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The Environmental Effects of Artificial Intelligence: A Bibliometric Perspective

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Abstract

Purpose: This paper aims to provide a comprehensive review of the environmental effects of Artificial Intelligence (AI), identifying key research forces, collaboration networks, and evolving trends. **Design/methodology/approach:** This study focuses on English journal articles published between 2015 and 2025 in the Web of Science Core Collection. Bibliometric and knowledge mapping analysis were conducted using CiteSpace and VOSviewer software to analyze the data. **Findings:** First, the collaboration network exhibits a multi-center structure. However, the network density remains low, suggesting potential for increased international collaboration. Second, research has grown rapidly since 2019, evolving from exploratory studies to practical applications. From 2023 to 2025, the focus shifted toward addressing climate change using AI, with advanced technologies such as deep reinforcement learning and explainable AI gaining prominence. Third, research hotspots include core AI technologies, AI's impact on energy and carbon management, and its role in sustainable development. Finally, the scope of AI applications is expanding into new areas, such as smart cities and clean energy, alongside growing attention to explainable AI and edge computing.
Research limitations/implications: Researchers should strengthen international collaboration, explore advanced techniques like explainable AI and edge computing, and address the dual challenge of maximizing AI's environmental benefits while minimizing its energy footprint. **Practical implications:** Practitioners should integrate AI tools such as deep learning and intelligent energy management systems to optimize energy efficiency, reduce carbon emissions, and support green transformation initiatives. **Originality/value:** This paper

contributes by offering a large-scale, systematic, and visual analysis of AI's environmental effects. The results clarify the current research landscape, highlight hotspots, and map evolving trends.
Keywords: Artificial Intelligence, Environmental Effect, Bibliometric Analysis, Visualization

Introduction

With the rapid advancement of industrialization and urbanization, environmental issues such as excessive resource consumption, ecosystem degradation, and escalating climate change have become increasingly prominent, posing a severe threat to global sustainable development (Nguyen et al., 2023). This has attracted considerable attention from countries worldwide. In 2015, the United Nations established 17 Sustainable Development Goals (SDGs) in the 2030 Agenda for Sustainable Development. Environmental sustainability, along with economic and social sustainability, forms the three main pillars of sustainable development, with environmental sustainability being a prerequisite for both economic and social sustainability (Little et al., 2016)

In recent years, the rapid development of Artificial Intelligence (AI) has provided new technological means to improve environmental quality and address climate issues (Chen et al., 2023) AI has become a key driver for promoting green, low-carbon transformation and achieving environmental sustainability. As an intelligent technology with autonomous learning, sensory perception, and efficient decision-making capabilities, AI has shown enormous potential in carbon emission control and energy management, gradually gaining widespread attention in the academic community (Nishant et al., 2020; Chen et al., 2021; Liu et al., 2021; Liu et al., 2022; Zhong et al., 2024). Numerous studies have explored the mechanisms and effectiveness of AI technologies, such as machine learning, deep learning, big data analysis, and intelligent industrial robots, in carbon emission performance, carbon intensity control, and energy system efficiency optimization (Li et al., 2022; Meng et al., 2022; Tomazzoli et al., 2023; Yu et al., 2023; Dong et al., 2024). Most of these studies conclude that the environmental effects of AI are positive, contributing to sustainable environmental development. However, as computational demands continue to increase, the energy consumption and environmental footprint of AI have also raised concerns, which has led to the emergence of the "green AI" (Bolón-Canedo et al., 2024).

Despite the growing body of research, systematic reviews based on large-scale data remain scarce, limiting our ability to identify collaboration patterns, research hotspots, and future directions. This paper aims to provide a comprehensive review of the English literature on AI's environmental effects in the Web of Science Core Collection, using bibliometric methods. Through CiteSpace and VOSviewer, this study conducts a full-sample, visual, and quantitative analysis to outline the current state of research on AI in the environment. It also identifies the key research forces, international collaboration patterns, and summarizes the hotspots and evolving trends, offering a comprehensive and systematic perspective to guide future research directions.

