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Review Article

Bibliometric and Visualization Analysis of Biomass Burning Research in Thailand (1997–2024)

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Abstract

Biomass burning is a major driver of air pollution and climate-related impacts in Thailand, but a national-level synthesis of research efforts is lacking. This study conducts a comprehensive bibliometric and qualitative review of 256 peer-reviewed publications from 1997–2024, using Scopus-indexed data to explore research trends, thematic patterns, and existing gaps. The analysis reveals a strong emphasis on atmospheric chemistry, air quality modeling, and remote sensing, which collectively account for more than 60% of the research landscape. Studies frequently focus on pollutants such as $PM_{2.5}$, PAHs, carbon monoxide, and heavy metals, with biomass burning identified as a dominant source, especially during the dry season in northern Thailand. Remote sensing platforms (e.g., MODIS, MOPITT) and chemical transport models (e.g., WRF-Chem) are commonly used to analyze emission patterns and pollutant dispersion, although empirical ground-based validation remains limited. Thematic clustering identified six qualitative research themes: air pollution and public health; atmospheric and environmental monitoring; emission inventories and climate; environmental policy and management; pollution source identification; and temporal and geographical variability. While monitoring and modeling approaches are well developed, significant research gaps exist in long-term health impacts, policy evaluation, and socio-environmental dimensions. Underrepresented areas include indoor air quality, agroecological transition, and the southern and border regions of Thailand. This review offers a foundational roadmap to guide future research and policy, highlighting the need for interdisciplinary integration, empirical data collection, and regional coordination to address the multifaceted impacts of biomass burning on Thailand's environment and public health.

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Introduction

Biomass burning in Thailand—particularly in rural, agricultural, and forested areas—has long posed serious environmental and public health challenges due to its substantial contribution to air pollution and land degradation [1]. Seasonal activities such as crop residue burning intensify this issue during the dry season, releasing large quantities of smoke and particulate matter (PM) into the atmosphere [2]. Over the years, research has expanded in response to mounting concerns over the health impacts and environmental costs of such practices [1]. Emissions from biomass combustion—originating from agricultural fields, grasslands, and forest fires—have been identified as major contributors to PM pollution in provinces such as Mae Hong Son, Chiang Mai, and Chiang Rai [3]. These emissions often exceed

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national regulatory standards for air quality, posing acute and chronic health risks to local populations [4]. Moreover, the impacts extend beyond national boundaries: transboundary haze episodes, particularly across Southeast Asia, have become persistent and politically sensitive environmental problems, complicating regional air quality management and policy enforcement [5].

Despite growing awareness and research interest, policy responses remain fragmented and often limited in effectiveness, partly owing to the lack of consolidated scientific evidence linking biomass burning to both localized and transboundary outcomes. The absence of a systematic synthesis of the literature has hindered the translation of research into actionable policy recommendations. Therefore, there is an urgent need to bridge this science–policy gap through a comprehensive, evidence-based review that can inform both national and regional strategies.

This review addresses this need by employing bibliometric and visualization techniques to assess the evolution of biomass burning research in Thailand critically. Using the Bibliometrix and VOSviewer applications, we systematically analyzed 256 publications to uncover research trends, thematic developments, and collaborative networks over the past two decades. The combination of quantitative bibliometric analysis and qualitative content synthesis offers a robust methodlogy to map the knowledge landscape and identify priority areas for future research and policy intervention.

The insights derived from this study are expected to support more coherent and coordinated responses to biomass burning—particularly with respect to transboundary pollution—by highlighting knowledge gaps, research hotspots, and underexplored themes relevant to public health, climate change, and governance. Ultimately, this review contributes to building an interdisciplinary framework that can support evidence-based policymaking and more sustainable fire and land management practices across Thailand and the wider Southeast Asian region.

Methodology

1) Methodological framework

This study applies a structured bibliometric review methodology that combines descriptive statistics with science mapping techniques to provide transparent, reproducible, and data-driven insights into the biomass burning research landscape in Thailand. The Scopus database was selected for its broad coverage of peer-reviewed academic publications [6], robust citation indexing, and compatibility with bibliometric tools such as Bibliometrix and VOSviewer. These features ensure high standards of quality assurance and control in the selection of relevant literature.

2) Data source and search strategy

The literature collection process involved two main steps. The first step was a search conducted on 3 October 2024, which targeted the fields "Article title, abstract, keywords" via the query "biomass burning" AND "Thailand". These keywords were intentionally selected to capture the core body of research directly addressing biomass combustion activities within the national context. Broader or interdisciplinary terms such as “transboundary pollution” and “agricultural practices”, while relevant to the root causes of the issue, were not included in the initial query to maintain thematic precision. This narrow scope does represent a limitation, potentially excluding studies that address biomass burning-related phenomena without explicitly using the targeted terms. In addition, document types such as book chapters, short surveys, conference reviews, and errata were excluded in favor of peer-reviewed articles, conference papers, and reviews, which are considered more standardized and traceable within citation databases (Figure 1). A preliminary scan of excluded document types suggested that many were gray literature or lacked the detailed bibliometric metadata required for systematic analysis.

The final search string used was TITLE-ABS-KEY ("biomass burning" AND "Thailand") AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "cp") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(LANGUAGE, "English")), resulting in a total of 256 relevant documents (Supplementary material (SM) 1).

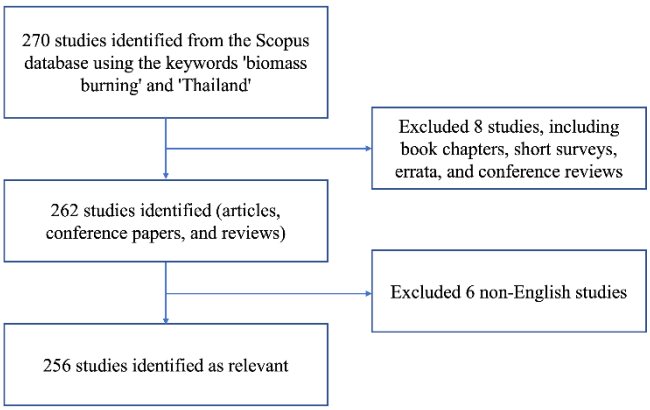

Figure 1 Flow diagram of the identification of biomass burning studies.

3) Data export and inclusion criteria

In the second step, the metadata for these 256 records were exported in CSV format, which included citation details (author names, document titles, publication year, EID, source title, volume, issue, page numbers, citation count, document type, publication stage, DOI, and open access status), bibliographic information (institutional affiliations, serial identifiers, publishers, editors, languages, correspondence addresses), and abstracts and keywords (both author and indexed).

4) Analytical tools and indicators

The dataset was analyzed via Bibliometrix, an R-based package for scientometric and bibliometric analysis developed by Aria and Cuccurullo [7], and VOSviewer (v1.6.20), developed by Van Eck and Waltman at Leiden University [8]. Microsoft Excel 2023 was used to support additional data organization and verification. A bibliometrix was used to perform descriptive statistical analysis, including measures such as annual scientific production, author productivity, source impact (via total citations), and collaboration metrics. VOSviewer was used to visualize coauthorship, cocitation, and keyword cooccurrence networks. Settings within VOSviewer were standardized to ensure replicability: coauthorship analysis was based on authors, organizations, and countries; cooccurrence analysis focused on all keywords with a full counting method; and citation analysis used source journals as the unit of analysis.

5) Statistical metrics and visualization settings

The key metrics included the frequency of publication per year, author-level outputs and average citations, journal impact scores (such as SJR and impact factor), and coword clustering. A minimum threshold of five keyword occurrences or ten citations was applied to reduce visual noise and ensure analytical focus. In VOSviewer-generated maps, the node size reflects topic prominence, whereas the spatial proximity and line thickness between nodes indicate the strength of co-occurrence and topic relationships [9-10]. Node color denotes thematic clusters, and in time-overlay visualizations, topics closer to the blue spectrum represent earlier publications, whereas yellow nodes represent more recent and emerging research themes [11-12].

6) Theme identification and quality assurance

To further refine the thematic structure of the field, research titles and abstracts were analyzed via the AI tool ChatGPT (OpenAI) over multiple iterations. This natural language processing approach was employed to identify dominant research themes related to the impacts of biomass burning in Thailand. The identified themes were then critically reviewed and validated by the authors to ensure consistency with disciplinary knowledge and the results of bibliometric clustering. Abstracts and article contents were manually extracted into a tabulated file (SM 2), and several key publications were selected for detailed summarization within each research theme.

7) Limitations and considerations

This integrative and multimethod approach ensured a comprehensive review of the biomass burning literature in Thailand, producing statistically robust insights while maintaining transparency and analytical rigour. Although the exclusion of certain document types may limit the inclusion of gray or region-specific literature, the study's focus on peer-reviewed and citation-indexed works ensures alignment with internationally recognized research standards.

Results and discussion

1) The changing trend of research on biomass burning in Thailand

The first article found in the Scopus database containing the terms "Biomass burning" and "Thailand" in the abstract was published in 1997 by Arndt et al. [13]. This pioneering study highlighted that biomass burning was a significant contributor to sulphur dioxide (SO_2) emissions in Asia, accounting for approximately 16.7% of total emissions in Southeast Asia and the Indian subcontinent from 1987–1988. Since then, the number of research publications focused on biomass burning in Thailand has increased markedly, with an exponential growth trend ($R^2 = 0.811$) observed between 1997 and 2024, as illustrated in Figure 2. This sharp rise is closely linked to growing awareness of the environmental and public health impacts of biomass burning, including its contribution to transboundary haze pollution, greenhouse gas emissions, and respiratory ailments.

