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Application Status, Hotspots, and Future Trends of Artificial Intelligence in the Field of Sustainable Environmental Governance

Xuemei Jiang[1,2], Tingyin Deng[1,2,*], Wenying Zhang[2]

[1] Sichuan Key Provincial Research Base of Intelligent Tourism, Sichuan University of Science and Engineering, Zigong 643000, China;
[2] School of Fine Arts & Colored Lantern, Sichuan University of Science and Engineering, Zigong 643000, China;

* Correspondence: 1275811251@qq.com

Abstract. Amidst the increasingly severe global environmental crisis, the application of artificial intelligence (AI) in the fields of environmental governance and sustainable development has become a hot topic in current scientific research and practice. The complexity and urgency of environmental issues have made the integration of AI technology particularly important and pressing. To comprehensively understand the research status, hotspots, and future trends in this field, this study employed Citespace and VOSviewer literature analysis tools to construct a knowledge map based on data from 2004 to 2024. The analysis results reveal that, in terms of research regions, Asia (especially China) has made the most significant contributions, while North America and Europe (particularly the United States and some EU countries) have closely collaborated, forming the core research regions. The top five authors in terms of publication volume are Liu J, Vinuesa R, Nishant R, Bag S, and Benzidia S. Regarding research hotspots, the current themes in this field focus on four clusters: intelligent management and green innovation for performance lifecycle assessment, smart cities and sustainable development, and AI-enabled environmental management. These highlight the vast potential of AI in enhancing environmental governance efficiency and promoting sustainable development. As for future trends, the number of publications in this field has shown a continuous upward trend in recent years, with predictions indicating that future research will continue to concentrate on keywords such as AI, life cycle, assessment, and the Internet of Things. In summary, AI is forming an active and expanding field within environmental governance, and future research will deepen understanding of the topic, explore the integration of AI with environmental science, address global challenges, and drive environmental governance towards a smart, efficient, and sustainable direction.

Keywords: Artificial Intelligence; Environmental Governance; Sustainable Development

1. Introduction

In the era of the burgeoning artificial intelligence (AI) technology, the application of AI in environmental governance (EG) and sustainable development (SD) is increasingly highlighting its irreplaceable research value. The exploration of this field is not only related to the advancement of environmental protection technology but is also closely linked to global climate change mitigation,

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efficient resource utilization, and the SD of the socio-economy, making it an urgent research focus in the new era.

In recent years, the rapid development of AI technology has led to an increasing application in EG and SD, with its importance and urgency gaining significant attention from both academia and industry. Numerous scholars have actively engaged in research, achieving remarkable results. For instance, Liu J et al.[1] utilized industrial data from China spanning 2005 to 2016 to explore the impact of AI on carbon intensity; Ding, C assessed the potential of AI in the construction sector, focusing on mid-sized office buildings in the United States and developing a method to evaluate and quantify potential emission reductions[2]; Bibri et al. explored the role of AIoT in the seamless integration of data-driven governance systems to advance EG in smarter ecological cities[3]. These studies cover various dimensions of technological innovation and practical applications of AI in EG. Despite the fruitful outcomes, there is still a lack of systematic integration and prediction of future trends in this field of research. Consequently, this study selects the core database of the Web of Science, employing bibliometric and visualization tools to comprehensively review the application of AI in EG and SD, revealing research hotspots and future trends, providing a reference for researchers and practitioners, and promoting the intelligent and SD of EG[4].

2. Research method and data sources

2.1. Research methods

VOSviewer and CiteSpace are commonly used information visualization software tools in the field of scientific research, enabling insights into literature associations and research trends [5,6]. The article's data is sourced from the Web of Science (WOS) database, based on literature related to network environment security from 2004 to 2024. VOSviewer and Scimago software were employed to map countries, while CiteSpace was used to create cluster maps and burst term maps of research topics.

2.2. Data sources

The relevant data for this study were first retrieved from the WOS Core Collection, using the keywords "artificial intelligence (AI) " , "environmental governance " , and "sustainable development"as the subject search terms.

The search covered a time span from January 1, 2004, to December 31,2024, yielding 735 articles . Secondly, with no discipline restrictions but limiting the language to English,irrelevant documents other than papers were excluded, resulting in a final set of 508 valid articles.