Data Sources and Research Methods

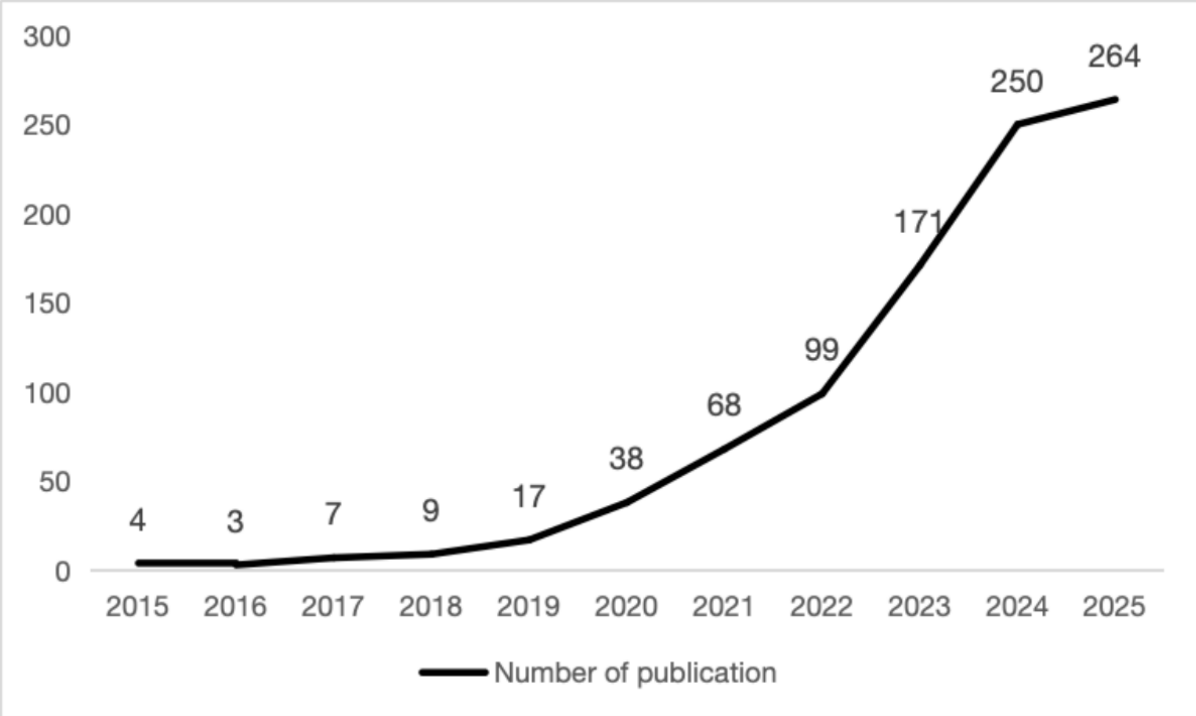
This study focuses on English journal articles related to the environmental effects of AI published between 2015 and 2025 in the Web of Science (WoS) Core Collection. Since 2015, the number of studies in the field of AI has significantly increased (Nishant et al., 2020), coinciding with the adoption of the Paris Agreement, which established a global carbon reduction framework that involved nearly all countries. This has greatly stimulated research on topics such as carbon peak and carbon neutrality. Besides, limiting the review to studies after 2015 enables us to capture the technologically relevant context, as many earlier studies focus on traditional computing systems rather than modern AI architectures (e.g., deep learning, large-scale data centers, AI-driven optimization). Including older literature may introduce conceptual noise and reduce comparability.

The environmental effects of AI are broad, and academic research in this area has mainly focused on two key areas: carbon emissions and energy efficiency. This paper defines the keywords for the carbon emissions category as “carbon emission” and “carbon intensity,” and for energy efficiency, the keyword is “energy efficiency.” “Carbon emission” is a fundamental and widely-used term in this field, commonly used to describe the total amount of carbon dioxide emissions, and is one of the core indicators for measuring climate change and greenhouse gas management. “Carbon intensity” refers to the amount of carbon emissions per unit of output and reflects emission efficiency. The chosen keywords, which consider both the total volume and efficiency of carbon emissions, allow for a comprehensive selection of relevant literature. Additionally, the keywords “environmental impacts” and “environmental performance” were included to ensure broader coverage of related studies. Therefore, the search expression in WoS Core Collection was as follows: TS=(“Artificial Intelligence”) AND TS=(“Carbon Emissions” OR “Carbon Intensity” OR “energy efficiency” OR “environmental impacts” OR “environmental performance”) AND PY=(2015-2025).