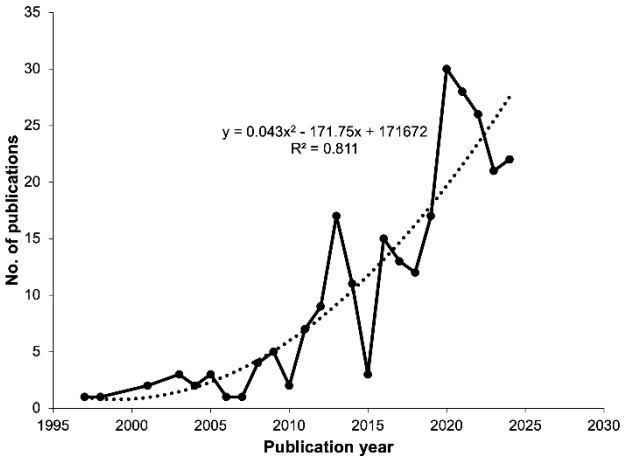

Figure 2 Literature growth trend of biomass burning research in Thailand.

When compared regionally, Thailand's research trajectory aligns with broader trends observed across Asia. Streets et al. [14] estimated that in a typical year, Asia burns approximately 730 Tg of biomass, with Southeast Asia—particularly Thailand, Indonesia, and Myanmar—identified as key contributors due to extensive forest and agricultural burning. China (25%) and India (18%) contributed the largest shares, but Thailand's regional relevance is evident given the concentration of biomass burning in mainland Southeast Asia. These estimates were further refined via AVHRR satellite fire counts and advanced spatial modeling techniques, revealing a strong correlation ($R^2 = 0.71$–0.78) between the observed fire activity and national inventories.

Moreover, Granier et al. [15] reviewed global emission inventories from 1980--2010 and identified considerable discrepancies in regional biomass burning estimates. While data from North America and Europe were more consistent, large uncertainties remained in Southeast Asia, especially in countries such as Thailand and Myanmar. The authors reported that differences in biomass burning inventories ranged from 50–80%, driven by variations in estimated burned areas and biomass loads. This lack of consensus further highlights the importance of sustained, localized research efforts in regions such as Thailand to improve data accuracy and emission modeling.

The increasing number of Thai publications also mirrors global patterns in environmental science, where spikes in research often follow heightened public and governmental concerns. Recent increases may be attributed to advances in satellite remote sensing, emission modeling, and health risk assessment, as well as increasing international collaboration and financial support for mitigating haze and air pollution.

Relevant studies in other regions have demonstrated that intensified research activities often align with periods of public alarm and policy reform, which in turn stimulate academic interest and funding [16-17]. This pattern is apparent in Thailand, where recurring seasonal haze events have pushed biomass burning into the policy spotlight, catalyzing academic inquiry and data-driven environmental governance. Consequently, the Thai trajectory reflects a broader shift wherein localized environmental crises are increasingly situated within global research frameworks and transboundary policy dialogs [18].

2) Disciplinary trends and core publication sources in biomass burning research

Figures 3 and 4 provide a comprehensive overview of the research landscape on biomass burning in Thailand on the basis of 256 Scopus-indexed publications from 1997--2024. To facilitate clearer interpretation and avoid double counting—since individual articles may be indexed under multiple Scopus subject areas—the publications were grouped into six broader thematic categories: (1) Environmental and Earth Sciences, (2) Agricultural and Life Sciences, (3) Medical and Health Sciences, (4) Energy and Engineering, (5) Social and Policy Sciences, and (6) Others.

Environmental and Earth sciences dominate the field, accounting for more than 70% of the total research output (Figure 3). This reflects a sustained scholarly focus on air pollution, ecosystem degradation, and climate dynamics associated with biomass burning. Moreover, Agricultural and Life Sciences and Medical and Health Sciences have emerged as growing areas of interest, particularly since the mid-2010s. The notable rise in health-related research after 2018 suggests increasing concern over public health impacts such as respiratory illnesses caused by haze and particulate exposure. In contrast, fields such as energy and engineering and social and policy sciences remain relatively underrepresented, despite their critical relevance to developing technological solutions, renewable alternatives, and evidence-based policymaking.

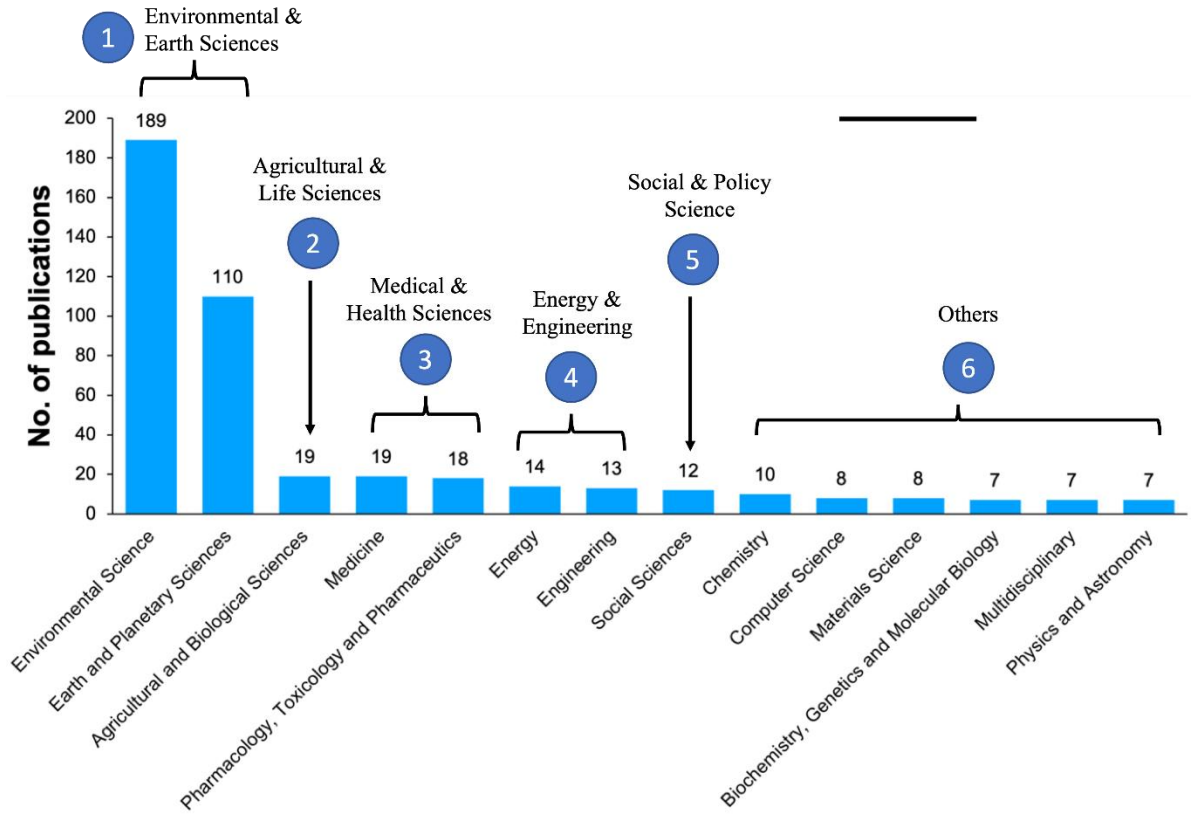

Figure 3 Six broad disciplinary categories of biomass burning studies in Thailand.

3) Top contributors to biomass burning research in Thailand: Institutions and countries (1997–2024)

Figure 4 presents the top ten institutions contributing to biomass burning research in Thailand between 1997 and 2024, with Chiang Mai University emerging as the most prolific, followed by National Central University (Taiwan), Prince of Songkla University, and Kanazawa University (Japan). The notable presence of institutions from Taiwan, Japan, and China underscores the strong international interest in the environmental and public health implications of biomass burning in Thailand.

However, these institutional contributions should be considered alongside the data in Table 1, which outlines country-level contributions. While Thailand leads with 664 publications, several neighboring and regionally impacted countries—including China (349 publications), Japan (172), and Malaysia and Singapore (14 each)—also make substantial contributions. Despite being directly affected by regional haze episodes, countries such as Malaysia, Singapore, and Vietnam are not prominently represented among the top institutions in Figure 4, although their involvement is evident at the national level.

This discrepancy indicates that although Thai institutions dominate in terms of publication output, research on regional haze and its transboundary impacts is conducted collaboratively across borders, often through partnerships with institutions located outside Southeast Asia. The significant contributions from countries such as China, Japan, and Taiwan highlight the broader regional recognition that biomass burning constitutes a shared environmental challenge, necessitating coordinated international research efforts.

The combined insights from Figure 4 and Table 1 also reveal a notable gap: countries severely affected by biomass burning and transboundary haze—such as Laos, Cambodia, and Myanmar—are either absent or only marginally represented. This underrepresentation may reflect the limited research capacity or institutional infrastructure in these nations. Given their geographical proximity and shared exposure to biomass burning emissions, strengthening collaborative frameworks with these countries is vital. Doing so would foster a more comprehensive and inclusive understanding of the regional haze problem and support the development of integrated, evidence-based solutions across Southeast Asia.

4) Citation metrics and research visibility

To better understand the influence and visibility of biomass burning research in Thailand, this study incurporates citation-based indicators, including total citations and average citations per article. These metrics offer insight into the academic reach and impact of research outputs beyond mere publication counts. While total citations reflect the cumulative influence of a body of work, average citations serve as a normalized measure that accounts for variation in publication volume across institutions and countries.

These indicators are widely recognized in bibliometric analyses for evaluating research performance and are particularly useful in identifying high-impact contributors. However, they represent only part of the broader picture. For a more nuanced assessment, additional metrics such as the range of citations (minimum to maximum), the h-index, and the i10-index could be incorporated. These would offer greater depth in evaluating the consistency, longevity, and influence of research across time and sources.