3. Analysis of the status of research

3.1. *Distribution of national publications*

In-depth analysis was conducted using two visualization software tools, VOSviewer and Scimago [7,8]. The research period spanned from 2004 to 2024, during which a total of 48 countries participated in the field of research. As depicted in Figure 1, China published 124 papers in the field of AI for EG and SD, accounting for 24.40% of the total publications, thereby establishing its position as the leading research country in this field. Following closely are India, the United States, the United Kingdom, Iran, and Australia, with respective shares of the total publications at 13.77%, 13.58%, 9.84%, 6.88%, and 5.51%. By analyzing the size, color, and connections of the nodes between countries, the intensity of international collaboration can be discerned. Figure 2 visually presents the strength of collaboration through the density of gradient-colored arcs, with the size of the circles representing the number of papers published by each country. It is observed that the United States, the United Kingdom, China, Australia, and India maintain close cooperative relationships within this research field.

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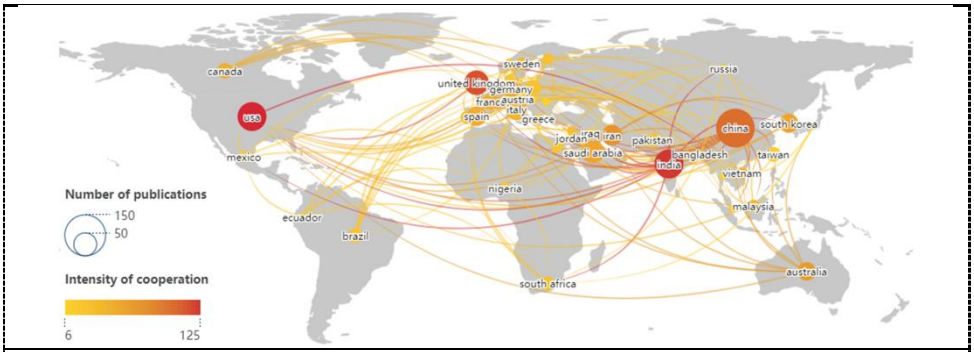

Figure 1. Map of international research capacity.

3.2. *Distribution of national publications*

Analyzing the output of prolific authors can clearly reveal the distribution of core author groups within the research domain of AI in EG and SD, aiding in deepening the understanding of the leaders and current state of research in the field [9]. According to statistics, the total number of authors involved in this field of research is 487. Among them, Liu J, Vinuesa R, Nishant R, Bag S, and Benzidia S are the top contributors (see Table 1). Chinese scholar Liu J leads with 17 publications. Furthermore, an in-depth analysis of highly cited documents in this field can effectively map out the cutting-edge trends and academic standards, providing a solid foundation for organizing the research context and predicting future development directions. Vinuesa R's paper "The role of AI in achieving the SD Goals" has been cited 756 times, which not only fully demonstrates its significant academic impact but also highlights the important contribution of the paper to the research in this field [10].

Table 1. Publication of articles by prolific authors.

Number	Author	nationality	institution	Number of publications	Centrality	Source publications	Top Cited Articles	Number of citations
1	Liu J	China	Nanjing University of Information Science & Technology	17	0.02	Socioeconplansci	The effect of artificial intelligence on carbon intensity: Evidence from China's industrial sector	101
2	Vinuesa R	Sweden	KTH Mech	14	0.04	Nat Commun	The role of artificial intelligence in achieving the SustainableDevelopment Goals	788
3	Nishant R	Canada	Université Laval	13	0.01	Int Jinformmanage	Artificial intelligence for sustainability: Challenges, opportunities, and a research agenda	285
4	Bag S	South Africa	University of Johannesburg	11	0.01	TechnolForecast Soc	Role of institutional pressures and resources in the adoption of big data analytics powered artificial intelligence, sustainable manufacturing practices and circular economy capabilities	351

