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Dynamic modeling in environmental planning: A global synthesis of research addressing urban air quality

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ABSTRACT
This research constitutes bibliometric analysis about the utilization of System Dynamics (SD) in mitigating air pollution. This project aims to investigate the use of system dynamics models in simulating and assessing urban transportation regulations, industrial emissions, and the incorporation of cleaner technology. The applied methodology encompasses a synthesis of current studies and the execution of bibliometric analysis to discern trends, prominent academics, and the most impactful papers in this domain. An exhaustive analysis of the current literature uncovered several significant findings. Investments in public transportation, the introduction of fuel taxes, and the advancement and deployment of sophisticated car technologies are recognized as essential solutions for mitigating air pollution. Case studies from places such Greater Cairo, Kuwait, Tehran, and Mexico City illustrate the efficacy of SD in forecasting long-term environmental consequences and facilitating adaptive policy. This research primarily contributes to the visualisation of the intellectual framework of the research domain, the identification of keyword clusters, and the elucidation of links between topics that may have previously lacked obvious mapping. This research addresses a methodological deficiency by clearly illustrating how the combination of quantitative bibliometric analysis and systematic review can enhance comprehension of the developmental dynamics within a scientific subject.

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1. INTRODUCTION

Air pollution remains a pressing environmental challenge, significantly affecting both human health and ecological stability. Defined by the accumulation of harmful substances such as particulate matter, gaseous emissions, and biological agents in the atmosphere, its primary drivers include transportation emissions, industrial outputs, and rapid urbanization. Urban regions face elevated risks due to higher pollutant concentrations stemming from dense traffic and industrial density [1]. Among the various sources, the transport sector plays a dominant role, contributing large volumes of nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter. These emissions not only degrade local air quality but also accelerate climate change through the release of greenhouse gases [2]–[4].

The health consequences of air pollution are both profound and far-reaching. Exposure has been linked to respiratory illnesses, cardiovascular diseases, and a considerable number of premature deaths—an estimated 58,000 annually in the United States alone [5]. This alarming figure reinforces the urgency for comprehensive policy interventions and the adoption of cleaner technologies. Mitigation strategies often focus on regulating emissions, promoting sustainable transportation options such as electric vehicles, and rethinking urban planning and mobility policies [2], [5]. Without these measures, the continuing impact of air pollution will jeopardize both public health and the broader goals of environmental sustainability [6], [7].

A dynamic system refers to a system whose behavior evolves over time due to the interactions among its components, often characterized by feedback mechanisms and nonlinear relationships. Its defining feature is the time-dependent nature of variable interactions, which may respond to both internal dynamics and external stimuli [8]. The framework of system dynamics enables researchers to simulate such systems, making it possible to observe and analyze their trajectories across specified time periods. This modeling approach is especially effective for examining systems where change occurs gradually or in response to compounded interactions over time.

System Dynamics (SD) have broad applications across diverse fields, particularly in urban and environmental studies where complexity and interdependence are central [9]–[12]. In urban contexts, dynamic models have been used to understand the interplay between economic growth, land expansion, and environmental consequences, enabling policymakers to design strategies that align development with sustainability goals [13], [14]. Furthermore, the use of simulation in dynamic system modeling supports scenario-based assessments of policy decisions, such as in energy planning and pollution control [15]. These models offer valuable insights into long-term impacts, enabling informed decisions by projecting the outcomes of current trends or interventions [16]. As such, dynamic systems serve as a powerful analytical tool for exploring, understanding, and managing the evolving nature of complex socio-environmental systems.

The integration of SD into air pollution research represents a significant advancement in modeling environmental complexity and formulating strategic interventions. SD offers a robust framework for examining the intricate feedback mechanisms, nonlinear behavior, and time-dependent dynamics that define air quality systems. A notable application lies in transportation policy evaluation, such as the study by Jia et al. [17], who modeled driving restrictions in Beijing and observed that while initial reductions in emissions were achieved, these gains diminished over time due to behavioral adaptation—a phenomenon they described as the "fading effect." Similarly, Zhou and Zhou [18] utilized SD to explore atmospheric environmental capacity (AEC) and atmospheric environmental carrying capacity (AECC) in China, illustrating how the methodology supports air quality management amid ongoing economic development. These studies collectively affirm the utility of SD in anticipating long-term policy outcomes and optimizing environmental governance.

Beyond transportation, SD models have been effectively applied to energy policy, urban pollution control, and industrial emissions. For instance, Huang et al. [19] developed a comprehensive System Dynamics (SD) framework to simulate energy consumption trends and their influence on PM10 emissions in China, integrating clean energy variables to assess various policy scenarios. Urban-scale modeling has also yielded impactful results, as seen in studies by Shahsavari-Pour et al. [1] in Tehran of which demonstrated the value of dynamic simulations in informing local pollution mitigation strategies. In the industrial domain, [20] employed System Dynamics (SD) to optimize boiler fuel compositions, achieving both regulatory compliance and operational efficiency in controlling SOx and NOx emissions. These diverse applications underscore the versatility of SD modeling in addressing air pollution across sectors, offering policymakers a data-driven foundation for sustainable planning and decision-making.

Dynamic systems modeling has become an indispensable tool in the analysis of air pollution due to its ability to capture the complex, interrelated factors influencing environmental quality. System Dynamics (SD) models allow for the simulation of interactions among emissions, regulatory actions, technological transitions, and human behavior over time. This facilitates the identification of causal pathways that traditional static models may fail to detect. For instance, Guo et al. [15] applied SD to examine how emission policies influence China's coal supply chain, providing insights into the strategic behavior of stakeholders under environmental regulation. Similarly, Jia et al. [17] used a systems-based approach to evaluate the interconnected impacts of vehicular emissions on health and transportation systems, enabling a more holistic understanding of pollution dynamics. Such applications underscore the model's capacity to analyze feedback loops and temporal dependencies, informing policies that are not only reactive but also adaptive to evolving conditions.

The research gap concerning SD and air pollution lies in our understanding of the long-term significance of SD in addressing evolving environmental challenges, particularly in the context of new technologies and urbanisation. Although SD has proven useful, there is currently a lack of comprehensive mapping of its application across sectors and regions, as well as insufficient synthesis of theoretical and practical insights to guide future research. Furthermore, the role of SD in evaluating and alleviating air pollution, particularly in terms of long-term policy impacts and its effectiveness in reducing pollution over time in dynamic urban environments, remains underexplored.

The purpose of this study is to map the existing distribution of System Dynamics and identify gaps in sectoral and regional applications in order to investigate the future usefulness of this field in air pollution research. The study will integrate current theoretical frameworks and empirical findings to inform future research directions, emphasizing the efficacy of SD models in assessing, alleviating, and diminishing air pollution over the long run. The objective is to offer insights into maximizing sustainable development for effective air quality management and guiding future policy decisions.