Furthermore, this analysis has not yet distinguished between self-citations and external citations. While self-citations can reflect legitimate continuity in a researcher's work, an overreliance on them may artificially increase perceived impact. Future iterations of this study should consider separating these values to provide a more accurate understanding of the genuine scholarly influence.

The role of open access (OA) publishing also deserves attention. OA publications are often associated with higher visibility and citation counts due to their unrestricted accessibility, particularly in low- and middle-income countries. Incorporating OA status into the analysis would further clarify how dissemination channels influence research impact in the field of biomass burning.

The above considerations contextualize the use of the citation data presented in Tables 1 and 2 and Figure 5, which together reflect not only the research output but also its relative academic influence. While these current indicators serve as useful benchmarks, a more comprehensive bibliometric approach that includes citation ranges, h-index values, self-citation rates, and OA accessibility would further enhance the interpretative value of this analysis.

Table 1 Frequencies of publications, total citations, and average article citations by country

Country	Frequency	Total citations	Average article citations
Thailand	664	2,802	24.60
China	349	1,002	21.80
Japan	172	970	31.30
United States	131	803	47.20
United Kingdom	34	141	35.20
India	30	113	22.60
Malaysia	14	27	27.00
Singapore	14	131	26.20
Switzerland	14	17	17.00
South Korea	10	2	2.00

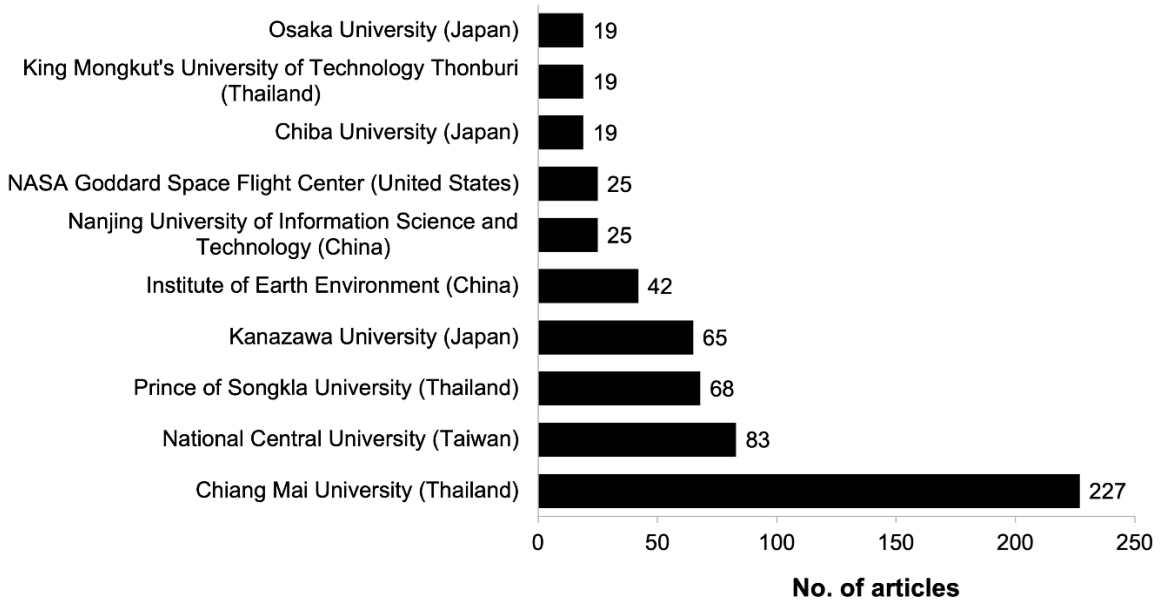

Figure 4 Top ten universities/institutions publishing articles on biomass burning in Thailand.

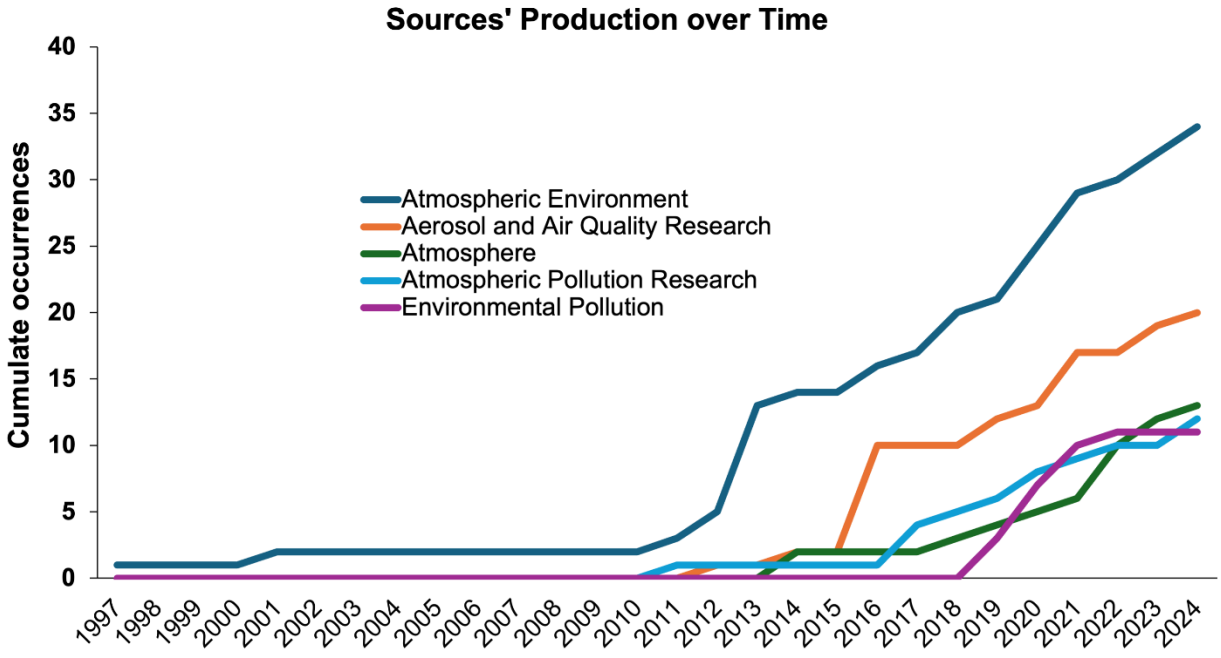

Figure 5 Trends in the number of articles published in the top five journals related to biomass burning studies in Thailand.

Table 2 Top 10 journals that published articles on biomass burning in Thailand

Journal	Country	Publication count	Citation	Journal Scimago Quartile (Q1-Q4) 2023
Atmospheric Environment	United Kingdom	34	1,640	Q1
Aerosol And Air Quality Research	Taiwan	20	492	Q2
Atmosphere	Switzerland	13	270	Q2
Atmospheric Pollution Research	Netherlands	12	392	Q1
Environmental Pollution	United Kingdom	11	479	Q1
Atmospheric Chemistry and Physics	Germany	8	347	Q1
Science of the Total Environment	Netherlands	7	417	Q1
Atmospheric Research	Netherlands	6	195	Q1
Chemosphere	United Kingdom	6	192	Q1
Air Quality Atmosphere and Health	Netherlands	5	72	Q2
Journal of Geophysical Research Atmospheres	United States	5	227	Q1
Journal of Environmental Sciences	China	4	150	Q1

5) Leading authors and institutions in biomass research in Thailand

In this analysis, authorship roles were not limited to aggregating publication counts but also differentiated by position, particularly the first author and corresponding author. The first author typically reflects the primary contributor and research lead, whereas the corresponding authorship denotes the individual responsible for communication and often indicates the research coordinator or supervisor. Tables 3 and 4 present the top contributing authors and institutions, with further interpretation of the research leadership and collaboration dynamics undertaken through examination of these authorship positions. Future iterations of this study may benefit from more detailed author disambiguation, including coauthor contribution strength and collaborative network mapping.

Tables 3 and 4 present the leading contributors to biomass burning research in Thailand from 1997–2024, examined at both the individual and institutional levels. Table 3 outlines the most prolific authors by total publication output while also detailing their roles as first and corresponding authors—key indicators of research leadership and scholarly responsibility. Notably, Chantara, S. of Chiang Mai University, which has the highest number of publications and citations alongside a significant presence as the corresponding author, emerges as a central figure, thereby demonstrating sustained academic influence in the field.

Table 4 shifts the focus to institutional contributions, revealing Chiang Mai University as the foremost research hub, with the greatest number of publications and citations across all the institutions surveyed. The presence of other prominent institutions—such as National Central University (Taiwan), the Prince of Songkla University, and Kanazawa University (Japan)—emphasizes the interplay between national academic leadership and international collaboration. Moreover, the involvement of globally recognized research entities, including the NASA Goddard Space Flight Center and the Institute of Earth Environment (China), reflects the cross-border nature of biomass burning as an environmental challenge and underscores the value of multilateral research partnerships.

Together, Tables 3 and 4 offer a comprehensive depiction of research productivity, authorship patterns, and institutional leadership, illustrating both the domestic concentration of expertise and the growing international engagement essential to addressing the complex regional dimensions of biomass burning.