To ensure the relevance and focus of the literature review, subject categories in the Web of Science database were limited to Energy & Fuels, Environmental Sciences, Green & Sustainable Science & Technology, and Computer Science – Artificial Intelligence during the search process. This approach helps to exclude irrelevant articles, thereby improving the thematic consistency and analytical quality of the literature. These categories cover the core interdisciplinary areas of AI and environmental research, providing essential support for constructing a more systematic review framework. Furthermore, the document type was limited to articles, early access, or review articles, and only English-language publications were included. After retrieval, duplicate records and irrelevant studies were removed. Subsequently, the remaining items underwent manual title and abstract screening to ensure their relevance to AI-related environmental impacts, resulting in a final dataset of 930 publications. Bibliometric and knowledge-mapping analyses of the selected literature were conducted using CiteSpace and VOSviewer software.

Research Overview

From January 2015 to July 2025, publications on AI’s environmental effects gradually increased, with a sharp rise after 2019 (see Figure 1). Although 2025 data are incomplete, publications have already exceeded the total for 2024, indicating growing academic attention to AI’s environmental effects. The field developed in two stages. From 2015–2018, publication growth was slow, reflecting limited attention and an exploratory phase. From 2019–2025, research expanded rapidly as AI technologies entered real-world environmental management, attracting greater academic interest. Notably, since 2022, research on AI’s environmental effects has surged, highlighting its critical role in achieving environmental sustainability goals.



Note: The data was conducted on July 30, 2025.
Figure 1. Publication trends of the environmental effects of AI research from 2015 to 2025

Collaboration Network Analysis
Using CiteSpace software, collaboration networks among key research countries, institutions, and authors were mapped based on the constructed literature database (see Figure 2 to Figure 5). In these maps, nodes represent countries, institutions, or authors, and the size of the nodes corresponds to the number of publications from each country, institution, or author, with larger nodes indicating higher publication volume. The lines connecting the nodes represent collaborative relationships between the countries, institutions, or authors. The color of the lines reflects the time when the collaboration was established, with colors transitioning from blue to red to represent earlier to more recent periods.

National Collaboration Network
Figure 2 shows the national collaboration network, which identifies 95 nodes and 123 collaboration links. The network density is 0.0275, indicating that while the overall collaboration relationships are relatively sparse, a distinct collaboration network has formed between the core countries. Table 1 presents the top ten countries by publication volume in the field of AI's environmental effects from 2015 to 2025, with China leading with 276 articles, followed by the United States with 92 articles. As major AI research and development nations and key players in global environmental governance, both China and the United States place significant emphasis on AI's environmental effects.

It is evident that China holds a dominant position in this field, not only with the highest number of publications but also showing a significant increase in activity in recent years (2023-2025). However, its betweenness centrality (0.10) suggests that while China is highly productive, its role as a "bridge" connecting other countries is limited, primarily conducting self-led research. In contrast, although England has a relatively lower publication volume (77 articles), its centrality is as high as 0.27, with the highest degree (45), indicating a broader international collaboration network and playing a key role as a central hub in the network. Saudi Arabia (with a betweenness centrality of 0.18 and a degree of 37) follows closely, showing strong intermediary capabilities in the network.