This paper investigates the changing significance of system dynamics and air pollution research, focusing on five critical topics for resolution. RQ1: Is system dynamics and air pollution an important subject for future academic investigation? RQ2: What is the current distribution of research on system dynamics and air pollution? RQ3: What theoretical and practical findings can inform future research trajectories? RQ4: How can dynamic systems address air pollution? and RQ5: Can dynamic systems serve as an effective model for reducing air pollution in the future? Based on the research questions posed, this paper aims to provide a comprehensive understanding of the role and potential of system dynamics in addressing air pollution challenges. By analyzing the distribution of research, exploring theoretical and practical findings, and evaluating the effectiveness of system dynamics models, it is hoped that strong policy recommendations and innovative implementation strategies can be formulated for future air pollution mitigation.

2. MATERIALS AND METHODS

A bibliometric systematic literature review looks at the literature in a quantitative way to find trends, patterns, and important research entities in a subject [21]. This method uses frameworks like PRISMA to do a full and repeatable analysis of the literature, which makes the topic being studied clear and easy to see [22], [23]. The criteria for inclusion are: (1) studies that were published by July 9, 2025, (2) studies that were published in English, and (3) studies that were about system dynamics and air pollution. Using VOSviewer to show bibliographic data [24], a bibliometric analysis looked at citation networks, author collaborations, and co-occurring keywords. This helped to make the research field's intellectual structure and dynamics clearer. Researchers can combine bibliometric analysis with systematic review to combine real-world data and map out the research landscape, including finding key contributors and spotting new trends [25], [26]. Combining these two methods gives a full picture of the field's progress, past developments, and future directions. This is especially useful in multidisciplinary studies for getting deep insights [27]. The first step in this study is to find keywords using a macro (top-down) approach, which means starting with broad searches and moving on to more specific studies and topics. So, after looking at the problems with previous studies and the lack of research on predicting air pollution, this study chooses "System Dynamics" AND "Air Pollution" as the main topic in the title, abstract, and keywords section. Scholars use the Scopus database for a number of research purposes, such as reviewing the literature, finding experts in a field, and keeping an eye on research trends.

The selection method for articles in this systematic literature review began with an extensive analysis of the Scopus database on July 9, 2025, including publications from 1979 to 2025. The search methodology included a planned amalgamation of specific keywords: The System AND Dynamics AND Air AND Pollution framework was applied to the titles, abstracts, and keywords of the selected papers. The preliminary search yielded a total of 3.929 items (see Table 1 & Figure 1). The final screening phase utilized the targeted terms "System Dynamics" AND "Air Pollution," resulting in the elimination of 3.728 items considered irrelevant. Subsequent to the first screening, a further filtration process was conducted to remove articles devoid of the specified keywords "System Dynamics" AND "Air Pollution," resulting in the elimination of 197 articles that failed to meet the relevancy criterion. The supplementary screening was performed in accordance with rigorous exclusion criteria. The rejected publications encompassed a variety of genres, including conference papers (39), book chapters (4), reviews (3), conference reviews (3), books (2), and editorials (1). Furthermore, publications designated as "article in press" were excluded from the study to guarantee that only completed, accessible articles were included. Articles containing incongruent keywords, such as those from Article (34), priority journals (13), and sources classified as book series (1), were likewise excluded. After an extensive screening process, 108 articles were identified as relevant. During the eligibility evaluation step, the articles were evaluated for language and accessibility, resulting in the elimination of 4 articles in Chinese and 1 item in Russian. A total of 103 papers were ultimately selected for thorough study in this assessment (see Table 1 & Figure 1).

Table 1. Inclusion and exclusion criteria in research

Criteria	Description of Inclusion Criteria	Description of Exclusion Criteria
Database	Articles were searched extensively through the Scopus database.	Articles not from the Scopus database.
Search Date	The search was conducted on July 9, 2025.	The article you are looking for is outside the specified date range.
Publication Range	Publications between 1979 and 2025.	Publications outside the 1979-2025 timeframe.
Primary Keywords	The title, abstract, and keywords of the article must contain "System Dynamics" AND "Air Pollution".	Articles that do not contain "System Dynamics" AND "Air Pollution" in the title, abstract, and keywords (a total of 3,728 initial eliminations, plus 197 eliminations for not meeting the relevance criteria for keywords).
Document Type	Focus on articles that are not included in the exclusion list.	Publications with the following document types: conference papers (39), book chapters (4), reviews (3), conference reviews (3), books (2), editorials (1). Articles in the "article in press" stage are also excluded.
Keywords Not Relevant	Articles with relevant keywords.	Publications containing irrelevant keywords, such as Articles (34), priority journals (13), and book series (1).
Language	Only articles in English.	Articles in Mandarin (4) and Russian (1) are excluded.
Accessibility	The article is available and fully accessible.	Inaccessible or incomplete article.

This study employs the PRISMA framework to guarantee a transparent and replicable approach for locating, selecting, and analysing literature, commencing with a comprehensive search in the Scopus database that produced 3,929 initial articles. Following a comprehensive screening process that involved the removal of irrelevant articles based on designated keywords and exclusion criteria pertaining to publication type and language, 103 scientific publications were ultimately chosen for detailed examination. Bibliometric analysis, facilitated by tools such as VOSviewer, allows for the detection of patterns, trends, intellectual frameworks, and significant research entities through citation networks, author collaborations, and keyword co-occurrences. This report offers a quantitative assessment of the research environment, identifies main contributors and emerging trends in "System Dynamics" and "Air Pollution," and gives significant suggestions for future research while addressing existing deficiencies. The focus on a broad approach to keyword identification and meticulous screening guarantees the relevance and quality of the analysed articles, establishing a robust basis for deriving conclusions and policy implications.