Table 3 Leading productive authors in biomass burning research in Thailand (1997–2024)

Author name	Total publications	First author (No.)	Corresponding author (No.)	Total citations	Affiliation
Chantara, S.	35	4	20	1,085	Chemistry Department, Faculty of Science, Chiang Mai University, Thailand
Prapamontol, T.	21	3	7	406	Research Institute for Health Sciences, Chiang Mai University, Thailand
Lin, N-H	19	0	4	726	Department of Atmospheric Sciences, National Central University, Taiwan
Phairuang, W.	19	9	17	487	Department of Geography, Faculty of Social Sciences, Chiang Mai University, Thailand
Furuuchi, M.	18	0	3	480	College of Science and Engineering, Kanazawa University, Japan
Hata, M.	16	0	2	431	Faculty of Geoscience and Civil Engineering, Institute of Science and Engineering, Kanazawa University, Kanazawa, Japan
Pongpiachan, S.	15	8	10	452	Center for Research & Development of Disaster Prevention & Management, School of Social and Environmental Development, National Institute of Development Administration (NIDA), Thailand
Kawichai, S.	14	5	1	136	Research Institute for Health Sciences, Chiang Mai University, Chiang Mai, Thailand
Wang, S-H	14	1	4	396	Department of Atmospheric Sciences, National Central University, Taiwan
Wiriya, W.	13	2	0	464	Environmental Science Program, Faculty of Science, Chiang Mai University, Thailand
Lee, C-T	13	0	2	517	Graduate Institute of Environmental Engineering, National Central University, Taiwan
Tekasakul, P.	11	0	5	188	Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Thailand

Table 3 Leading productive authors in biomass burning research in Thailand (1997–2024) *(continued)*

Author name	Total publications	First author (No.)	Corresponding author (No.)	Total citations	Affiliation
Cao, J.	11	0	1	309	SKLLQG, Institute of Earth Environment, Chinese Academy of Sciences (IEECAS), China
Chetiyanukornkul, T.	10	0	2	259	Department of Biology, Faculty of Science, Chiang Mai University, Muang, Thailand
Suwattiga, P.	10	1	0	219	Department of Agro-Industry, Food and Environmental Technology, Faculty of Applied Sciences, King Mongkut's University of Technology North Bangkok, Thailand
Surapipith, V.	10	0	2	207	National Astronomical Research Institute of Thailand (Public Organization), Chiang Mai, Thailand
Tsay, S-C	10	0	0	431	NASA Goddard Space Flight Center, Greenbelt, MD, United States

Table 4 Leading research institutions contributing to biomass burning research in Thailand (1997–2024).

Institution name	Total publications	First author (No.)	Corresponding author (No.)	Total citations
Chiang Mai University	227	44	42	947
National Central University	83	11	11	445
Prince of Songkla University	68	17	15	453
Kanazawa University	65	8	8	234
Institute of Earth Environment	42	0	0	0
Nanjing University of Information Science and Technology	25	2	2	9
NASA Goddard Space Flight Center	25	1	1	15
Chiba University	19	3	3	70
King Mongkut's University of Technology Thonburi	19	4	4	21
Osaka University	19	3	3	43

6) Top-cited publications in biomass burning research in Thailand

Table 5 lists the top ten most-cited documents in the field of biomass burning research in Thailand, which, on the basis of Scopus data, included publications from 2011--2019 that garnered significant citations both locally and globally. Each entry includes the title of the document, the journal in which it was published, the year of publication, the number of local citations received from researchers within Thailand, the total number of global citations, and a summary of the main findings. Notably, the most cited document is "The influence of the open burning of agricultural biomass on air quality in Chiang Mai, Thailand" by Phairuang W., which was published in Environmental Pollution in 2019 and has received 35 local citations and 97 global citations. Other highly cited studies address various aspects of biomass burning research, including the identification of molecular markers for emission sources, the analysis of atmospheric pollutants linked to biomass burning, investigations into particulate matter concentrations ($PM_{2.5}$ and PM_{10}) and their health impacts, the relationship between meteorological conditions and emissions, and the radiative effects of biomass burning aerosols. Overall, this study offers a comprehensive overview of influential research in this field, underscoring the critical contributions of Thai researchers and highlighting key areas of focus in biomass burning studies.

7) Co-occurrence analysis of keywords in biomass burning research

The co-occurrence analysis of author keywords, visualized via VOSviewer, yielded a total of 2,490 terms, with 120 keywords meeting the threshold of appearing at least ten times (Figure 6). The analysis reveals the centrality of terms such as “biomass burning,” “Thailand,” “biomass,”

and “particulate matter”, each with a total link strength exceeding 1,000. These findings suggest that sustained research should focus on the environmental and health impacts of biomass burning in Thailand, particularly regarding air quality degradation and the role of particulate pollutants such as $PM_{2.5}$.

The visualized keyword network is further structured into three major thematic clusters, delineating specific subfields within biomass burning research:

Cluster 1 (red) concentrates on topics related to air quality, aerosol dynamics, and the regional impacts of biomass burning, including connections to neighboring countries such as China and Taiwan. This cluster also links biomass burning to global environmental concerns, including climate change, long-range transport of pollutants, and forest fire dynamics. The inclusion of methodlogical keywords such as “remote sensing,” “atmospheric movement,” and “spatiotemporal analysis” highlights the scientific techniques employed to assess large-scale environmental processes.

Cluster 2 (green) focuses on the health and environmental consequences of biomass burning, emphasizing air pollution, the chemical composition of particulate matter, and exposure to toxic compounds such as $PM_{2.5}$ and PAHs. This cluster also reflects the significant role of agricultural practices, especially crop residue burning, in northern Thailand (notably in Chiang Mai) as major contributors to ambient pollution and public health concerns.

Cluster 3 (blue) shifts attention to urban and regional contexts, including Bangkok, central, and southern Thailand, where research has focused on the chemical characterization of pollutants, such as carbonaceous aerosols and nanoparticles. The presence of keywords such as “drought” and “dry season” indicates the influence of seasonal climatic conditions, which often exacerbate fire events and pollution levels across Thailand.

Beyond the dominant themes, examining the least frequent keywords that met the minimum threshold (10 occurrences) provides valuable insight into emerging or underrepresented research areas. Terms such as “wind,” “air sampling,” “exhaust gas,” “forestry,” “light absorption,” “dry seasons,” “spatiotemporal analysis,” “crop residue,” and “nitrogen dioxide” suggest a growing interest in meteorological dynamics, pollutant monitoring methodologies, the radiative properties of aerosols, and the role of land use and seasonality. Although these terms appear less frequently, their presence reflects potential knowledge gaps and the development of new research frontiers, particularly those related to atmospheric processes, land management, and emission source differentiation.

Overall, this co-occurrence analysis illustrates the interdisciplinary nature and regional breadth of biomass burning research in Thailand. The thematic diversity spans atmospheric science, public health, environmental monitoring, and climate studies. Notably, the appearance of terms such as “priority journal” underscores the strategic importance of this research in the context of global environmental discourse and the need for its dissemination in high-impact academic platforms.

8) Evolution of biomass burning research focus areas in Thailand: From regional impacts to health concerns (1997–2024)

To obtain information on major trending topics over time, Bibliometrix provides a visualization based on the parameters of minimum frequency per year and the number of keywords displayed. In this study, the parameters used were a term frequency of at least three and a minimum of five terms per year. The topic trend visualization in Figure 7 shows 41 keywords that meet these criteria, which appear from 2004–2024. The analysis of biomass burning research in Thailand, as depicted in Figure 7, reveals a clear evolution of focus areas over time. In early years, particularly before 2008, research focused on the broader geographical impacts of biomass burning across Eurasia and Asia, emphasizing atmospheric and environmental issues related to biomass combustion. For example, studies highlighted the significant impact of biomass burning emissions on air quality in Southeast Asia, with regional pollution episodes peaking between January and May, particularly in March [29–30]. Satellite observations have been crucial in constraining the interannual and seasonal variability of these emissions, offering key insights into the atmospheric implications of biomass combustion across large areas [29, 31].

From 2009–2014 (Figure 7), the research focus began to diversify, expanding to include the Philippines and various atmospheric phenomena such as seasonality, optical radar, and mixing ratios. This period also attracted increased attention from meteorological factors, including boundary layer dynamics, rainfall patterns, and tropospheric processes. Research has indicated that biomass burning activities in Southeast Asia, particularly from February to April, significantly influence tropospheric ozone levels and carbon monoxide concentrations, raising concerns about the chemical composition of emissions and their broader impact on air quality and public health [30, 32]. The transport of biomass burning emissions has been shown to affect regions far beyond source areas, with studies documenting the influence of these emissions on air quality in neighboring countries, including the Philippines and southern China [33–34].

Table 5 Top 10 most-cited documents on biomass burning research in Thailand. Asterisks (*) indicate the corresponding author