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5	Benzidia S	France	University of Lorraine	10	0.01	TechnolForecast Soc	The impact of big data analytics and artificial intelligence on green supply chain process integration and hospital environmental performance	250
6	Di Vaio A	Italy	University of Naples "Parthenope"	10	0.01	J Busres	Artificial intelligence and business models in the sustainable development goals perspective: A systematic literature review	347
7	Dubey R	Austria	University of Applied Sciences	8	0.02	INT Jprodecon	Big data analytics and artificial intelligence pathway to operational performance under the effects of entrepreneurial orientation and environmental dynamism: A study of manufacturing organisations	366
8	Acemoglu D	Turkey	MIT	8	0	J Politecon	Robots and Jobs: Evidence from US Labor Markets.	1073
9	Allam Z	Australia	Curtin University	8	0.07	Cities	On big data, artificial intelligence and smart cities	466
10	Belhadi A	Morocco	Cadi Ayyad University	8	0.04	Annop erres	Artificial intelligence-driven innovation for enhancing supply chain resilience and performance under the effect of supply chain dynamism: an empirical investigation. Annals of Operations Research	167

4. Analysis of research themes

A total of 508 documents were imported into VOSviewer for co-word clustering, resulting in four clusters in the field of AI in EG and SD [11]. The software analysis results show different colors representing different clusters, namely Efficiency Life Assessment, Intelligent Management and Green Innovation, Smart Cities and SD, and AI-Empowered Environmental Management. Figure 2, which presents keyword clustering, reveals the hot topics in the field.

Cluster #1, "Efficiency Life Assessment," focuses on core terms such as efficiency life cycle and assessment, highlighting the urgency and importance of enhancing efficiency and optimizing lifecycle assessments. Ligozat, AL et al. explored the potential negative effects of AI for Green, systematically reviewed the types of AI impacts, and discussed various assessment methods, demonstrating the application of lifecycle assessment in AI services. This cluster is concerned with maximizing resource

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utilization efficiency at every stage from design, operation to disposal, emphasizing the importance of scientific assessment methods to ensure that products, services, or projects remain efficient and sustainable throughout their lifecycle.

Cluster #2, "Intelligent Management and Green Innovation," encompasses keywords such as adoption, AI, big data analytics, capabilities, and circular economy. This cluster emphasizes the integration of intelligent technologies into management practices, leveraging big data analytics to enhance decision-making capabilities, and driving the advancement of green innovation and the circular economy. Xu, X. et al., based on a balanced panel data of 30 Chinese provinces from 2006 to 2019, used a two-way fixed-effects model to reveal the significant role of AI in reducing carbon emissions [12, 13]. This cluster delves into the application of AI technology in optimizing resource allocation, adopting environmentally friendly technologies, and constructing a closed-loop economic system, aiming to achieve dual benefits of economy and environmental protection.

Cluster #3 "Smart Cities and SD" encompasses key terms such as agricultural, analytics, AI, and big data. This cluster focuses on how to utilize modern information technology, particularly AI and big data analysis, to promote the intelligent transformation of urban management and thereby achieve sustainable urban development. Lin, J. empirically found that AI can facilitate green product and process innovation in agricultural enterprises, enhancing environmental performance; and elucidated how green culture moderates the relationship between AI and green product innovation [14]. This cluster provides an in-depth analysis of practices in fields such as smart agriculture, intelligent transportation, and energy management, aiming to improve resource efficiency, mitigate environmental pollution, and promote the harmonious coexistence of economy, society, and environment, offering theoretical and practical support for corporate SD strategies.

Cluster #4, "AI-Empowered Environmental Management," includes keywords such as algorithm, AI, artificial neural network, city, etc. This cluster emphasizes the application potential of AI technology, especially artificial neural networks, in environmental monitoring, pollution forecasting, and resource management. Wu, X. et al. innovatively introduced an AI-assisted rule confidence measurement framework (AI-CRBM) for accurately predicting the reform of EG costs [15]. By constructing highly accurate predictive models, AI assists decision-makers in precisely capturing environmental change trends, formulating efficient and environmentally friendly strategies, and promoting the intelligent and refined development of environmental management in cities and broader areas.