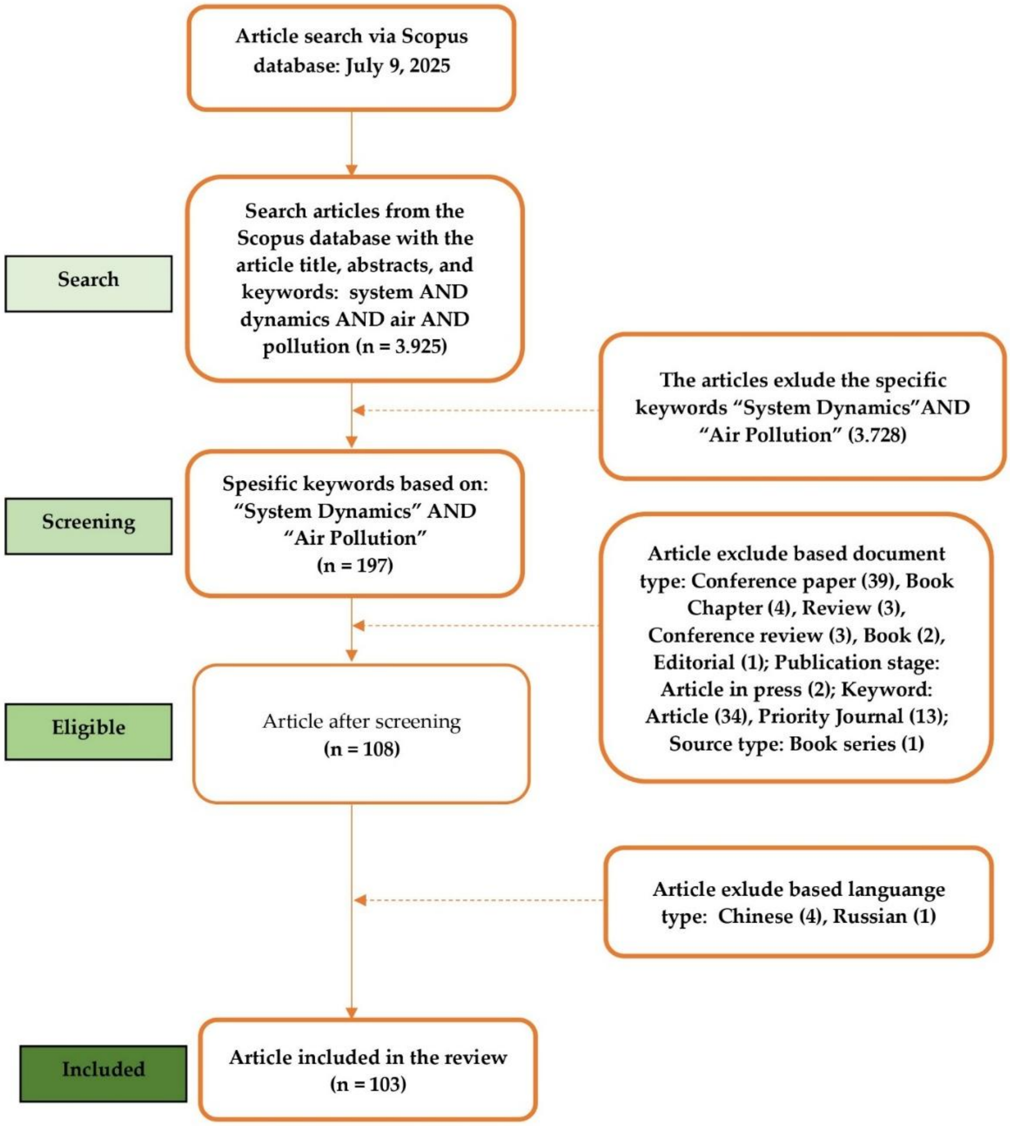

Figure 1. Workflow of the Bibliometric-Systematic Literature Review (B-SLR).

3. RESULTS

The findings of the present study concentrate on insights derived from 103 academic papers catalogued in the Scopus database pertaining to System Dynamics and Air Pollution. This information is obtained via the assessment of article volume, publishing trends over several years, and journal sources. This study will delineate the most critical elements in System Dynamics and Air Pollution, encompassing the writers, their institutional affiliations, and the associated nations.

3.1. Research Trends in System Dynamics and Air Pollution

Research on dynamic systems and air pollution is one of many studies contributing to solving environmental issues, particularly air pollution. To assess the extent to which this topic contributes to addressing air pollution issues, one can examine research trends. Similarly, to answer the research question *RQ1: Is System Dynamics and Air Pollution an important subject for future academic investigation?*

Data from the Scopus database indicates that over the past four decades, there have been 103 scholarly articles on air pollution prediction, suggesting that research on dynamic system prediction and air pollution is still very limited, as depicted in Figure 2.

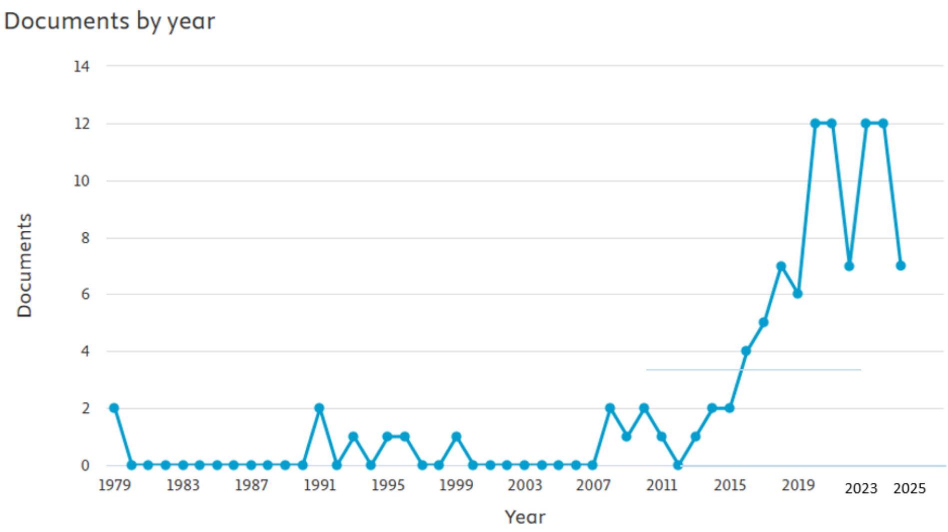

Figure 2. Graph showing the appearance of documents on sytem dynamis and sir pollution from 1979 to 2025 (sources: Scopus database)

Research on air pollution forecasting has progressed markedly during the past decade, particularly since 2015. The preliminary research, entitled "Urban Transportation Policy Planning Methodology: System Dynamics Approach," was conducted in [28]. Sloane and Dickinson [29] conducted a system dynamics study in that year titled "Computer Modelling for the Lake Tahoe Basin: Impacts of Extreme Land-Use Policies on Key Environmental Variables," which preceded research on system dynamics models and air pollution. The progression of research in system dynamics and air pollution is attracting the attention of many scholars, focussing on the improvement of organisational value, machine learning algorithms, spatiotemporal data, IoT and Blockchain technology, and the optimisation of predictive systems [30]–[33]. Moreover, investigations into dynamic systems and air pollution significantly improve public health services, increase public awareness, and promote societal understanding of pollution's environmental impacts, thus aiding in the development and implementation of informed policies [34].

3.2. Distribution of Research on System Dynamics and Air Pollution

This study emphasises the dispersion of research concerning dynamic systems and air pollution. Research Question RQ2: "What is the distribution of research concerning dynamic systems and air pollution?" has effectively offered a clear and thorough summary of the research distribution related to dynamic systems and air pollution prediction. The analysis of air pollution prediction research across 103 publications entailed classifying them by criteria such as country, region, affiliation, source, and author, with a limitation of picking only the top 10 papers in each category. Understanding the geographical regions relevant to air pollution forecasting will assist researchers and practitioners in establishing future research objectives, especially in sustainable development related to air pollution management and mitigation using dynamic systems. China leads the distribution of academic research on dynamic systems and air pollution, with 44 articles, followed by the United States with 14 articles, Iran with 7 pieces, and India, Indonesia, and Italy each contributing 5 papers. Furthermore, Germany, Japan, and Turkey each supplied three papers, whereas Australia generated two pieces (see in Figure 3).