Authors	Journal	Title	Year	Local citations	Global citations	Main findings
Phairuang W.*, Suwattiga P., Chetiyanukornkul T., Hongtieab S., Limpaseni W., Ikemori F., Hata M., Furuuchi M. [19]	Environmental Pollution	The influence of the open burning of agricultural biomass and forest fires in Thailand on the carbonaceous components in size-fractionated particles	2019	35	97	A study on size-segregated ambient particles down to $PM_{0.1}$ in Thailand revealed that the Char-EC/Soot-EC ratio aligned with the Emission Inventory (EI) of black carbon from biomass burning for particles smaller than 1 µm. Additionally, $PM_{0.1}$ was found to be highly sensitive to the EI of biomass burning, emphasizing its significant contribution to ultrafine particle emissions.
Thepnuan D., Chantara S.*, Lee C-T., Lin N-H., Tsai Y.I.* [20]	Science of the Total Environment	Molecular markers for biomass burning associated with the characterization of $PM_{2.5}$ and component sources during dry season haze episodes in Upper Southeast Asia	2019	31	108	Biomass combustion was identified as the major source of organic compounds in $PM_{2.5}$ aerosols, with forest and agricultural waste burning being the primary contributors. Oxalate mainly originated from biomass burning emissions, and long-range transport of $PM_{2.5}$ into Northern Thailand occurred from the west and southwest.
Chantara S.*, Sillapapiromsuk S., Wriya W. [21]	Atmospheric Environment	Atmospheric pollutants in Chiang Mai (Thailand) over a five-year period (2005–2009), their possible sources and relation to air mass movement	2012	26	56	A 5-year analysis of atmospheric pollutants in Chiang Mai, Thailand, found that ammonium from agriculture and sulfate from fuel combustion were the dominant ions. The primary air mass came from the southwest, highlighting the impact of long-range transport and local emissions. The haze during the dry season was closely linked to open burning practices.
Khamkaew C., Chantara S.*, Janta R., Pani S.K., Prapamontol T., Kawichai S., Wiriya W., Lin N-H. [22]	Aerosol and Air Quality Research	Investigation of biomass burning chemical components over Northern Southeast Asia during 7-SEAS/BASELInE 2014 campaign	2016	23	54	$PM_{2.5}$ concentrations from near- and far-biomass burning sources were strongly correlated, with major ions and elements including SO_4^{2-}, NO_3^-, Na^+, K, Al, and Mg. Biomass burning was the primary source of ambient $PM_{2.5}$ during smoke haze episodes, with dominant air masses coming from the southwest.
Kim Oanh N.T.*, Leelasakultum K. [23]	Science of the Total Environment	Analysis of meteorology and emission in haze episode prevalence over mountain-bounded region for early warning	2011	22	91	Severe haze episodes in Northern Thailand occur every March, with stagnant meteorology and high emissions, notably in March 2007. A climatological approach identified synoptic patterns linked to elevated PM_{10} levels, enabling episode warnings, and allowing a statistical model to predict PM_{10} levels 24 hours in advance.

Remark: Asterisks (*) indicate the corresponding author

Table 5 Top 10 most-cited documents on biomass burning research in Thailand *(continued)*

Authors	Journal	Title	Year	Local citations	Global citations	Main findings
Wiriya W., Prapamontol T., Chatara, S.* [24]	Atmospheric Research	PM_{10}-bound polycyclic aromatic hydrocarbons in Chiang Mai (Thailand): Seasonal variations, source identification, health risk assessment and their relationship to air-mass movement	2013	22	95	During the dry (open burning) season, PM_{10} and PAH concentrations were high, mainly due to open burning. Long-range transport had a greater impact than local emissions, with rain and humidity influencing ambient levels. Toxicity equivalence levels of polycyclic aromatic hydrocarbons (PAHs) suggested potential long-term health effects.
Pani S.K., Lin N-H.*, Chantara S.*, Wang S-H., Khamkaew C., Prapamontol T., Janjai S. [25]	Science of the Total Environment	Radiative response of biomass-burning aerosols over an urban atmosphere in northern peninsular Southeast Asia	2018	22	70	The impacts of biomass burning on aerosol properties were investigated in Chiang Mai during the 7-SEAS/ BASELInE 2014 campaign. This study quantified the radiation budget over the BB-affected urban site for the first time, revealing an atmospheric heating rate of up to 3.6 K d^{-1} and significant surface cooling. Severe haze episodes linked to BB pose serious health risks and could alter regional climate conditions.
Punsompong P.*, Chatara S. [26]	Atmospheric Pollution Research	Identification of potential sources of PM_{10} pollution from biomass burning in northern Thailand using statistical analysis of trajectories	2018	21	60	Trans-border air pollution from biomass burning affects PM_{10} concentrations in Northern Thailand during haze episodes, with sources including forest fires and agricultural residue burning. Open burning practices in Thailand and neighboring countries underscore the need for regional cooperation in air quality management.
Tsai Y.I.*, Sopajaree K., Chotruksa A., Wu H-C., Kuo S-C. [27]	Atmospheric Environment	Source indicators of biomass burning associated with inorganic salts and carboxylates in dry season ambient aerosol in Chiang Mai Basin, Thailand	2013	20	89	PM_{10} pollution in Chiang Mai, Thailand, was studied at two sites comparing episodic and nonepisodic pollution. High levoglucosan levels indicated that biomass burning was the main cause of PM_{10} episodes, while the levoglucosan-to-mannosan ratio suggested significant contributions from hardwood burning.
Phairuang W.*, Hata M., Furuuchi M. [28]	Journal of Environmental Sciences	Influence of agricultural activities, forest fires and agro-industries on air quality in Thailand	2017	20	76	Emission inventories in northern, central, and northeastern Thailand evaluated the impact of agricultural activities, especially crop residue burning and forest fires, on air quality. Monthly emissions of PM, NO_x, and SO_2 were estimated and validated against Pollution Control Department data, highlighting the sugar processing industry as the main contributor to air pollution and showing significant effects of agriculture and forest fires on ambient PM concentrations.

Remark: Asterisks (*) indicate the corresponding author

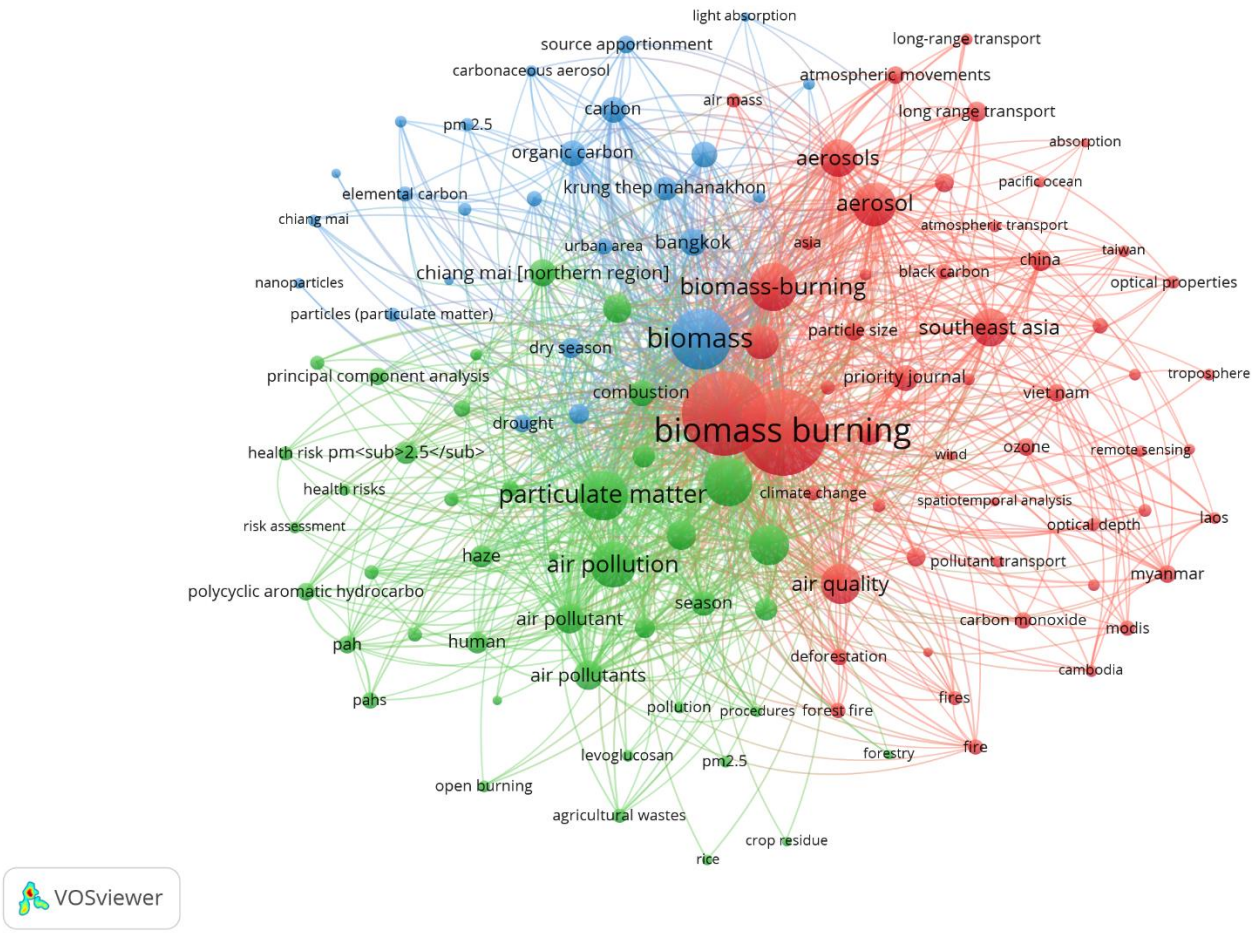

Figure 6 Keyword co-occurrence network in biomass burning research in Thailand (1997–2024), visualized via VOSviewer. Each node represents a keyword, with the node size indicating the frequency of occurrence and the line thickness denoting the co-occurrence strength. Three major thematic clusters are identified, reflecting research on air quality and aerosol dynamics (red), health and pollution impacts (green), and urban-regional pollution and seasonal influences (blue).