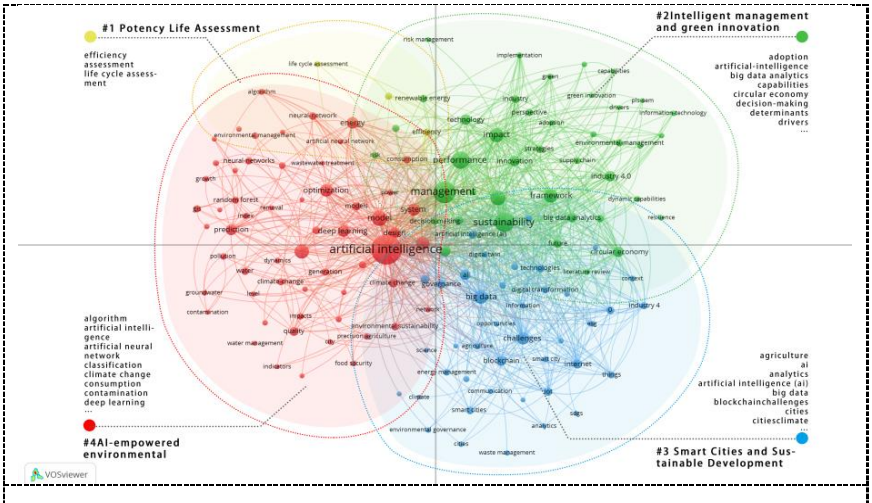

Figure 2. Keyword clustering map.

5. Analysis of research hotspot trends

Figure 3 illustrates the trend of annual growth in research literature on AI in EG and SD from 2004 to 2024. The timeline in the figure represents the research hotspot terms for each period. During

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this period, the number of relevant documents in the WOS database has continued to rise, reflecting the gradual maturation of the field.

From 2004 to 2020, the field was in its initial development phase, with a limited number of publications and emerging keywords, and discussions were lengthy. During this phase, "decision support" and "case-based reasoning" became enduring research focuses. Wang, H.'s team proposed an Urban Land Ecological Safety (ULESM) model based on the Modified Artificial Bee Colony Algorithm (MABCA) [16]. This model optimized the spatial grid of the ABCA, constructed a computational framework, data structure, etc., and integrated a model for the spatial coupling coordination degree of ecological safety to achieve spatial detection of ecological risk areas. This phase marked the preliminary exploration of AI in EG and SD, laying a foundation for professional knowledge.

Starting from 2020, the field entered a stable growth phase, with both the number of publications and the number of emerging keywords showing a positive synchronous increase, reaching a peak in 2024. In this phase, "Industry 4.0" became the keyword with the highest mutation intensity, followed by "AI," which are the core keywords of this period and are influencing the research trends of the time. Saxena, A., upon reviewing the literature, found a scarcity of discussions on the application of Industry 4.0 technology in ESG data collection and assessment. Therefore, the focus of the research is to emphasize the importance of ESG data and reporting in assessing organizational sustainability [17]. Through in-depth analysis, the study aims to fill the existing knowledge gap and promote the effective integration of Industr 4 0 technolog with ESG assessment.