China dominates air quality research due to the urgency of the pollution situation, great political commitment, and huge investment in monitoring infrastructure and research [35]. Its serious pollution crisis provides China a "giant field laboratory" for testing mitigation solutions, providing unique real-world data and experience. China is investing extensively in research and policy implementation to build advanced monitoring infrastructure like 5,000 real-time monitoring stations and laser radar and satellite technology [36]. This focus on technical innovation, particularly hybrid air quality forecast models, has put Chinese research institutions at the forefront of atmospheric science.

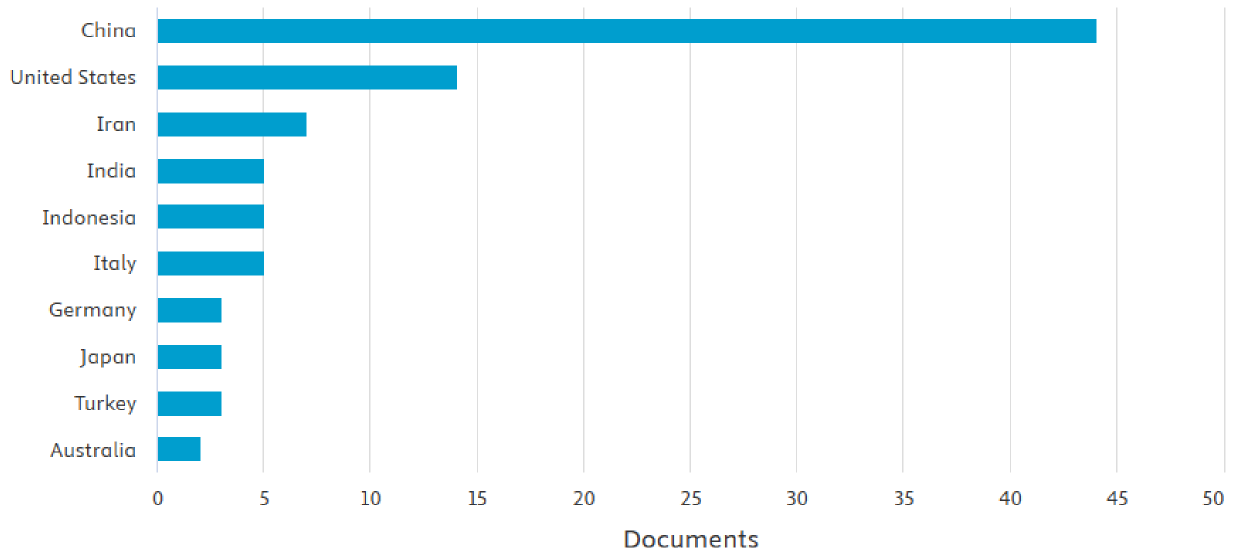

Figure 3. Top 10 countries publishing articles on air pollution forecast (source: Scopus database)

Future air quality research has considerable gaps despite its dominance. Research must better understand the synergistic interactions of complex pollutants (e.g., PM2.5 and ozone) and climate change on air quality. To eliminate health disparities, air pollution measures must be applied uniformly across China and the world. Finally, ensuring the long-term sustainability of air pollution solutions without hindering economic development, integrating clean air policies into climate strategies, and addressing difficult-to-control emission sources like agriculture and heavy transport are the key gaps.

The findings suggest that the management of air pollution through dynamic systems has garnered the interest of numerous countries, encompassing both developed Western nations and emerging Eastern countries, underscoring the worldwide significance of this issue. The researchers will evaluate the interrelations across countries engaged in air pollution prediction research utilizing VOSviewer software. This stage is essential for developing a systematic prospective research agenda. The VOSviewer results from this investigation illustrate the interconnections among countries in the research of dynamic systems and air pollution (refer to Figure 4). This network map depicts global research collaboration on dynamic systems and air pollution, highlighting China and Italy as the predominant contributors (shown by bigger node size), followed by India, whereas the United States and Indonesia exhibit lesser contributions. The connecting lines signify collaborative interactions among countries, illustrating their interconnection in research activities about this critical environmental issue (refer to Figure 4).

These findings further substantiate the notion that air pollution is a concern not only in Western nations associated with urban development, such as the United States and Europe, but also garners attention in several developing countries, including India and Indonesia. Concerns regarding the adverse effects of air pollution, both currently and in the future, have driven numerous researchers and scientists to engage in the pursuit of solutions for air pollution reduction through a dynamic systems approach. Secondly, it is essential to examine the distribution of campuses that have contributed to the publication of works about dynamic systems and air pollution. Henan Agricultural University: 17 documents; North China Electric Power University: 5 documents; University of Shanghai for Science and Technology: 4 documents; Fudan University: 4 documents; Nanjing University of Aeronautics and Astronautics: 3 documents; Massachusetts Institute of Technology: 3 documents; Islamic Azad University: 3 documents; Fars Agricultural and Natural Resources Research and Training Center: 2 documents; Ministry of Education of the People's Republic of China: 2 documents; Beijing University of Chemical Technology: 2 documents (refer to Figure 5).

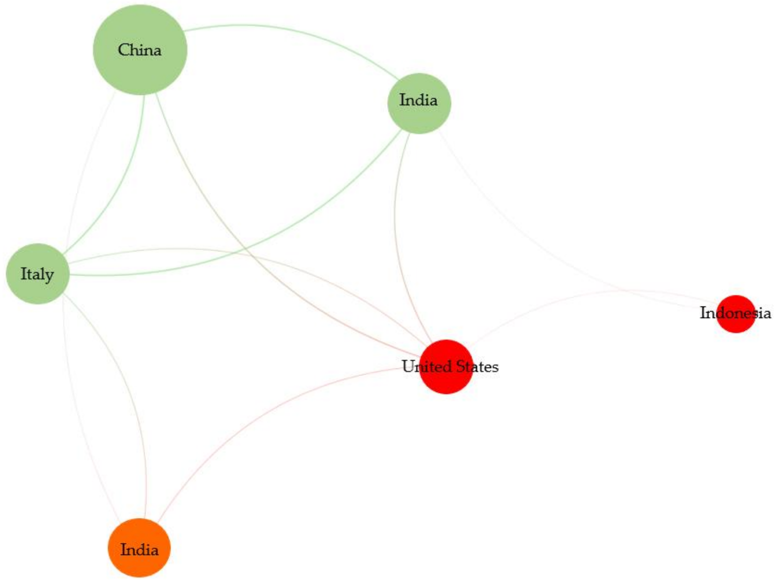

Figure 4. Network country visualization (source: output VOSviewer software)