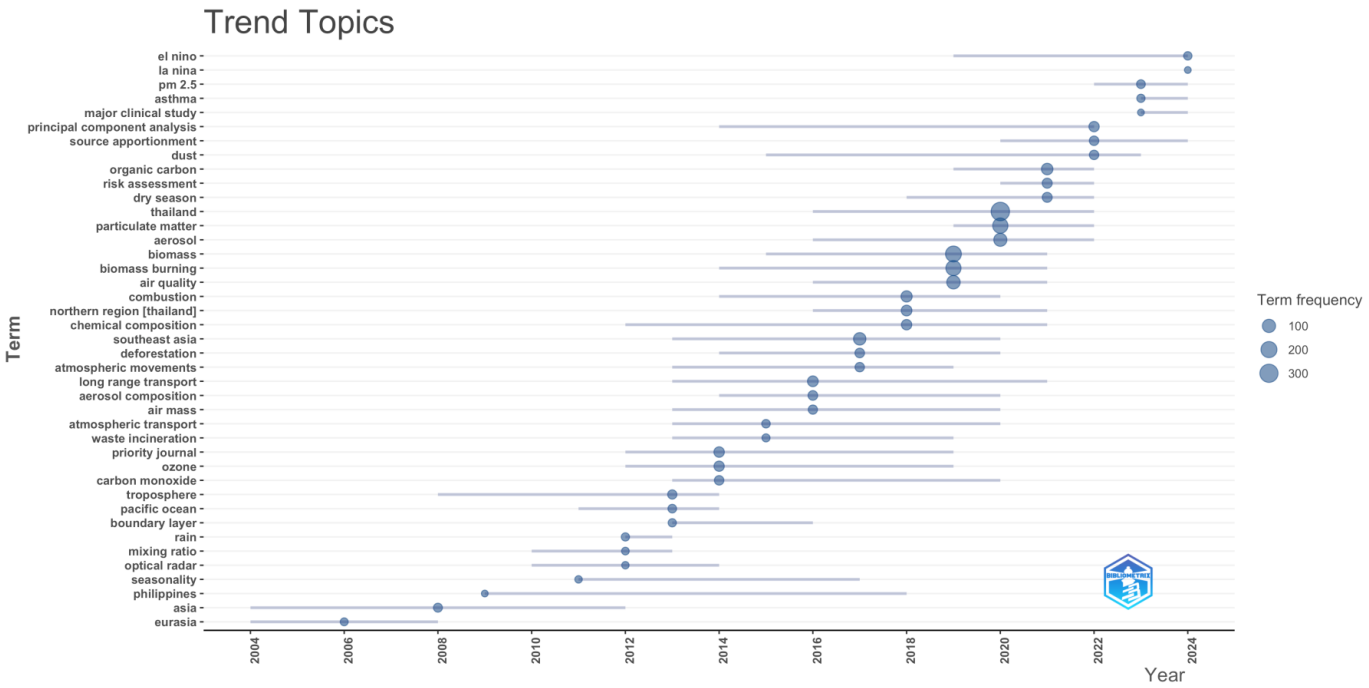

Figure 7 Trend topics in biomass burning in Thailand (2004–2024).

Research on biomass burning in Thailand increasingly focused on complex environmental and atmospheric transport phenomena between 2015 and 2019 (Figure 7). This period included the emergence of topics related to waste incineration, long-range pollutant transport, air mass movement, and deforestation, with a growing emphasis on Southeast Asia and northern Thailand. Studies have begun to examine how biomass burning affects regional air quality, with detailed analyses of aerosol and chemical compositions, indicating a more sophisticated approach to understanding the pollutants released during biomass combustion. For example, research has highlighted the significant role of biomass burning in contributing to PM_{10} pollution in northern Thailand, with statistical analyses revealing the transport pathways of pollutants and their sources [26, 35]. The investigation of the chemical composition of aerosols during this period demonstrated that biomass burning emissions were a major contributor to overall air quality degradation in the region, emphasizing the need for comprehensive monitoring and management strategies [26, 35].

In the most recent period, from 2020–2024 (Figure 7), research has become more targeted, focusing on pressing environmental and health issues. Topics such as $PM_{2.5}$, organic carbon, dust, and risk assessment suggest heightened concern about the health impacts of biomass burning. The inclusion of terms such as "asthma," "major clinical study," and "risk assessment" reflects growing attention to public health implications. Studies have indicated that $PM_{2.5}$ levels, which are significantly influenced by biomass burning, pose serious health risks, including respiratory diseases and cardiovascular issues [36]. Furthermore, the exploration of climate variability topics such as El Niño and La Niña events has emerged, revealing an increased awareness of how climatic events influence biomass burning patterns and their subsequent effects on air quality [37–38]. The interplay between climate phenomena and biomass burning has been documented, indicating that variations in precipitation and temperature associated with these events can significantly affect the frequency and intensity of biomass burning, thereby impacting regional air quality and public health [37–38].

Overall, the progression of research highlights a shift from broad regional assessments of biomass burning to a more detailed, health-focused approach, with significant attention now given to the atmospheric, chemical, and health-related impacts of biomass burning in Thailand and the surrounding region. This shift also indicates the development of more sophisticated methodologies, such as source apportionment and principal component analysis, for analyzing the sources and consequences of biomass burning emissions.

9) Evolving research dynamics in biomass burning: Contributions of pioneering and emerging scholars

Figure 8 presents a coauthorship network visualized by VOSviewer, illustrating collaboration patterns among scholars contributing to biomass burning research in Thailand. The size of each node reflects the frequency of an author's appearance in the dataset, whereas the color gradient (ranging from blue to yellow) indicates the average publication year, with blue representing earlier contributions and yellow representing more recent contributions. The thickness of the lines between nodes denotes the strength of coauthorship links.

Notable authors with prominent node sizes include Somporn Chantara, Neng-Huei Lin, and Tippawan Prapamontol, indicating their central roles in the research network. Their frequent collaborations with a broad range of coauthors reflect significant influence and sustained academic activity in the field. The visual clustering also suggests strong intragroup collaborations and recurring coauthorship patterns.

In contrast, figures such as Nguyen Thi Kim Oanh, Si-Chee Tsay, and Sheng-Hsiang Wang are positioned more peripherally but are linked to various groups, suggesting their involvement in cross-institutional or international collaborations. The color gradient shows the chronological development of the research network, with earlier contributions emerging around the mid-2010s and more recent activity becoming prominent after 2020. Scholars such as Worradorn Phairuang, Masami Furuuchi, and Thaneya Chetiyanukornkul appeared more frequently in the later period, signifying newer engagement in the field.

Overall, this figure provides insight into the temporal and collaborative structure of the scholarly community engaged in biomass burning research in Thailand, identifying both longstanding contributors and emerging researchers shaping the current academic landscape.

10) Collaboration networks of key researchers and institutions in biomass burning research in Thailand (1997–2024)

The collaboration network depicted in Figure 9A highlights key researchers in biomass burning research in Thailand from 1997--2024, illustrating the dynamics of author collaboration. Somporn Chantara stands out as a central figure in the green cluster, closely linked with Lin Neng-Huei, indicating their pivotal role in advancing discussions and projects within this field. The orange cluster features Pongpiachan S and Xing L, who demonstrate significant connectivity and contribute to specialized subfields of biomass burning research. Moreover, Masami Furuuchi anchors the purple cluster, representing a newer or niche network of researchers, suggesting a focus on specific topics such as air quality and emission monitoring. Additionally, Tippawan Prapamontol leads another key collaboration network along-

side researchers such as Kawichai S and Cao F, emphasizing contributions to health impact studies related to biomass burning. Smaller nodes, including emerging researchers such as Inerb M, indicate a developing collaboration that may gain prominence in the future. Overall, this network reveals a rich, multicluster collaborative environment that is essential for addressing the complex issues surrounding the environmental and health impacts of biomass burning in Thailand.

Figure 9B is a network diagram illustrating the collaboration among various research institutions engaged in biomass burning research in Thailand from 1997–2024. The thickness of the connecting lines signifies the strength of these collaborations. The key institutions highlighted in this period include Chiang Mai University, which serves as the central node (blue), highlighting its status as the most collaborative institution with strong links to numerous other organisations. King Mongkut's University of Technology Thonburi also demonstrates robust connections, particularly in environmental science and technology. The National Astronomical Research Institute of Thailand has established significant partnerships with Chiang Mai University and other institutions focused on atmospheric research. Interestingly, the National Central University in Taiwan (orange) appears prominently within the network, indicating substantial international collaboration despite its geographical distance. Silpakorn University is another notable player, forming strong ties with Chiang Mai University and other Thai universities, especially in environmental science. While this diagram offers valuable insights into institutional collaboration, it does not specify individual researchers. A deeper analysis of the Scopus database would be necessary to identify the most prolific and influential authors in the field of biomass burning research in Thailand.

