, 2021; Manisalidis et al., 2020). A systematic review and meta-analysis by Orellano et al. (2021) found positive associations between short-term ambient SO_2 exposure and all-cause and respiratory mortality, supporting the plausibility of health risks even over relatively short time windows. At the local level, Indonesian studies have reported non-carcinogenic exposure risks among landfill workers, street sweepers, and other groups who experience repeated exposure in high-activity settings (Fauziah, 2020; Ramdan et al., 2018; Rejeki Takuloe et al., 2023).

Beyond human health, SO_2 is also environmentally important because it participates in atmospheric oxidation processes that generate sulfuric acid and sulfate compounds. These transformation products can contribute to acid deposition, acidification of soil and water bodies, injury to vegetation, reduced material durability, and corrosion of buildings and infrastructure. However, compared with the growing number of studies on concentration measurement and respiratory risk, ecological impact studies on SO_2 in Indonesia remain sparse and fragmented. This imbalance is important because air-pollution governance should consider not only compliance with ambient standards but also the cumulative consequences of deposition, ecosystem sensitivity, land-use exposure, and long-term environmental degradation.

Previous Indonesian studies have provided valuable site-specific evidence, but the overall literature remains scattered across different methods, locations, and disciplinary emphases. Some studies focus on direct gas-detector measurements in markets or landfills, whereas others use dispersion modeling, spatial interpolation, laboratory-measurement validation, or environmental health risk assessment (EHRA). The findings are therefore informative but not yet fully integrated: emission sources are often discussed separately from ambient concentration patterns; health risks are not consistently linked to exposure scenarios; and control recommendations are usually proposed without evaluation of implementation effectiveness. This fragmentation makes it difficult for policymakers to identify which emission sources should be prioritized, which populations are most vulnerable, and which control strategies are best supported by evidence.

Several reviews and general discussions on air pollution have been published, yet previous reviews are insufficient for the specific objective of this paper for three reasons. First, many reviews address air pollution broadly and therefore do not isolate the source-exposure-impact-control pathway of SO_2. Second, Indonesia-focused publications are dominated by local case studies and narrative summaries, which limit their ability to compare evidence across regions, methods, and exposure settings. Third, existing syntheses have rarely combined PRISMA-based screening, critical appraisal, thematic synthesis, and bibliometric mapping to show both the empirical evidence base and the intellectual structure of SO_2-related research. As a result, what remains insufficiently known is how Indonesian SO_2 evidence is distributed across sources, concentration levels, health and ecological impacts, modeling approaches, and policy-relevant control strategies.

This review therefore makes a specific contribution by systematically synthesizing SO_2 studies in Indonesia from 2018 to 2025 and integrating them into an evidence framework that connects emission sources, ambient concentrations, health and ecological implications, control strategies, and research gaps. The review is also situated within international evidence by incorporating global health and policy literature on SO_2, including systematic reviews on mortality and comparative evidence on regulatory controls. The objective of this study is to identify, appraise, and synthesize empirical evidence on SO_2 pollution in Indonesia and to formulate policy-relevant recommendations for monitoring, emission management, risk reduction, and future research.

METHOD

Research Design

This study was designed as a systematic literature review (SLR) to identify, appraise, and synthesize empirical evidence on the sources, ambient concentrations, health and ecological impacts, monitoring approaches, and control strategies of SO_2 pollution in Indonesia. An SLR approach was selected because it offers a transparent and reproducible framework for integrating fragmented findings across different study designs, sites, and measurement methods (Snyder, 2019; Xiao & Watson, 2019). The reporting structure followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement to ensure clear documentation of identification, screening, eligibility assessment, inclusion, and synthesis procedures (Page et al., 2021).

Search Sources and Strategies

The literature search was conducted using international and national scholarly databases, including Scopus, ScienceDirect, PubMed/MEDLINE, Google Scholar, and WHO-related databases. The search covered publications from January 2018 to December 2025. This period was selected to capture recent empirical evidence after the rapid expansion of urban, industrial, and monitoring-related air-pollution studies in Indonesia, while still providing a sufficiently broad time frame for comparison across locations and methods.