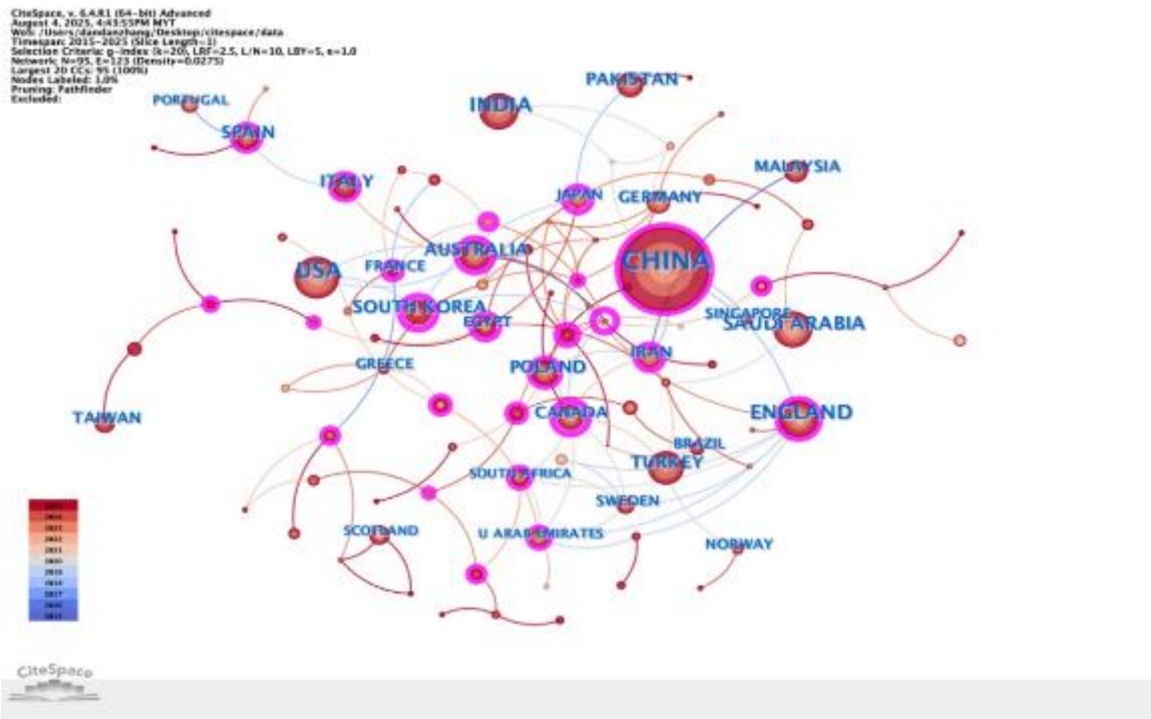


Figure 2. A visualization of the country collaboration network

Table 1
Top 10 Countries Based on Frequency

No.	Country	Frequency	Degree	Centrality	The starting Year
1	CHINA	276	33	0.1	2018
2	USA	92	34	0.08	2016
3	ENGLAND	77	45	0.27	2018
4	INDIA	74	33	0.1	2015
5	SAUDI ARABIA	63	37	0.18	2019
6	TURKEY	46	27	0.05	2019
7	AUSTRALIA	44	33	0.1	2016
8	ITALY	42	17	0.05	2018
9	SOUTH KOREA	40	27	0.08	2015
10	POLAND	40	19	0.09	2016

The international research collaboration in this field exhibits a multi-center network structure, with a peak in collaboration activity occurring after 2019, highlighting the growing global attention to this research topic and the strengthening of international cooperation in recent years.

Institution Collaboration Network

In the institution collaboration network, a total of 239 nodes and 261 collaboration links were identified, with a network density of 0.0092. The overall level of collaboration is relatively low, but several core collaborative groups have formed relatively stable and dense cooperation structures, which constitute the main body of the network. These include the

Middle East and North Africa collaboration cluster centered around the Egyptian Knowledge Bank, the Chinese academic research network represented by the Chinese Academy of Sciences and Tsinghua University, and the European collaboration network led by CNRS (see Figure 3).

In terms of publication volume (see

Table **2**), the Egyptian Knowledge Bank (EKB) has been particularly active in this field since 2021, with 20 publications, making it one of the most active and influential research institutions. The Chinese Academy of Sciences, with 17 publications, ranks second. Hong Kong Polytechnic University and Tsinghua University have been active in this research field since 2018, playing an important role in the research. Additionally, research institutions from Nordic and Middle Eastern regions have increasingly participated in recent years, reflecting the expanding geographical scope of research in this field.

In terms of collaboration time evolution, most institutions became active after 2021, with a significant number of red and orange nodes, indicating that international collaboration in this field has become increasingly close in recent years.