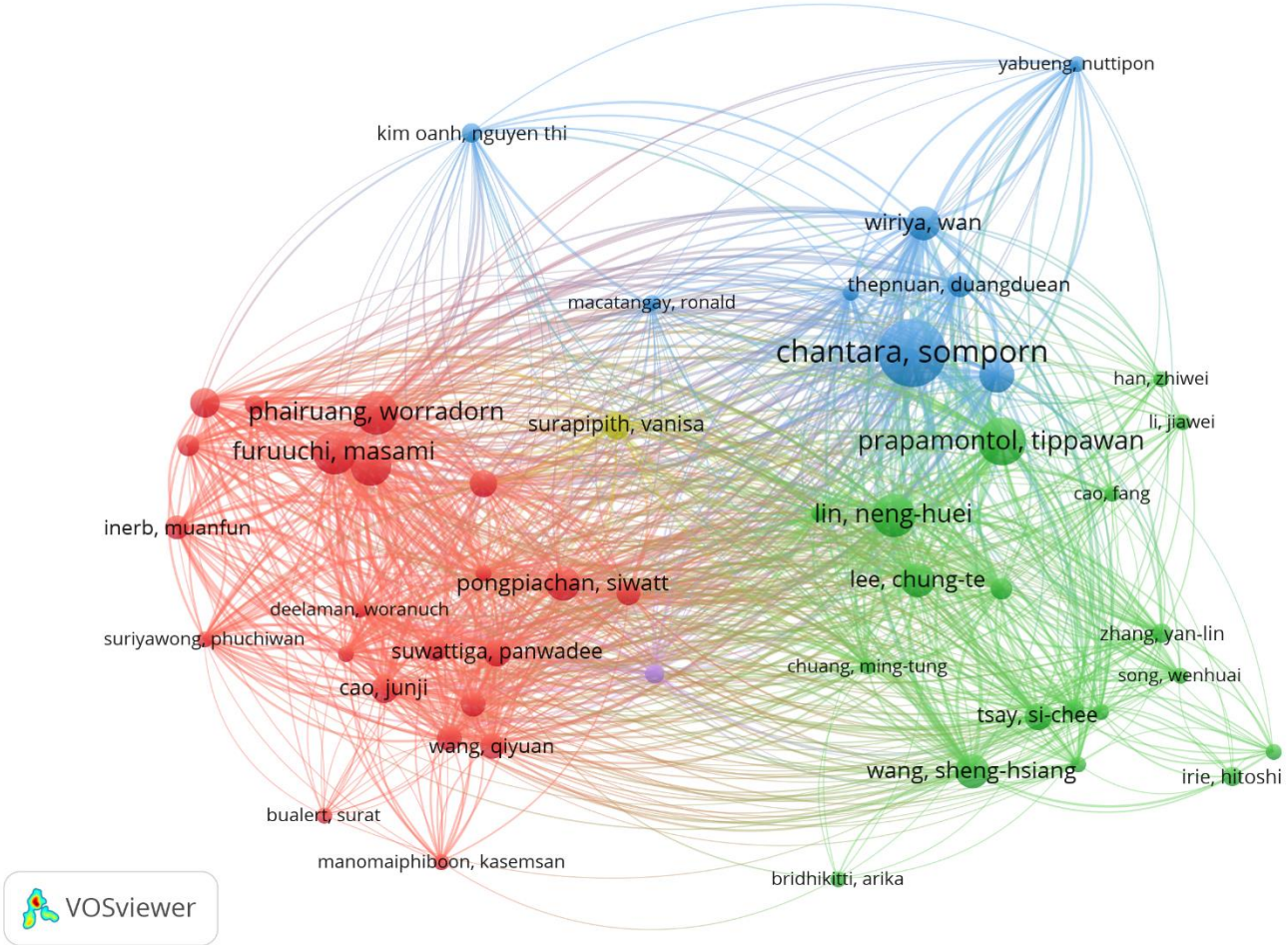

Figure 8 Times and hotspots of highly cited authors in the literature.

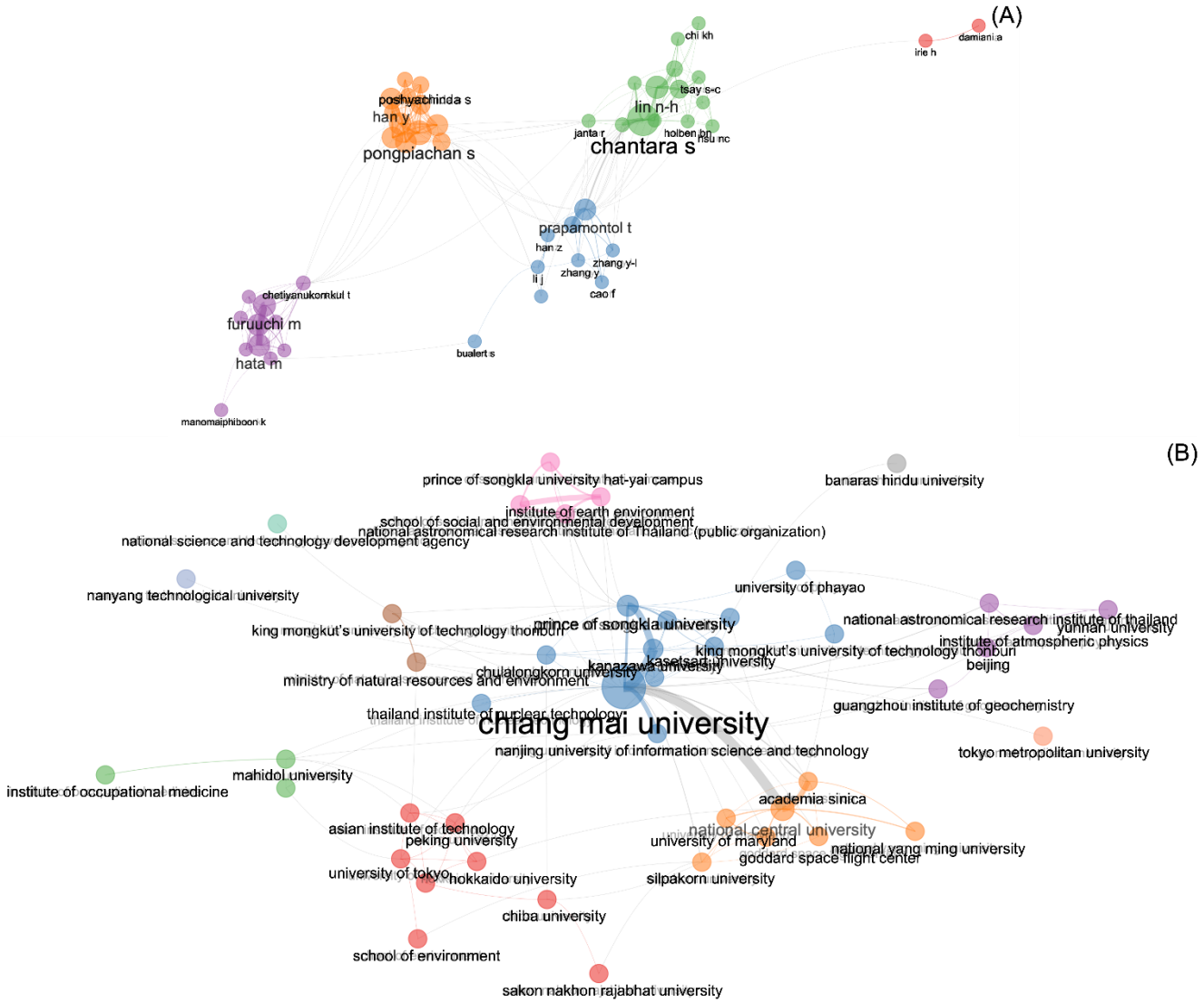

Figure 9 Collaboration networks of key researchers (A) and institutions (B) involved in biomass burning research in Thailand.

11) International collaboration in biomass burning research involving Thailand (1997–2024)

The international collaboration in biomass burning research involving Thailand from 1997–2024, as depicted in Figure 10, highlights the country's extensive engagement with global research networks. The strong ties with China and Japan, signified by the thickest lines on the map, indicate that much of Thailand's biomass burning research is conducted in partnership with these nations. This suggests a shared regional concern about the environmental and health impacts of biomass burning, which often affects air quality across Southeast Asia and East Asia. The significant collaboration with the United States underscores Thailand's involvement in global scientific efforts to address environmental challenges and develop mitigation strategies, particularly through advanced research methodologies and funding opportunities that the U.S. may provide.

Further collaboration with other Asian countries, such as South Korea, the Philippines, and India, likely points to regional cooperation focused on addressing similar environmental issues, such as air pollution and climate change impacts caused by biomass burning. This regional focus suggests an understanding of shared environmental problems that transcend national borders, especially in the context of transboundary air pollution in Asia.

Additionally, collaboration with European countries, including the United Kingdom, Sweden, and Germany, reflects Thailand's engagement with global scientific communities beyond Asia, fostering knowledge exchange and possibly leveraging technological innovations from Europe. These partnerships may involve joint research projects, participation in international conferences, or coauthored publications, promoting a global dialog on biomass burning and its impacts.

However, the map lacks details on the specific nature of these collaborations, such as whether they focus on technical innovations, policy development, or field studies in affected areas. To gain a deeper understanding of these partnerships, it would be necessary to analyze individual publications and author affiliations

in databases such as Scopus, which could reveal the research topics, methodologies, and outcomes associated with these international collaborations. This would also help identify key researchers and institutions driving this research globally, providing a more nuanced picture of Thailand's role in the global scientific community on biomass burning.

12) Key qualitative research themes

To complement the bibliometric and quantitative analysis, this section presents a thematic synthesis of research on biomass burning in Thailand, derived through qualitative content analysis of selected publications (SM 2). By closely examining the aims, contexts, and findings of the studies, six dominant thematic areas were identified: (1) Air pollution and public health, (2) Atmospheric and environmental monitoring, (3) Climate change and emission inventory, (4) Environmental policy and management, (5) Pollution source identification, and (6) Temporal and geographical variability. These themes reflect the evolving scientific and policy-relevant concerns surrounding biomass burning, ranging from direct health impacts and atmospheric processes to broader socio-environmental governance issues. The analysis highlights not only the thematic concentration of research in specific domains but also gaps in interdisciplinary integration and policy evaluation, offering guidance for future research and environmental planning.

(1) Air pollution and public health: Nineteen publications investigated the impacts of air pollution from biomass burning on public health in Thailand, with a focus on acute effects such as mortality, respiratory symptoms, cardiovascular health, birth outcomes, and urinary biomarkers. The long-term health risks associated with PM exposure include DNA damage, cancer risk, and adverse outcomes linked to $PM_{2.5}$- or $PM_{0.1}$-bound toxicants such as PAHs, polychlorinated dibenzo-p-dioxins, and heavy metals. Many studies emphasize vulnerable groups, including residents in biomass-burning areas, outdoor workers, pregnant women, children, and individuals with preexisting conditions.

However, research that explicitly evaluates the effectiveness of air quality policies remains limited. One exception is the study by Yabueng et al. [39], which assessed the effects of a zero-burning policy in northern Thailand. The findings revealed that while $PM_{2.5}$ concentrations declined, haze events persisted for longer durations, and PAH levels were paradoxically higher in Nan than in Chiang Mai. These results underscore the potential trade-offs in spatial and temporal exposure patterns arising from blanket fire suppression policies. Thus, further studies are needed to evaluate both the intended and unintended consequences of mitigation strategies for public health.