The search strategy combined pollutant-specific, topic-specific, and country-specific terms. The main search string was: ("sulfur dioxide" OR "sulphur dioxide" OR "SO_2" OR "SO2") AND ("air pollution" OR "ambient air" OR "air quality" OR "emission" OR "dispersion modeling" OR "environmental health risk assessment") AND ("Indonesia"). Additional manual searches were conducted through reference list checks to identify relevant studies not retrieved by the database search.

Inclusion, Exclusion, and Quality Appraisal

Studies were included if they met all of the following criteria: (i) journal articles, proceedings, theses, or technical academic reports with sufficient methodological information; (ii) studies addressing outdoor or ambient SO_2 exposure, emission sources, concentration measurements, dispersion modeling, health risk assessment, ecological effects, or control strategies; (iii) studies conducted in Indonesia; (iv) publications written in Indonesian or English; and (v) full text available for screening. Studies were excluded if they focused exclusively on unrelated indoor exposures; animal or laboratory experiments lacking environmental relevance; pollutants other than SO_2 without separable SO_2 findings; editorials; opinion papers; or publications lacking clear measurement, modeling, or risk-assessment information.

To address methodological heterogeneity among the included studies, quality appraisal was conducted using an adapted critical appraisal approach informed by the Mixed Methods Appraisal Tool (MMAT) and guidance on systematic review methodology (Hong et al., 2018; Xiao & Watson, 2019). Each study was examined for the clarity of the objective, the appropriateness of the measurement or modeling method, the transparency of the sampling location and period, the relevance of the exposure or outcome indicators, and the clarity of the policy or control implications. The appraisal was used to guide interpretation rather than to mechanically exclude studies, because the evidence base included observational measurements, dispersion modeling, spatial interpolation, and EHRA studies that were not directly comparable using a single quantitative effect-size metric.

PRISMA 2020 Selection Process

The PRISMA flow diagram is presented in Figure 1. A total of 112 records were identified through database searching and reference list checking. After removing 8 duplicate records, 104 records were screened by title and abstract. At this stage, 35 records were excluded because they were not directly related to SO_2 pollution, did not concern ambient air quality, or did not provide Indonesia-specific evidence. The remaining 69 reports were assessed in full text. Fourteen reports were excluded after full-text assessment because they lacked usable SO_2 data, focused on unrelated pollutants, did not provide sufficient methodological detail, or did not meet the geographic and thematic scope of this review. Finally, 55 studies were included in the qualitative synthesis.

The included studies consisted mainly of field-measurement studies, spatial and dispersion-modeling studies, environmental health risk assessments, and applied monitoring studies. Most studies were concentrated in Java, Sumatra, Sulawesi, Kalimantan, and several eastern Indonesian locations, with dominant settings including traditional markets, landfills, industrial areas, roadsides, petrol stations, and public facilities.

Bibliometric Analysis (VOSviewer)

Bibliometric mapping was conducted using VOSviewer to complement the thematic synthesis. Keyword co-occurrence analysis was used to identify dominant conceptual clusters, while co-authorship analysis was used to explore collaboration patterns in the broader SO_2 and air-pollution research landscape. The bibliometric output was interpreted as a mapping tool rather than a substitute for systematic evidence synthesis; therefore, it was used to contextualize the structure of the literature and identify research concentrations and gaps.