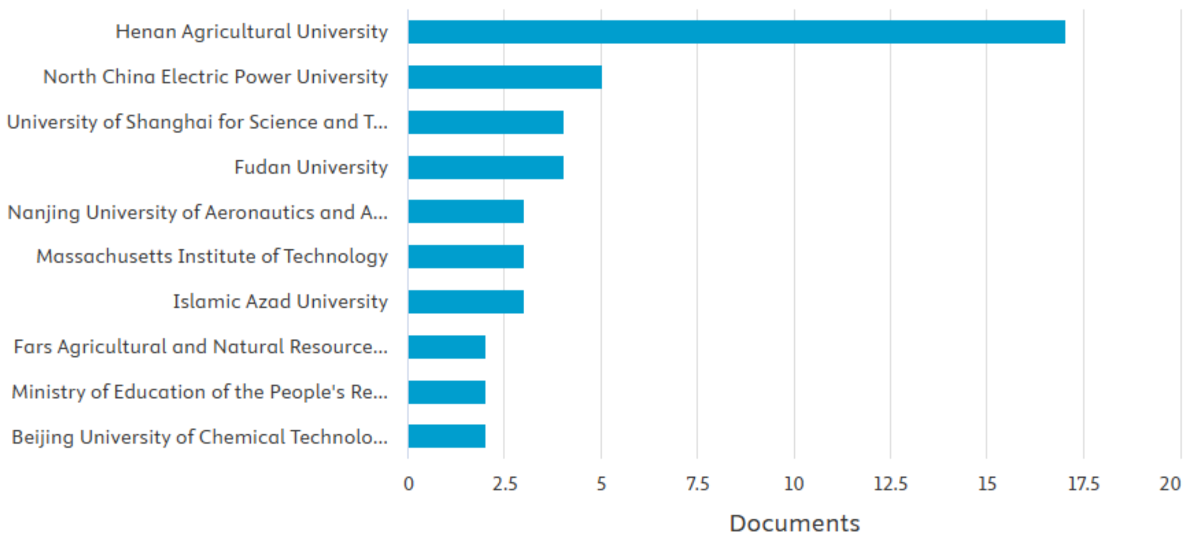

Figure 5. Affiliations of documents releasing articles on air pollution prediction (source: Scopus database)

The distribution of scientific publications on air pollution modelling utilising dynamic systems among the top 10 affiliated institutions reveals that this topic not only attracts academic interest in educational institutions in the United States and China but has also recently gained attention in Asian countries like India and Iran.

The examination of research on air pollution prediction reveals that "Environmental Science and Pollution Research" is the leading journal, with the highest publication count of six, so highlighting its dominance in the field. The second position is occupied by "Sustainability Switzerland" and "Sustainable Cities and Society," both with 5 publications, indicating significant contributions in their respective fields. Simultaneously, journals such as "Clean Technologies and Environmental Policy," "Energies," and "Journal of Cleaner Production" demonstrate moderate representation with four publications each, indicating significant involvement in the research dataset. Three journals, including "Energy Policy," "Environment Development and Sustainability," and "Systems," each include three publications, indicating an equitable contribution to contemporary research. In contrast, the "Arabian Journal for Science and Engineering" had the lowest number of publications, totalling 2 (see in Figure 6).

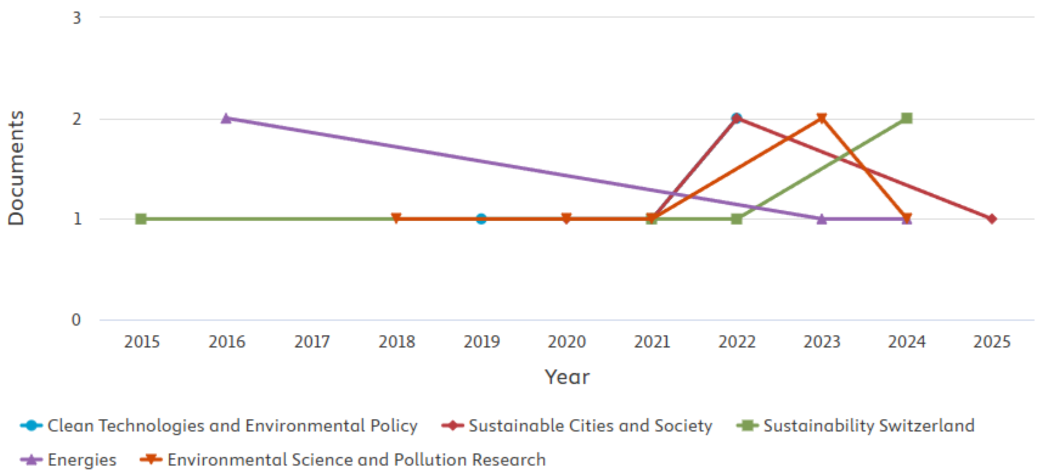

Figure 6. Number of publications based on sources (sources: Scopus database)

The distribution of research concerning air pollgution prediction, as attributed to authors, has a notable imbalance. Jia, S authors 17 papers, followed by Chen, Z with 5 articles; Guo, X and Li, B each with 4 articles; Guo, X, Liu, X, and Ye, X each contributing 3 documents; and Kucukvar, M and Mubaseri, M each creating 2 documents (refer in Figure 7).

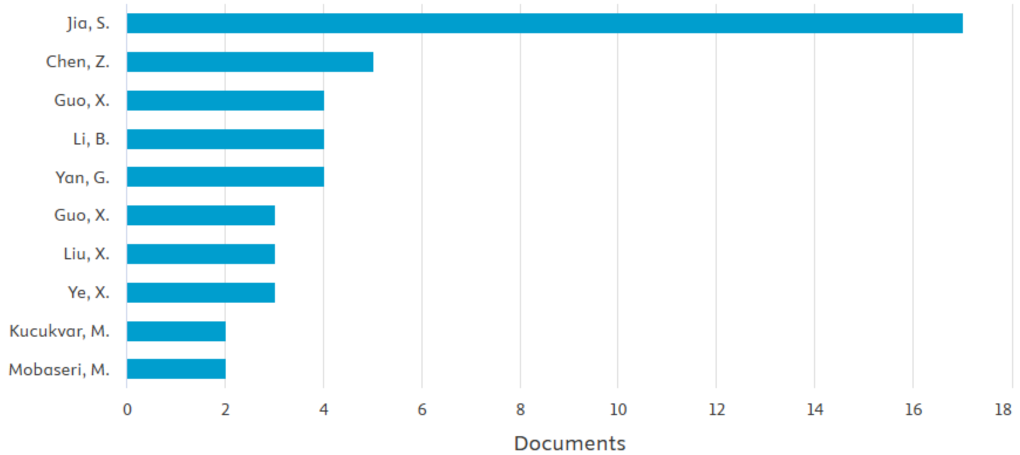

Figure 7. Distribution of research related to dynamic systems and air pollution by author (sources: Scopus database)

This pattern provides insight into who the most active key authors are in the literature on dynamic systems and air pollution. Analysis of Figure 7 shows that Jia, S. is the most productive contributor with the highest number of documents, approaching 17, indicating strong leadership or specialization in this field. Other authors such as Chen, Z. and Guo, X. also made significant contributions, although on a smaller scale. Conversely, researchers like Mobaseri, M. and Kucukvar, M. have the fewest number of documents, around 2-3, indicating they may be new to the field or have a narrower focus in their research.