(2) Atmospheric and environmental monitoring: Forty-one publications focus on atmospheric and environmental monitoring, particularly those that target the detection and characterization of air pollution plumes during haze episodes. Commonly investigated pollutants include $PM_{2.5}$ and associated species, which are measured via a combination of ground-based monitoring, satellite remote sensing, and chemical transport modeling. Many studies have applied advanced instrumentation to examine aerosol optical properties, vertical profiles, and aging processes that influence aerosol behavior and composition.

Figure 10 International collaboration in biomass burning research involving Thailand.

Geographically, most monitoring efforts are concentrated in northern Thailand—especially Chiang Mai—while Bangkok hosts a smaller number of studies. Southern Thailand remains notably underresearched in this context. Importantly, some studies have introduced innovative air pollution monitoring technologies. For example, Kanabkaew et al. [40] employed low-cost IoT-based $PM_{2.5}$ sensors in Mae Sot, demonstrating their ability to effectively track plume movement, detect diurnal variations, and identify lag time and wind effects on pollutant concentrations. This technology offers a scalable, nearly real-time solution for air quality forecasting and management during biomass burning seasons.

Similarly, Bootdee et al. [41] validated passive nitrogen dioxide (NO_2) samplers against chemiluminescence analyzers in urban Chiang Mai. Their study revealed elevated NO_2 levels in traffic-heavy and biomass-affected areas, highlighting the utility of samplers as cost-effective spatial monitoring tools for NO_2 distribution, especially where continuous monitoring infrastructure is lacking.

These contributions underscore the critical role of monitoring technologies in improving the spatiotemporal resolution of pollution assessments and informing responsive air quality policies in Thailand.

(3) Climate change and emission inventory: Twenty-one publications address the role of biomass burning in contributing to climate change and shaping emission inventories. These studies have focused largely on carbonaceous aerosols, greenhouse gases (GHGs), and black carbon, which are key components of atmospheric radiative forcing. For example, satellite-based analysis via MOPITT data revealed strong seasonal patterns of carbon monoxide (CO) emissions, with peak levels during the dry season closely aligning with biomass burning activity, particularly in regions with low ground monitoring coverage across Thailand [42]. WRF-Chem simulations further demonstrated the significant impact of biomass burning on regional air quality, showing that it contributed an additional 29% of ozone (O_3) and 16% of CO concentrations in March compared with December, surpassing the influence of anthropogenic inventories alone [43]. These findings underscore the dominant influence of open biomass combustion relative to industrial and traffic sources. Consistent with these results, satellite observations across South Asia and Southeast Asia revealed that smoke aerosols—especially fine, UV-absorbing particles—are prevalent during haze episodes and differ seasonally across regions such as the Indo-Gangetic Plain (IGP) and Southeast Asia [44]. Together, these studies emphasize the need to integrate biomass burning dynamics into regional and national emission inventories and climate modeling frameworks.

(4) Environmental policy and management: Twenty publications have addressed environmental policy responses to biomass burning, with a strong emphasis on PM2.5 control strategies, particularly in northern Thailand. These studies utilize tools such as life cycle assessments to identify opportunities for reducing the carbon footprint of agricultural practices. Emission inventories play a critical role in informing regional air quality policies, whereas stakeholder surveys help explore feasible alternatives to open-field burning. Scenario analyses targeting the year 2030 have assessed the implications of black carbon emission reductions under various policy interventions.

The impacts of COVID-19 lockdowns have also provided novel yet valuable insights into emission dynamics. For example, Kaewrat and Janta [45] analyzed hourly air quality data across Thai cities and reported that while air quality significantly improved in metropolitan and industrial zones during lockdown periods, $PM_{2.5}$ levels in northern provinces remained high because of persistent biomass burning. Similarly, Wetchayont [46] showed that although lockdowns in Greater Bangkok led to reductions in some pollutants, biomass burning and local emissions continued to contribute to overall pollution levels, suggesting that structural interventions beyond temporary activity reductions are necessary.

In terms of renewable energy innovation, a study introduced a rice husk gas stove (RHGS) tailored for rural communities in Lampang Province. The design optimization, including airflow rates and combustion chamber dimensions, achieved a thermal efficiency of 34% under ideal conditions. The stove also demonstrated pollutant emissions within acceptable limits for rural kitchens and had short payback periods of approximately seven months and 28 days, highlighting its economic feasibility. This development points to the potential of decentralized biomass energy systems in supporting clean energy transitions and reducing reliance on open biomass burning [47].

Overall, these findings underscore the importance of integrating emission inventories, behavioral insights, and technology development into comprehensive policy frameworks aimed at sustainable air quality and climate cobenefits.

(5) Pollution source identification: Thirty-four publications investigated pollution source identification, with a focus on tracing the origins and composition of air pollutants in Thailand. A variety of techniques are employed, including receptor modeling, stable isotope analysis, backward trajectory modeling, chemical speciation, satellite monitoring, and emission inventories. Research in Chiang Mai prominently highlights biomass burning as the primary source of $PM_{2.5}$. For example, stable isotope analysis by Kawichai et al. [48] confirmed that 74% of PM2.5 originated from C3 plants and 26% from C4 plants, identifying biomass burning as the dominant source. Similarly, Chansuebsri et al. [49] used

positive matrix factorization and chemical speciation to map seasonal contributions, showing that biomass burning is the major contributor during haze periods, whereas traffic becomes more significant in nonhaze seasons. Additionally, Akbari et al. [50] quantified metal emissions from forest burning, estimating 11 kilotonnes of $PM_{2.5}$ and substantial ash and metal residues, highlighting the need for effective source control. Together, these studies reinforce the crucial role of both local and transboundary biomass burning in driving air pollution across urban and rural northern Thailand.

(6) Temporal and geographical variability: Thirty publications on temporal and geographical variability highlight seasonal pollutant concentration variations related to weather patterns, particularly during the dry season, when biomass burning peaks. Diurnal variations in pollutants are linked to human activities such as traffic and cooking, with temperature inversions trapping pollutants. Research has focused primarily on northern Thailand's burning issues, central Thailand's urban pollution dynamics, and southern Thailand's coastal air quality influences (SM 2).

13) Limitations, gaps, and future directions

Despite significant advances in biomass burning research in Thailand, several limitations persist across thematic areas that restrict a comprehensive understanding of its multifaceted impacts. The dominant focus of the literature remains in technical domains such as atmospheric chemistry, environmental monitoring, and emissions modeling. These studies offer valuable insights into pollutant dynamics and plume dispersion via tools such as remote sensing, WRF-Chem simulations, and receptor modeling. However, this focus has come at the expense of broader interdisciplinary integration, particularly in areas relating to long-term public health, behavioral factors, and socioeconomic or policy evaluations.

One key gap is the underrepresentation of longitudinal and population-level health studies linking chronic exposure to biomass smoke with diseases such as cardiovascular disorders, cancers, or neurodevelopmental conditions. While acute respiratory effects and biomarker assessments have been explored, they are generally short-term and geographically limited. Furthermore, the disproportionate focus on northern Thailand—especially Chiang Mai—leaves southern and coastal regions relatively understudied, despite documented haze events in those areas.

Another limitation lies in the lack of ground-truth validation for many emission models and inventories. While satellite-based analyses are valuable in data-scarce regions, they often lack integration with empirical air quality data or do not capture localized emissions with sufficient granularity. Additionally, policy effectiveness is seldom evaluated in detail. For example, studies such as Yabueng et al. [39] assess the effects of zero-burning policies on $PM_{2.5}$ and PAHs, but very few studies have attempted to monitor behavioral compliance, economic feasibility, or unintended trade-offs such as temporal haze displacement.

Emerging technologies—such as IoT sensors, passive sampling methods, and alternative biomass stoves—represent promising mitigation strategies. However, these are often presented as proof-of-concept without long-term evaluation of adoption rates, cost efficiency, or integration into community-scale interventions. Moreover, the role of social science in understanding public attitudes, local practices, and the political economy of biomass burning is conspicuously absent from most research, despite being essential for shaping context-appropriate policies.

Future studies should aim to bridge these gaps by fostering cross-disciplinary collaboration. Priority should be given to integrating public health surveillance with environmental data, conducting policy impact assessments, and expanding research to neglected regions. There is also scope for participatory approaches that engage local communities in data collection, awareness-building, and sustainable land-use practices. Enhanced coordination between governmental agencies, researchers, and civil society is crucial for transforming scientific insights into actionable strategies for pollution mitigation, health protection, and climate resilience.

Conclusions

This review provides a comprehensive assessment of biomass burning research in Thailand, combining bibliometric mapping with qualitative synthesis to highlight dominant themes, methodological approaches, and critical gaps. Over the past two decades, research has focused heavily on atmospheric chemistry, remote sensing, and air quality modeling, with particular emphasis on pollutants such as $PM_{2.5}$, PAHs, and carbonaceous aerosols. Most studies are geographically concentrated in northern Thailand, especially Chiang Mai, due to recurrent haze episodes, leaving other regions relatively understudied.

Despite notable advancements in monitoring and emissions modeling, the integration of public health data, socioeconomic impacts, and policy evaluations remains limited. Emerging technologies such as IoT sensors and isotopic analysis offer promising tools for enhancing source apportionment and real-time monitoring but require broader validation and scaling. Moreover, studies on the long-term health implications of biomass smoke, policy effectiveness, and community-based interventions are lacking.

Addressing these limitations requires a more interdisciplinary approach that links environmental science with epidemiology, social sciences, and governance. Future research should prioritize longitudinal health

studies, regional equity in research coverage, and the evaluation of policy interventions. Collaborative efforts between researchers, policymakers, and local communities are essential to generate actionable insights for sustainable fire management, air quality improvement, and climate resilience.

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