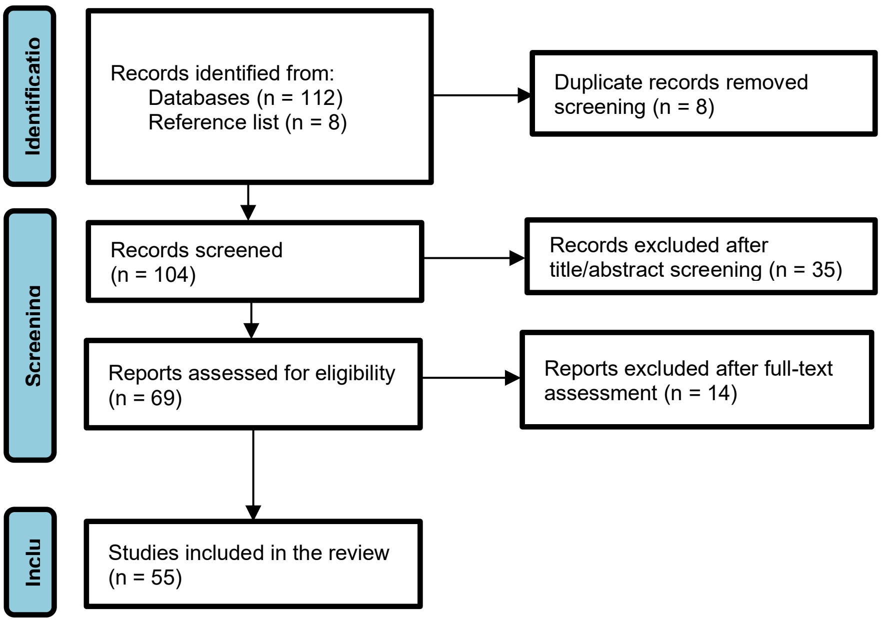

Figure 1. PRISMA Systematic Literature Review Flowchart of Sources, Impacts, and Control Strategies for Sulfur Dioxide (SO_2) in Indonesia.

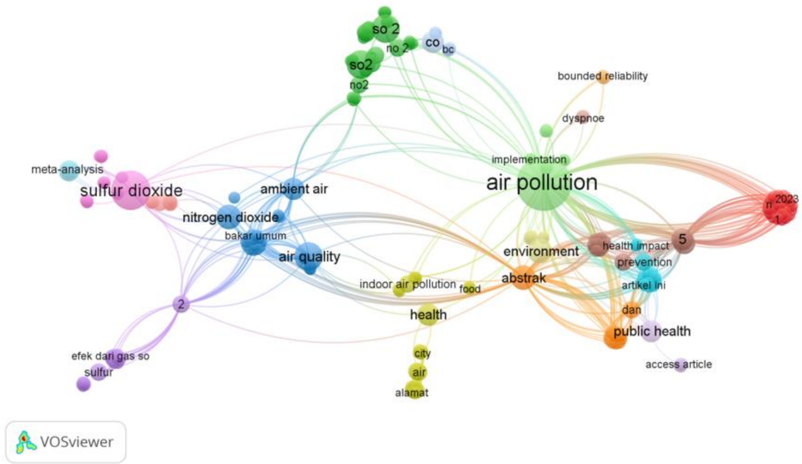

Figure 2. Keyword Co-occurrence Network Visualization Generated with VOSviewer.

The keyword co-occurrence visualization in Figure 2 shows that the largest and most central cluster centers on the term air pollution. This cluster is connected to public health, the environment, prevention, health impact, ambient air, and air quality, indicating that SO_2 research is embedded in a broader interdisciplinary field that links environmental monitoring, exposure assessment, and health-oriented policy responses. A second cluster is centered on sulfur dioxide and is linked with meta-analysis, nitrogen dioxide, ambient air, and air quality. This pattern suggests that SO_2 is commonly analyzed alongside other gaseous pollutants and that international research has increasingly shifted toward evidence synthesis and comparative health risk estimation.

Other clusters in the VOSviewer map indicate methodological and contextual subthemes. The cluster containing SO_2, NO_2, CO, and black carbon represents multi-pollutant monitoring and combustion-related emissions, whereas the cluster containing implementation, prevention, and public health reflects policy translation and the relevance of interventions. The presence of terms such as indoor air pollution, food, city, and health indicates that some studies extend beyond outdoor monitoring to microenvironmental and population health contexts. Overall, the cluster structure supports the central argument of this review: SO_2 pollution cannot be understood solely as a concentration-measurement issue but must be interpreted in terms of source attribution, exposure settings, health outcomes, environmental effects, and control feasibility.