3.3. Theoretical and practical findings in research on dynamic systems and air pollution

Analysis in several studies related to dynamic systems and air pollution has yielded several results that offer hope in terms of theoretical concepts and technical levels. Therefore, this subchapter also answers research question RQ3: *What are the theoretical and practical ramifications for future research?*

This study was performed on 103 publications obtained from the Scopus collection. VOSviewer is employed to demonstrate that the findings of this research may possess theoretical and practical significance for forthcoming studies on air pollution forecasting. The outcomes of the metadata analysis conducted with VOSviewer will assist researchers and practitioners in comprehending the assumptions and conclusions pertaining to air pollution forecasting. The bibliometric analysis conducted with VOSviewer reveals extensively investigated variables and those that remain underexplored, so establishing a basis for future research endeavors. The findings of the literature analysis conducted with VOSviewer will assist practitioners in the future implementation of sustainable Islamic leadership and the promotion of the Islamic leadership model in organizations globally.

Table 2. Number of keyword link strengths in air pollution prediction research

Rank	Keyword	Total Link strength
1	System Dynamics	254
2	Air Pollution	178
3	Atmospheric Pollution	162
4	System Theory	158
5	Emission Control	125
6	China	94
7	Traffic Congestion	71
8	Greenhouse gases	69
9	Traffic Emission	65
10	Carbon Emission	62

Table 2 provides an overview of the ten most influential or closely related keywords in the field of air pollution prediction research. At the top position, we find "System Dynamics" dominating with a total link strength of 254. This figure far exceeds other keywords, indicating that the "System Dynamics" approach or discipline is a central core in understanding and modeling air pollution predictions. Then, in succession, followed by two fundamental keywords, "Air Pollution" with a link strength of 178 and "Atmospheric Pollution" with 162, confirming the main focus of the research on the issue of air pollution directly. Keywords such as "System Theory" (158) and "Emission Control" (125) also show high relevance, underscoring the importance of theoretical frameworks and mitigation efforts in this field.

Further analysis reveals a significant geographical dimension, as evidenced by the appearance of "China" in sixth place with a link strength of 94. This indicates that China may be an active research center or a frequent focus of case studies in the context of air pollution prediction. Additionally, specific aspects related to the source and type of emissions are also clearly depicted, although with a lower strength of connection. Keywords such as "Traffic Congestion" (71), "Greenhouse gasses" (69), "Traffic Emission" (65), and "Carbon Emission" (62) indicate that the research also highlights the role of transportation and greenhouse gas emissions as important components of air pollution issues, although not to the same extent of interconnectedness as "System Dynamics" or the concept of pollution in general.

Figure 8 is a visualization of a network map of keyword clusters related to dynamic systems and air pollution, grouping related topics into three main clusters marked in red, blue, and green. The red cluster is dominated by core issues such as "air pollution", "atmospheric pollution", and "system dynamics", which are also highly connected to the country "China" as well as aspects of "traffic congestion" and "emission control", indicating a focus on air pollution and its management. The blue cluster tends to group keywords related to conceptual frameworks and environmental protection such as "system theory", "sustainable development", and "environmental protection", emphasizing theoretical approaches and sustainable solutions. Meanwhile, the green cluster highlights topics related to environmental impact and vehicle solutions, such as "climate change", "greenhouse gases", "urban transport", "vehicles", and "electric vehicles", indicating a focus on emissions from transportation and environmentally friendly technologies. Overall, this map illustrates the complex interconnections between air pollution, system dynamics, transportation, environmental policy, and climate change.

Analysis of prior research reveals deficiencies, as the majority of earlier studies were conducted in regions outside Southeast Asia, including America, China, India, and technologically advanced European countries (see in Figure 3 and Figure 4). Consequently, subsequent research may be undertaken in Southeast Asian nations, including Indonesia, Malaysia, and Thailand. Indonesia, possessing the fourth largest population globally, is undergoing substantial urban expansion, urbanization, land use alterations, and industrialization, so rendering air pollution a prospective hazard in the future. This research can rectify the deficiencies in prior studies and furnish more extensive data on air pollution forecasting for air quality management.

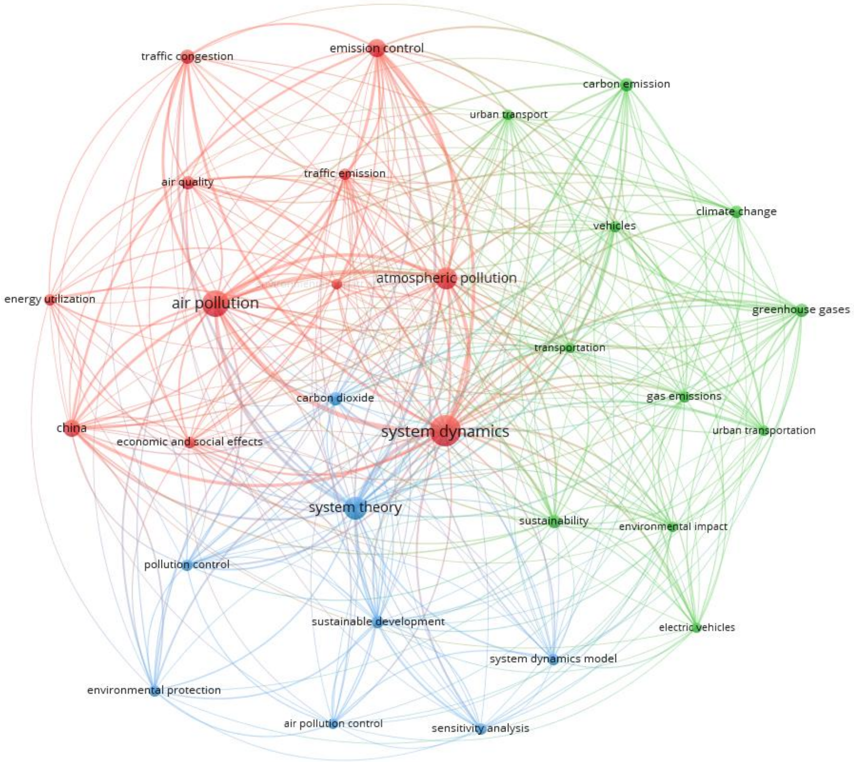

Figure 8. Co-occurrence framework and representation of key terms (source: output VOSViewer software)

4. DISCUSSION

4.1. System Dynamics Can Overcome Air Pollution

Air pollution is a problem that cannot be ignored. Awareness and effort are needed to mitigate air pollution. To answer research question RQ4: How can dynamic systems address air pollution? In order to respond to the research question regarding the capacity of dynamic systems to counteract air pollution, a synopsis of ten pertinent articles is hereby presented. These articles offer a concise synopsis of the methodologies, variables, instruments, policies, and salient findings employed in these studies (see in Table 3).