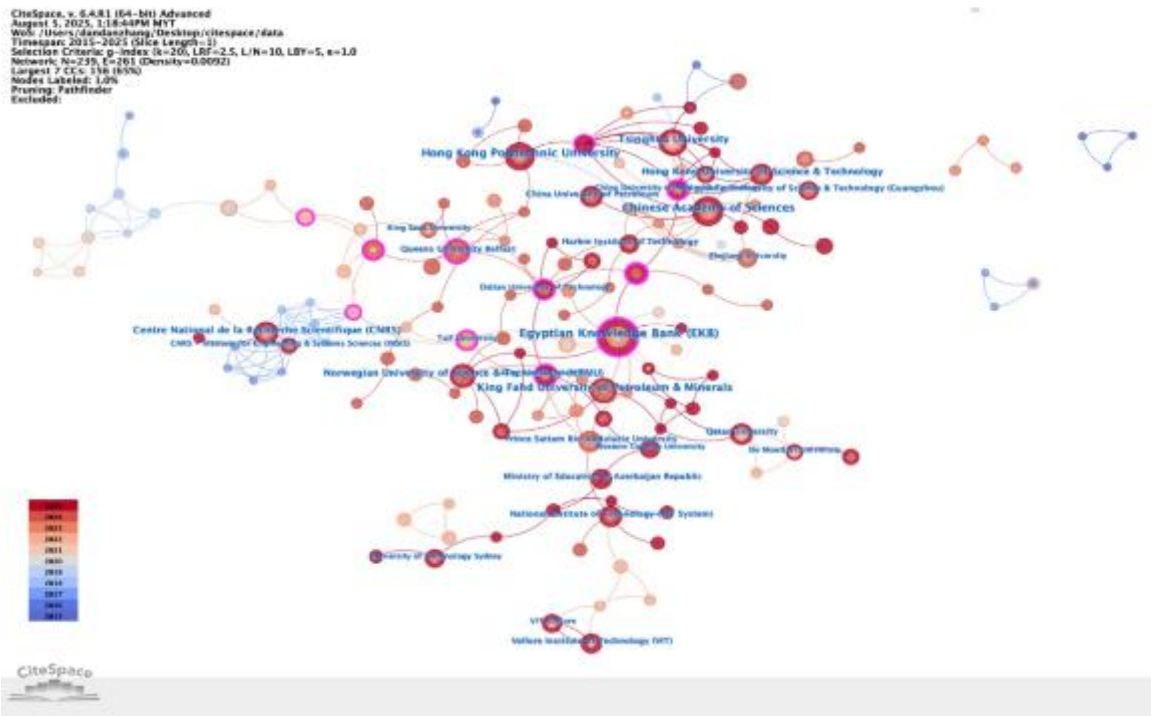


Figure 3. A visualization of the institution collaboration network

Table 2
Top 10 Institutions Based on Frequency

No.	Institution	Country	Frequency	The Starting Year
1	Egyptian Knowledge Bank (EKB)	Egypt	20	2021
2	Chinese Academy of Sciences	China	17	2020
3	Hong Kong Polytechnic University	China	15	2018
4	Tsinghua University	China	14	2018
5	King Fahd University of Petroleum & Minerals	Saudi Arabia	13	2022
6	Centre National de la Recherche Scientifique (CNRS)	French	12	2017
7	Norwegian University of Science & Technology (NTNU)	Norway	10	2024
7	Hong Kong University of Science & Technology	China	10	2022
9	Ministry of Education of Azerbaijan Republic	Azerbaijan	9	2024
10	Queens University Belfast	United Kingdom	8	2023
10	Qatar University	Qatar	8	2021
10	Prince Sattam Bin Abdulaziz University	Saudi Arabia	8	2023
10	National Institute of Technology (NIT System)	Japan	8	2022
10	China University of Petroleum	China	8	2023

Author Collaboration Network
The author collaboration network reveals the current academic collaboration patterns and key research groups. Figure 4 displays the top five author collaboration clusters, with 458 nodes and 747 collaboration links identified. The network density is relatively low (0.0071), and the entire network consists of several smaller author clusters, with core authors concentrated in specific areas. Research teams represented by Bensaali, Faycal; Himeur, Yassine; and Amira, Abbes have formed a relatively tight-knit collaboration, with larger nodes and dense links, and have been particularly active in recent years. This team focuses on the application of AI in energy management and environmental sensing, and has become an important force in this field.

The field is still in a relatively loose collaborative stage, with cooperation among researchers not yet forming a large-scale integrated structure. This may be due to differences in academic backgrounds, research interests, and disciplinary areas. In the future, increasing the frequency of cross-group collaboration and enhancing network connectivity will help further promote the development of AI technologies in environmental effect research.