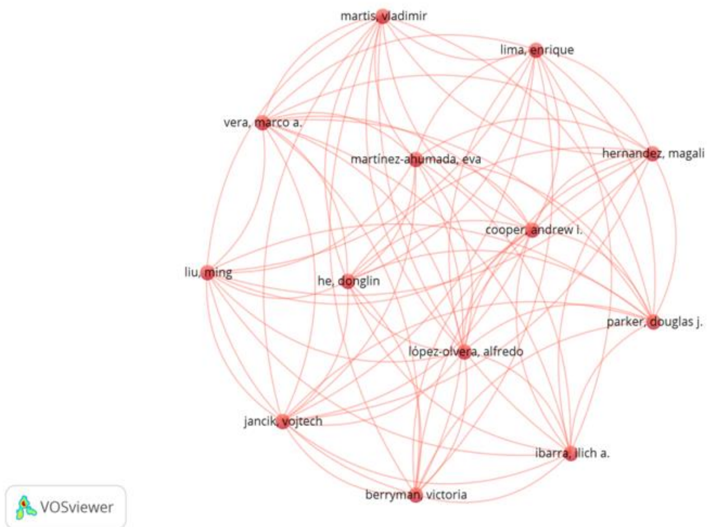

Figure 3. Co-authorship Network Visualization Generated with VOSviewer.

The co-authorship network in Figure 3 shows a dense collaboration structure among several authors in the broader SO_2 research domain. This pattern indicates that part of the international literature has developed through relatively cohesive research groups. For Indonesia, however, the reviewed empirical studies remain more geographically and institutionally dispersed, with limited cross-site standardization of methods and limited longitudinal monitoring. This contrast reinforces the need for stronger national collaboration, shared monitoring protocols, and integrated databases to support comparable SO_2 evidence across Indonesian regions.

RESULTS and DISCUSSION

The 55 included studies provide evidence that SO_2 pollution in Indonesia is shaped by interactions among emission sources, local activity patterns, meteorological conditions, monitoring methods, and population exposure. Rather than treating sources, concentrations, impacts, and control strategies as independent topics, the synthesis indicates a sequential pathway: anthropogenic emissions increase ambient concentrations in specific microenvironments; elevated concentrations create exposure risks for workers and nearby communities; and the effectiveness of control depends on whether monitoring, source management, and policy enforcement are implemented continuously. Table 1 summarizes representative studies from the 55 included publications, while Table 2 organizes the main evidence themes. The figures in Table 2 should be read as representative counts of thematic evidence rather than mutually exclusive totals, because several studies addressed more than one theme.

Overall, the strongest evidence base concerns emission-source identification and ambient-concentration measurement. Fewer studies examine health impacts, ecological consequences, or the effectiveness of control interventions. This imbalance explains why Indonesian SO_2 research has generated useful local observations but has not yet produced a fully integrated national evidence system.

Table 1. Representative characteristics of included studies in the systematic review.

No	Author(s)	Location/ setting	Method	SO_2 evidence	Key finding	Main recommendation
1	Prastian et al. (2024)	Sumberrejo traditional market	Gas detector measurement	Exceeded 150 µg/m³ during peak hours	Market activity and traffic contributed to concentration peaks	Continuous monitoring, traffic management, and market zoning
2	Andriani et al. (2025)	Air Dingin landfill, Padang	Field measurement	173 µg/m³	SO_2 exceeded the ambient air quality threshold	Control of open burning and improvement of landfill management
3	Fauziah (2020)	Cipayung landfill	Environmental health risk assessment	Worker exposure scenario	Potential non-carcinogenic risk among landfill workers	Use of PPE, emission reduction, and worker health surveillance
4	Ramdan et al. (2018)	Road-sweeper exposure, Samarinda	Spectrophotometry and EHRA	0.0043 mg/m³	The risk quotient was below 1, but repeated exposure remains relevant	Health promotion and periodic monitoring
5	Wijayanti et al. (2020)	Petrochemical industry	Gaussian dispersion modeling	Gas-turbine emission scenario	Modeling identified emission distribution patterns	Use dispersion modeling for control planning
6	Rahmawati et al. (2024)	Urban/industrial context	Observational review evidence	Repeated exposure	Air pollution exposure was linked to respiratory health concerns	Strengthen source control and health-oriented monitoring
7	Al Hajj (2024)	Hospital basement, Yogyakarta	Indoor-adjacent air-quality measurement	SO_2 included in multi-pollutant analysis	Indoor environments may be affected by outdoor and ventilation conditions	Improve ventilation and periodic indoor-air monitoring