Table 3. Comparative Review of 10 Studies on System Dynamics and Air Pollution: Methodology, Key Findings, and Variables (source: Scopus database)

Author	Methodology	Important Variables/Parameters	Tools/Software Used	Policy Recommendations	Key Finding
[2]	System Dynamics (SD) model using causal loop diagrams, stock and flow diagrams, and simulations of various policy scenarios.	Traffic demand, vehicle emissions, air quality, road pricing, public transport infrastructure.	STELLA software for simulation, historical data validation.	Investing in public transportation, implementing road pricing strategies, and promoting cleaner vehicle technologies.	Public transportation investment and road pricing are most effective for reducing CO2 and vehicle emissions in Greater Cairo.

Author	Methodology	Important Variables/Parameters	Tools/Software Used	Policy Recommendations	Key Finding
[1]	Simplified System Dynamics (SD) model simulating the impact of fuel taxes and free public transport on CO2 and GHG emissions.	Fuel tax rates, public transportation service levels, vehicle emissions, number of private vehicles, CO2 and GHG emissions.	Vensim software for modeling, Jupyter Notebook and Python for processing simulation results.	Implementing high fuel taxes, promoting free public transportation, and encouraging the use of electric vehicles.	A high fuel tax combined with a free public bus service is the most effective strategy for reducing CO2 emissions and private vehicles in Kuwait.
[37]	System Dynamics (SD) model with subsystems for urban transportation and air polluting industries, and scenario-based simulations.	Traffic emissions, public transport development, industrial emissions, pollution reduction technologies, air quality.	Simulation and historical data analysis.	Road construction, technology improvement in fuel/automotive industries, traffic control plans, and public transportation infrastructure development.	Technology improvements in fuel and automotive industries and public transportation development are the most effective policies for reducing air pollution.
[38]	System Dynamics simulation to analyze motor vehicle impact, waste burning, and industry on air pollution.	Vehicle emissions, waste burning, industrial emissions, public transportation, coal power usage.	Powersim software for cognitive mapping and system dynamics.	Reduction in coal usage, promotion of electric vehicles, and stricter regulations on motorized vehicle numbers.	Motorized vehicles are a significant cause of pollution, but coal-based power plants and industrial emissions contribute as well. Immediate actions are necessary.
[18]	System Dynamics approach using gray system theory for simulating vehicle pollutant reduction management with sensitivity analysis.	Pollution charging fee, vehicle trips, PMx emissions, subsidy policies, public transport supply.	Simulation and sensitivity analysis, gray system theory for parameter determination.	Combining subsidy policies with air pollution fees to reduce emissions and improve public transportation infrastructure.	Increasing air pollution charging fees reduces PMx generation and vehicle trips, while combining subsidies and fees improves traffic conditions.
[39]	System Dynamics model for evaluating the impact of different shore power incentive policies on economic and environmental outcomes.	Shore power utilization, electricity price, subsidies, emission reductions, economic benefits.	System Dynamics model for life cycle cost analysis, sensitivity analysis for policy effectiveness.	Provide preferential subsidies for electricity price reduction to increase shore power usage and reduce emissions.	Price subsidies are more effective than construction subsidies in promoting shore power adoption, resulting in emission reductions.

Author	Methodology	Important Variables/Parameters	Tools/Software Used	Policy Recommendations	Key Finding
[6]	System Dynamics simulation model evaluating scenarios for policy effectiveness in promoting zero- and low-emission vehicles.	Vehicle types (electric, hybrid, internal combustion), emissions reduction, electricity price, policy incentives.	Simulation model for energy transition, sensitivity analysis for policy scenarios.	Promote hybrid electric vehicles and discourage internal combustion engines and natural gas vehicles.	Hybrid electric and plug-in hybrid electric vehicles are the most effective solutions for reducing emissions, compared to internal combustion engines.
[16]	System Dynamics model using causal loop diagrams, stock and flow diagrams, and scenario simulations.	Public transport growth, private vehicle usage, air quality, subsidies for clean energy, public awareness.	System Dynamics modeling software for scenario analysis.	Focus on public transport expansion, subsidies for clean energy, and awareness campaigns.	Public transportation development can reduce private vehicle usage and improve air quality in Depok.
[38]	System Dynamics simulation to analyze motor vehicle impact, waste burning, and industry on air pollution.	Vehicle emissions, waste burning, industrial emissions, public transportation, coal power usage.	Powersim software for cognitive mapping and system dynamics.	Reduction in coal usage, promotion of electric vehicles, and stricter regulations on motorized vehicle numbers.	Motorized vehicles are a significant cause of pollution, but coal-based power plants and industrial emissions contribute as well. Immediate actions are necessary.
[3]	System Dynamics (SD) model to analyze the relationship between complex variables affecting livability, including public transport safety, accessibility, and air pollution.	Public transport safety, accessibility, air pollution levels, public health, land use, mitigation strategies.	Vensim software, Causal Loop Diagrams, Stock and Flow Diagrams.	Improve public transport quality, safety, accessibility, and reduce air pollution.	Improvement of public transport quality and reduction in air pollution can increase transportation livability by 71%.

The methodology employed in these studies involves the use of System Dynamics (SD) models, which simulate the dynamic interactions between variables like traffic congestion, vehicle emissions, public transportation infrastructure, and environmental policies. The studies use causal loop diagrams, stock and flow diagrams, and scenario simulations to model complex systems and predict the impact of different policy interventions on air quality. Various software tools, such as Vensim [1]. Powersim [38], and STELLA [2], are used to construct these models, and some studies incorporate historical data validation to ensure the accuracy of the predictions. In particular, the use of sensitivity analysis in articles like [2] helps to test the robustness of the results across different scenarios.

The tools and software used for modeling in these articles include various System Dynamics platforms, such as Vensim [1], STELLA [2], and Powersim [38]. These tools facilitate the creation of simulation models that help researchers analyze the behavior of complex systems over time. They allow for scenario-based forecasting, where different policy interventions can be simulated to assess their effectiveness in mitigating air pollution. Additionally, some studies used Python and Jupyter Notebook [1] for data processing and sensitivity analysis to test the robustness of the results. These tools are integral to examining the temporal and causal relationships in the SD models and ensuring reliable and actionable results.

The important variables or parameters in these models include factors such as vehicle emissions, traffic demand, public transportation infrastructure, fuel types, pollutant emissions (e.g., CO2, NOx, PM10), and economic factors (e.g., fuel taxes, subsidies). Other important parameters include vehicle kilometers traveled (VKT), electric vehicle adoption rates, and government policy actions [1], [38]. These variables are crucial for understanding the interactions between different components of the transportation system and predicting how changes in one variable might affect others, ultimately impacting air pollution levels. The DESTEP factors (Demographic, Economic, Social, Technological, Environmental, and Political) used in the Mexico City study[38] help provide a more holistic perspective on pollution management.