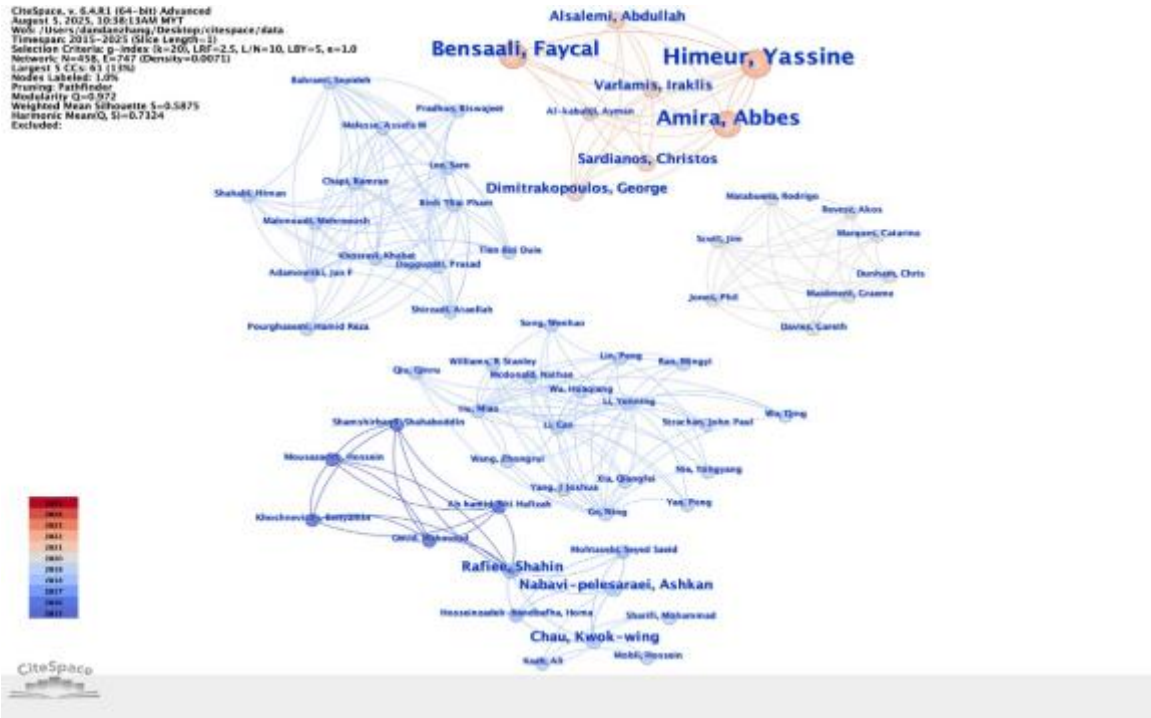


Figure 4. A visualization of the author collaboration network

Research Hotspots and Evolution Trends

This study first employed VOSviewer to perform keyword co-occurrence analysis, identifying high-frequency research terms and their associations, and providing an initial categorization of research themes. Then, using CiteSpace's clustering algorithm, we grouped keywords semantically to clarify the thematic structure and temporal evolution of research hotspots, allowing for a systematic analysis of AI's environmental effects and the identification of evolution trends.

Hotspot Analysis

Using VOSviewer software, a standardization process was applied to the terms from 930 articles. After merging some synonyms, the top ten high-frequency keywords were identified (see

Table **3**), which help to preliminarily identify the core concepts and research focuses in this field. In addition to the theme keyword "artificial intelligence," the top ten keywords are "energy efficiency," "machine learning," "sustainability," "deep learning," "carbon emissions," "renewable energy," "internet of things," "optimization," and "energy consumption." Among these, "energy efficiency" has the highest frequency (161) and total link strength (200), reflecting that the primary focus of research in this field is on how AI can optimize energy efficiency management and energy structures.