8	Fauzi (2018)	East Java	Spatial cokriging interpolation	Interpolated SO_2 levels	Spatial methods supported hotspot identification	Use spatial mapping for regional planning
9	Umah & Gusmira (2024)	Urban Indonesia	Literature review	Industrial and fossil-fuel sources	SO_2 contributes to respiratory irritation and disease aggravation	Stricter emission policy and public-health protection
10	Sudalma & Sumarni (2022)	Laboratory/measurement context	Tetrachloromercurate/ pararosaniline method	Measurement-method validation issue	Metabisulfite interference may affect SO_2 measurement	Strengthen laboratory standardization
11	Aprilia et al. (2025)	Palm-oil processing industry, Jambi	AERMOD dispersion modeling	Stack-emission dispersion	Modeling the estimated spatial distribution of SO_2 and NO_2	Apply source-based modeling for industrial control
12	Yusianti et al. (2024)	Kendari urban area	Air pollution index analysis	SO_2, CO, NO_2, PM_{10} indicators	Multi-pollutant evidence supports urban air-quality assessment	Integrate pollutant monitoring into city-level control

Emission Sources and Ambient Concentrations

The reviewed studies consistently indicate that SO_2 emissions in Indonesia are mainly associated with anthropogenic activities. Traditional market activities, road traffic, open burning in landfill areas, fossil-fuel use, industrial boilers, and petrochemical operations are repeatedly identified as major sources (Prastian et al., 2024; Andriani et al., 2025; Aprilia et al., 2025; Wijayanti et al., 2020). In several high-activity locations, reported SO_2 concentrations exceeded or approached the national ambient air quality threshold of 150 μg/m³ for short-term exposure under Government Regulation No. 22 of 2021. For example, Prastian et al. (2024) reported elevated concentrations during peak market activity, while Andriani et al. (2025) reported a concentration of 173 μg/m³ at the Air Dingin Landfill in Padang. These findings suggest that microenvironmental activity intensity is a major determinant of concentration peaks.

However, concentrations varied markedly across locations and methods. Some roadside and occupational settings reported lower measured concentrations, such as Ramdan et al. (2018) among street sweepers in Samarinda, whereas industrial and landfill settings tended to show more persistent source-related risks. The observed variation reflects differences in emission intensity, distance from sources, fuel type, traffic density, waste-burning behavior, topography, wind direction, humidity, and sampling time. Therefore, isolated measurements should not be interpreted as representing wider regional exposure without spatial and temporal replication.

Health and Ecological Impacts

The local health evidence indicates that SO_2 exposure is most relevant for populations with repeated exposure in specific work or residential settings. EHRA-based studies reported non-carcinogenic risk concerns among landfill workers, street sweepers, and petrol-station or traffic-adjacent populations (Fauziah, 2020; Ramdan et al., 2018; Rejeki Takuloe et al., 2023). Other studies link SO_2 and related air pollution exposure to respiratory complaints and chronic respiratory vulnerability, including COPD-related risks in industrial or urban settings (Santoso & Razif, 2022; Rahmawati et al., 2024). These findings are consistent with international evidence showing positive associations between short-term ambient SO_2 exposure and mortality outcomes (Orellano et al., 2021).

Ecological impacts are less frequently examined in the Indonesian evidence base. SO_2 can form sulfuric acid and sulfate compounds in the atmosphere, contributing to acid deposition, soil and water acidification, vegetation stress, and infrastructure corrosion. While these effects are well recognized in environmental science, Indonesian studies included in this review rarely directly quantify ecological endpoints. The limited ecological evidence represents an important research gap because SO_2 control strategies should consider both human-health protection and ecosystem protection.

Control Strategies, Modeling Approaches, and Research Gaps

Control recommendations in the reviewed studies generally fall into four categories: continuous monitoring, source-specific emission reduction, spatial planning, and worker or community protection. Continuous monitoring is frequently recommended for markets, landfills, industrial areas, and roadside environments because short-term measurements may fail to capture peak exposure conditions. Source-specific recommendations include traffic management, activity zoning, reduction of open burning, control of industrial emissions, improved landfill management, and improved ventilation in indoor-adjacent environments (Prastian et al., 2024; Andriani et al., 2025; Al Hajj, 2024).