The policy recommendations derived from these studies highlight the importance of integrating public transportation development with emission reduction policies. Common recommendations include investing in cleaner technologies, improving public transportation infrastructure, and implementing road pricing and fuel taxes to discourage private vehicle use [2], [38]. Some studies also emphasize the need for collaboration between sectors (e.g., transportation, energy, and industry) to ensure the sustainability of air quality management strategies [3]. The effectiveness of these policies is often linked to public acceptance, economic feasibility, and long-term implementation. The research in Mexico City [38] and Kuwait [1] emphasizes the role of holistic policy frameworks for reducing urban emissions.

The key findings of these articles emphasize the importance of combining public transportation improvements with other strategies like fuel taxes, road pricing, and vehicle technology upgrades to reduce air pollution. Many studies found that public transportation investment has a significant impact on reducing vehicle emissions and improving air quality [1], [38]. In some cases, alternative fuels, electric vehicles, and energy transitions were shown to be effective in cutting down emissions in the long term [3], [17]. These findings suggest that holistic and multi-faceted strategies are necessary to address urban air pollution effectively, as demonstrated by the studies in Greater Cairo [1], [2].

4.2. Air Quality Management Policies and The Difficulties Faced By Developing and Developed Countries

Air pollution control is a worldwide concern necessitating policy adaptation to local contexts. China has exemplified the efficacy of a stringent centralized control strategy, characterized by substantial political commitment and considerable budget allocation, resulting in a large reduction of PM2.5 levels in major urban areas. This substantiates the notion that robust and systematic governmental action might facilitate swift transformation during crisis situations[40]. Conversely, India, characterized by its decentralized governance, encounters considerable implementation challenges despite the established legal framework, underscoring the necessity for robust coordination among various governmental tiers for effective policy execution.

Alternative approaches, shown by the United States through the Clean Air Act and the European Union via its pollution standard directives, illustrate that a legal framework and the harmonization of standards are essential. The United States prioritizes explicit emission rules and rigorous enforcement, whereas the European Union concentrates on establishing upper limits for air pollutants among its member states, albeit facing difficulties in reaching consensus and ensuring uniform enforcement [41]. These methodologies emphasize the necessity of a robust legal framework and standardized regulations to attain national and international air quality objectives.

This contrast highlights the significance of robust political commitment, an effective regulatory and law enforcement structure, and intergovernmental coordination, particularly for emerging nations. Moreover, investment in data monitoring and analytical infrastructure, as exemplified by China, is essential for informed decision-making. Aligning air quality standards with WHO recommendations and implementing a comprehensive strategy for pollutant sources are crucial measures for effective and sustainable air quality management.

4.3. System Dynamics for Mitigating Air Pollution in The Future

SD are one of several methods for addressing air pollution issues. To answer RQ5: *Can dynamic systems serve as an effective model for reducing air pollution in the future?* The following analysis will be conducted.

SD has shown significant potential in modeling and alleviating air pollution by simulating the effects of various policy measures. Studies have demonstrated how SD models can help clarify the complexities of air pollution and guide more effective policy-making for cleaner air [2], [19]. For example, Huang et al. used SD to examine China's energy framework and its impact on air quality, illustrating how transitioning to renewable energy can influence PM10 emissions based on different growth rates of clean power generation [19]. Additionally, SD has been used to model industrial emissions, where [20] showed that SD models could optimize fuel mix strategies to comply with SOx and NOx regulations, significantly reducing pollutants. In urban environments, SD has been applied to analyze transportation policies, such as driving restrictions in Beijing, demonstrating the necessity for adaptive strategies due to diminishing returns in emission reductions [3], [17].

The use of SD models for air pollution management extends to predicting the long-term outcomes of various policies, as shown by Godínez Cárdenas et al. [38] in their environmental simulation model for Mexico City, which predicted greater reductions in pollutants than official projections. Such models not only improve forecasting abilities but also help local governments implement more effective mitigation strategies. Moreover, SD modeling can enhance the transition to low-emission technologies like electric vehicles [5], showing how these technologies, when supported by favorable policies and infrastructure, can significantly reduce urban air pollution. Future research should focus on incorporating comprehensive modeling techniques that include stakeholder involvement and scenario analysis to better evaluate the long-term effects of different policies on air quality and health outcomes [2].

Future research in SD and air pollution should prioritize integrating technical innovations, such as autonomous electric vehicles and policy incentives for low-and zero-emission cars, to better align transportation systems with sustainable development goals [5]. Moreover, the significance of cross-sector collaboration is paramount. Guo and Yang [42] highlighted the importance of combining energy policies with air quality management to achieve comprehensive sustainability objectives. By integrating these advancements and fostering cross-sector collaboration, stakeholders can develop more effective and adaptable policies that promote cleaner technologies, address socio-economic considerations, and mitigate air pollution in the long term. In the Southeast Asian context, these findings from a comprehensive approach will help maintain public health and environmental integrity, as demonstrated by extensive research in this field.

5. CONCLUSION

This study affirms that the amalgamation of System Dynamics (SD) and air pollution research constitutes a vital and expanding domain of scholarly inquiry. The systematic literature review and bibliometric analysis indicate that SD has developed into a formidable tool for the analysis, forecasting, and assessment of intricate urban and environmental systems associated with air pollution. Empirical research reveal that DS is widely utilized across diverse geographical locations, especially in rapidly urbanizing areas, underscoring its global significance and the imperative for its application in air quality management. The research distribution indicates a concentration of studies in urban areas in Asia and the Middle East, specifically China, Iran, and Egypt, alongside an increasing interest in North America and Latin America. The majority of publications concentrate on the implementation of sustainable development in urban mobility, energy transition, and industrial emissions. This demonstrates the adaptability and relevance of this method in modeling the dynamic behavior of pollution sources under various policy interventions. SD theoretically provides a systems thinking framework that incorporates feedback loops, time delays, and the nonlinear characteristics intrinsic to air pollution dynamics. This allows policymakers to model different mitigation scenarios, including gasoline taxes, electric vehicle uptake, and public transportation spending, offering predictive insights for policy formulation. Empirical investigations in prior research demonstrate that SD can serve as a useful instrument for assessing emission patterns and enhancing decision-making processes. SD proficiently tackle air pollution by simulating the causal linkages among metropolitan elements, including traffic flow, industrial production, and energy use. These models facilitate the identification of leverage points for intervention and forecast the long-term effects of regulatory or technological modifications. In urban centers such as Beijing and

Mexico City, SD models have facilitated adaptive strategies for emissions reduction. Current data indicates that dynamic systems can function as efficient and scalable models for mitigating air pollution in the future. Their versatility, scenario analysis capabilities, and facilitation of participatory decision-making render them appropriate for environmental planning at both local and national scales. This research successfully addressed and synthesized research questions RQ1 – RQ5. The findings offer valuable insights for policy implications for regional development, aiding urban planners, energy policymakers, and environmental management, especially concerning air quality.

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