Table 3
Top 10 Keyword Based on Occurrences

No.	keyword	Occurrences	Total Link Strength
1	artificial intelligence	422	504
2	energy efficiency	161	200
3	machine learning	133	186
4	sustainability	101	188
5	deep learning	52	88
6	carbon emissions	40	51
7	renewable energy	40	62
8	internet of things	33	63
9	optimization	32	51
10	energy consumption	28	46

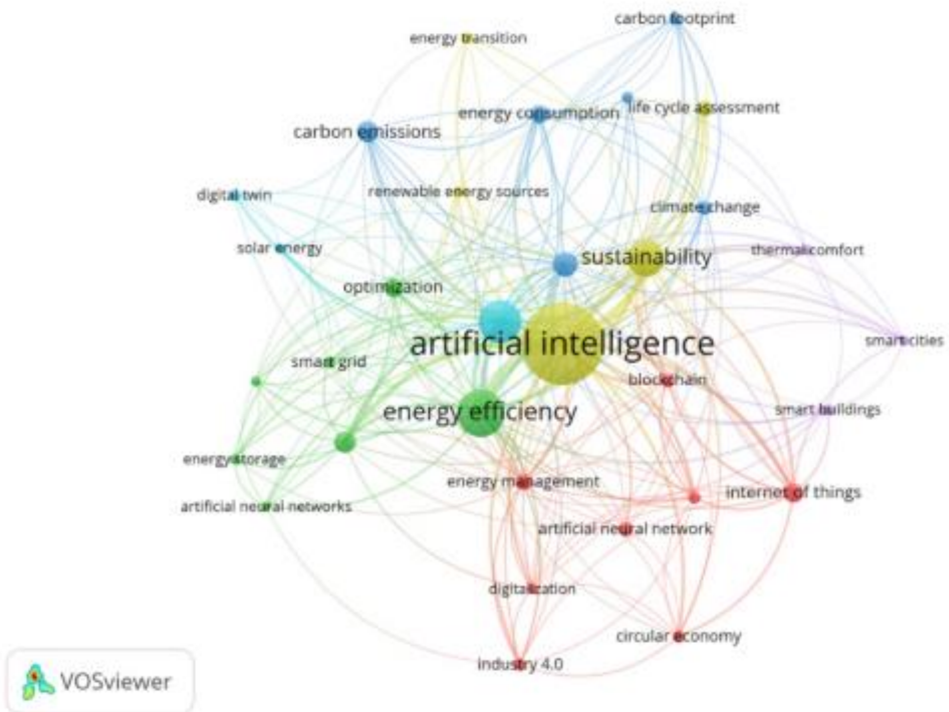


Figure 5. Network visualization for themes

After performing co-occurrence analysis of the relevant high-frequency keywords, this study used VOSviewer to generate a keyword co-occurrence network map (see Figure 5), which provides an initial reflection of the research theme structure and hotspot distribution of AI in the environmental field from 2015 to 2025. Six clusters were identified, each representing a distinct thematic direction in the current research.

Cluster 1 (Red) includes keywords such as “artificial neural network”, “big data”, “internet of things”, “blockchain”, “circular economy”, “digitalization”, “energy management”, and “industry 4.0”, focusing on emerging intelligent technologies like blockchain, big data, and IoT, and exploring their applications in energy management and the circular economy. Cluster 2 (Green) focuses on AI applications in energy system optimization, with keywords including “artificial neural network”, “demand response”, “energy efficiency”, “energy storage”, “optimization”, “renewable energy”, and “smart grid”. Cluster 3 (Blue) covers keywords such as “carbon emissions”, “carbon footprint”, and “climate change”, highlighting the application trends of AI methods such as “deep learning” and “neural networks” in carbon neutrality goals and climate change responses. Cluster 4 (Yellow) is represented by keywords like “sustainability,” “life cycle assessment”, and “energy transition”, emphasizing the role of AI in energy transitions and sustainable development strategies. Cluster 5 (Purple) includes keywords such as “smart buildings”, “smart cities”, and “thermal comfort”, focusing primarily on smart buildings and smart city research. Cluster 6 (Cyan) includes keywords “digital twin” and “solar energy”, focusing on the clean energy sector.