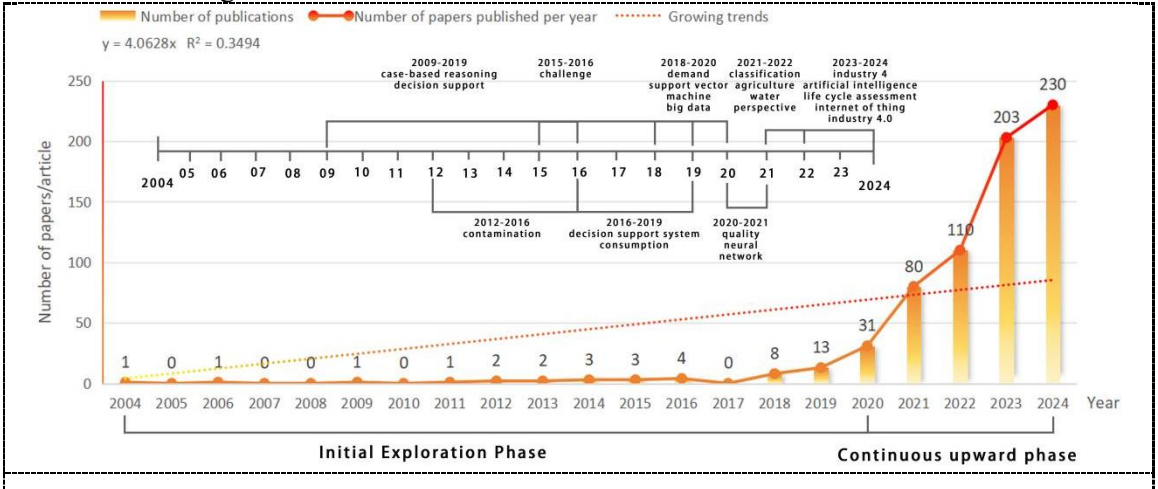

Figure 3. Schematic of the number of documents.

6. Analysis of research hotspot trends

6.1. Discussion

This study employs rigorous bibliometric analysis to delineate the current state and trends in research on SD in EG through AI. The following is a detailed discussion of the main findings of this research.

In the current state of research, Asia (especially China), North America, and Europe (particularly the United States and some EU countries) are the primary regions conducting research in this field, attributed to their strong scientific research foundations and policy support. Scholars with more than 10 publications include Liu J, Vinuesa R, Nishant R, and Bag S. Among them, Chinese scholar Liu J has an impressive publication count of 17, reflecting his profound research capabilities. Additionally, Vinuesa R's paper "The role of AI in achieving the SD Goals" has been cited 756 times. This figure powerfully demonstrates the paper's far-reaching academic impact and significance, and it also fully highlights Vinuesa R's outstanding contributions as a researcher in this field, as well as the notable achievements made in integrating AI with SD.

Research hotspots focus on four clusters: Efficiency Life Assessment (efficiency life cycle, assessment...), Intelligent Management and Green Innovation (adoption, AI, big data analytics...), Smart Cities and SD (agricultural, analytics, big data...), and AI-Empowered Environmental

Management (algorithm, AI, city...). These clusters showcase the immense potential of AI in enhancing the efficiency of EG and promoting SD. This phenomenon reveals that AI technology is gradually becoming a key force in driving environmental protection and social progress,demonstrating a new trend of harmonious coexistence between technology and nature.

The continuous growth in the number of publications in this field is primarily driven by technological advancements, intensifying global environmental challenges, and increased research investment. This trend is expected to continue in the future. Research keywords have evolved from initial terms like decision support and case-based reasoning, shifted towards future and algorithm in 2020, and have now focused on strategy, AI, and life cycle assessment. This change reflects the research field's deepening with technological development and practical needs, placing increasing emphasis on strategic, intelligent, and lifecycle assessments. This shift not only reflects the research's forward-looking and practical nature but also indicates that future hotspots will continue to revolve around keywords such as AI, life cycle assessment, and the internet of things, emphasizing the central role of intelligent technology and the IoT in EG and SD.

In summary, the application of AI in EG and SD is gradually forming an active and expanding field of research and practice. Future research is expected to further deepen the understanding of these core issues, explore deeper integration pathways between AI and environmental science, propose more innovative solutions in the face of global challenges such as climate change and resource management, and guide EG towards a wiser, more efficient, and sustainable direction.

6.2. *Discussion*

Utilizing two advanced bibliometric tools, CiteSpace 6.3.R3 and VOSviewer, this study conducted a deep excavation and systematic analysis of academic research on network environmental security in the era of AI. The conclusions are as follows: Currently, Asia (particularly China), North America, and Europe (especially the United States and some EU countries) are the primary research nations in this field. Scholars with high productivity, who have published more than 10 papers, include Liu J, Vinuesa R, Nishant R, and Bag S. Research hotspots are concentrated in four clusters: performance life assessment, intelligent management and green innovation, smart cities and SD, and AI-enabled environmental management. These hotspots demonstrate the significant potential of AI in enhancing EG efficiency and promoting SD. The number of publications in this field is expected to continue rising in the future, with predicted hotspots persistently focusing on keywords such as "AI," "life cycle," "assessment," and "internet of things." In summary, AI is forming an active research domain in the field of EG. Future research will deepen understanding of the topics, explore the integration of AI with environmental science, address global challenges, and promote smart, efficient, and sustainable EG.

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