Modeling studies provide an important bridge between measurement and policy. Gaussian dispersion modeling, AERMOD, WRF-Chem, and spatial interpolation can help identify hotspots, predict pollutant spread, and support land-use decisions (Wijayanti et al., 2020; Fauzi, 2018; Aprilia et al., 2025; Sari et al., 2025). Nevertheless, the evidence base still lacks rigorous evaluation of whether recommended interventions reduce SO_2 concentrations over time. International evidence from China shows that regulatory inspections can reduce SO_2 levels at targeted coal-fired power plants, but reductions may weaken once inspection pressure ends (Karplus & Wu, 2023). This finding is relevant for Indonesia because it suggests that emission control requires sustained enforcement rather than temporary compliance checks.

Four key research gaps emerge from the synthesis. First, most studies are cross-sectional or short-term and therefore cannot characterize seasonal or long-term SO_2 exposure. Second, geographical coverage remains uneven, with stronger evidence from urban and industrial areas than from many smaller cities and eastern Indonesian regions. Third, source attribution, concentration measurement, health risk estimation, and policy evaluation are rarely integrated into a single study design. Fourth, ecological impacts and intervention effectiveness are substantially under-researched. Addressing these gaps requires standardized monitoring protocols, multi-site longitudinal studies, integration of environmental and health datasets, and evaluation of real-world emission-control programs.

Table 2. Integrated synthesis of key findings by theme.

Theme	Representative evidence-based	Integrated interpretation	Policy and research implication
SO_2 emission sources	Markets, traffic corridors, landfills, industrial boilers, petrochemical facilities, and public facilities	Emission patterns are highly local and shaped by activity intensity, fuel use, open burning, and industrial processes.	Prioritize source-specific control rather than uniform national assumptions.
Ambient concentration and standards	Several studies reported concentrations approaching or exceeding 150 μg/m³ in high-activity settings.	Short-term concentration peaks are more visible in microenvironments with dense activity and weak emission control.	Develop continuous and seasonal monitoring in hotspots.
Health and ecological impacts	EHRA studies, respiratory-health studies, and international mortality meta-analysis	Health evidence is stronger than ecological evidence; high-exposure workers and nearby communities are the most visible risk groups.	Integrate SO_2 monitoring with health surveillance and add ecosystem endpoints.
Control strategy and modeling	Gaussian modeling, AERMOD, WRF-Chem, cokriging, ventilation improvement, traffic, and landfill management	Modeling can identify hotspots, but the effectiveness of interventions is rarely tested longitudinally.	Evaluate emission controls before, during, and after implementation.
Research gaps	Uneven geography, short monitoring	The evidence base is useful but not yet	Build standardized multi-site studies and

	periods, fragmented themes, and limited policy evaluation	sufficient for a national source-exposure-impact-control framework.	shared national databases.

CONCLUSION AND RECOMENDATIONS

This systematic literature review shows that SO_2 remains a policy-relevant ambient air pollutant in Indonesia. The reviewed evidence indicates that elevated concentrations are most frequently associated with traditional markets, landfills, industrial operations, transport corridors, and public facilities where combustion-related activities and open burning occur. Although the magnitude of SO_2 concentrations varies across locations and methods, the findings consistently indicate that local activity patterns and source proximity strongly influence exposure conditions.

The health evidence points to respiratory irritation and non-carcinogenic risks among high-exposure occupational and community groups, while ecological consequences remain insufficiently studied. Control recommendations are dominated by continuous monitoring, traffic and activity management, landfill modernization, industrial emission control, ventilation improvement, and the use of dispersion or spatial models to identify hotspots. However, the effectiveness of these control strategies has rarely been evaluated longitudinally.

The main contribution of this review is the integration of evidence on sources, concentrations, impacts, modeling, and control into a single synthesis for SO_2 pollution in Indonesia. Future studies should prioritize multi-site longitudinal monitoring, stronger source attribution, integrated environmental-health analysis, ecological impact assessment, and evaluation of policy implementation. These improvements are necessary to build a more reliable evidence base for sustainable SO_2 control and broader air-quality management in Indonesia.

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