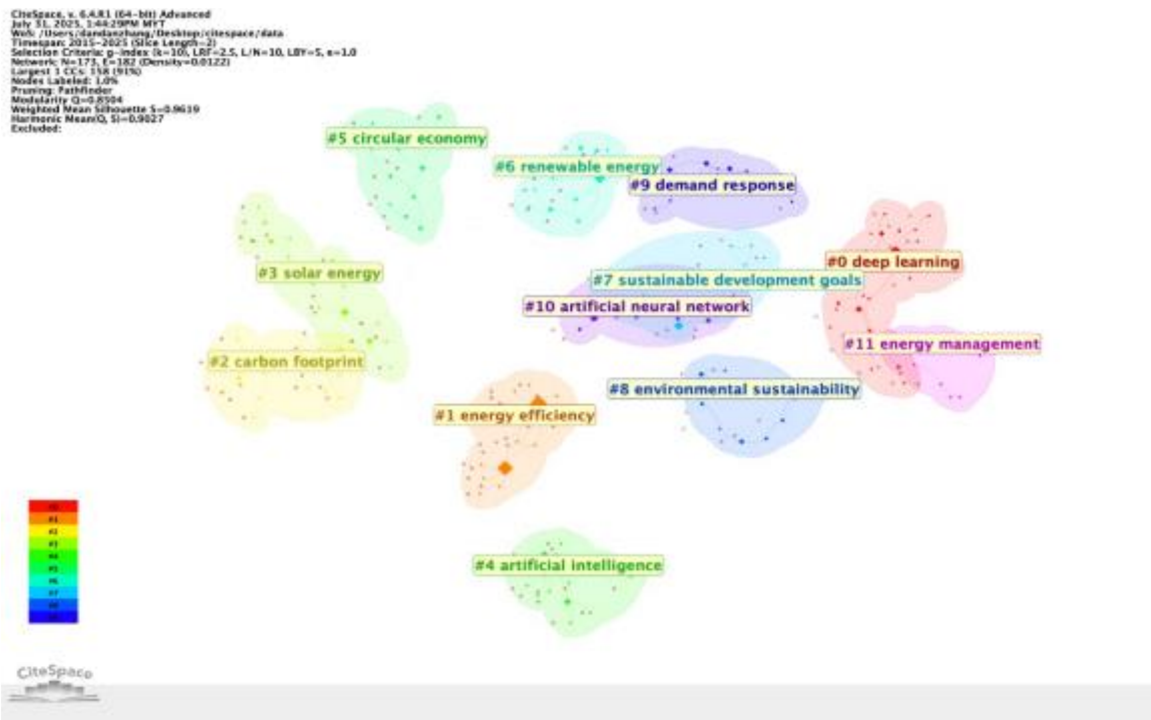


Figure 6. Cluster view of keywords
After performing a co-citation clustering analysis of literature on AI’s environmental effects from 2015 to 2025 using CiteSpace, 12 clustering modules were identified, as shown in Figure 6. The overall network structure is clear, and the module divisions are reasonable. The Modularity Q value is 0.8504, indicating a well-distinguished clustering structure; the average silhouette coefficient is 0.9619, demonstrating high internal consistency within the clusters and strong explanatory power of the clustering results.

As seen in Figure 6, the current clustering of keywords related to AI's environmental effects forms 11 categories. Combining this with the initial clustering results discussed earlier, this study divides the research hotspots in this field into the following three categories:
The application of core AI technologies. Clusters such as "#0 deep learning", "#4 artificial intelligence", and "#10 artificial neural network" form the technological foundation of the research. Deep learning and neural networks, as core AI technologies, are being widely applied across multiple subfields of the environment.

AI applications in energy and carbon management. Keywords like "#1 energy efficiency", "#2 carbon footprint", and "#11 energy management" highlight the growing importance of AI in optimizing energy efficiency and controlling carbon emissions. Research is increasingly focusing on practical applications in industrial systems, building energy management, and smart grids.

AI applications in sustainability and green development, approached from a broader, macro perspective. This includes five clusters: "#5 circular economy", "#7 sustainable development goals", "#8 environmental sustainability", "#6 renewable energy", and "#3 solar energy".

Evolution Trend Analysis
Figure 7 presents a timeline visualization of AI's environmental effect research, offering an intuitive view of the research themes for each year.

Table **4** lists 18 emerging keywords in AI's environmental effect research, reflecting the evolution of research hotspots and shifts in focus. Between 2015 and 2025, big data, climate change, smart grid, and energy storage were the four keywords with the highest burst intensity. Combining the two charts and categorizing them by theme and time, this study divides the evolution of research into three stages.

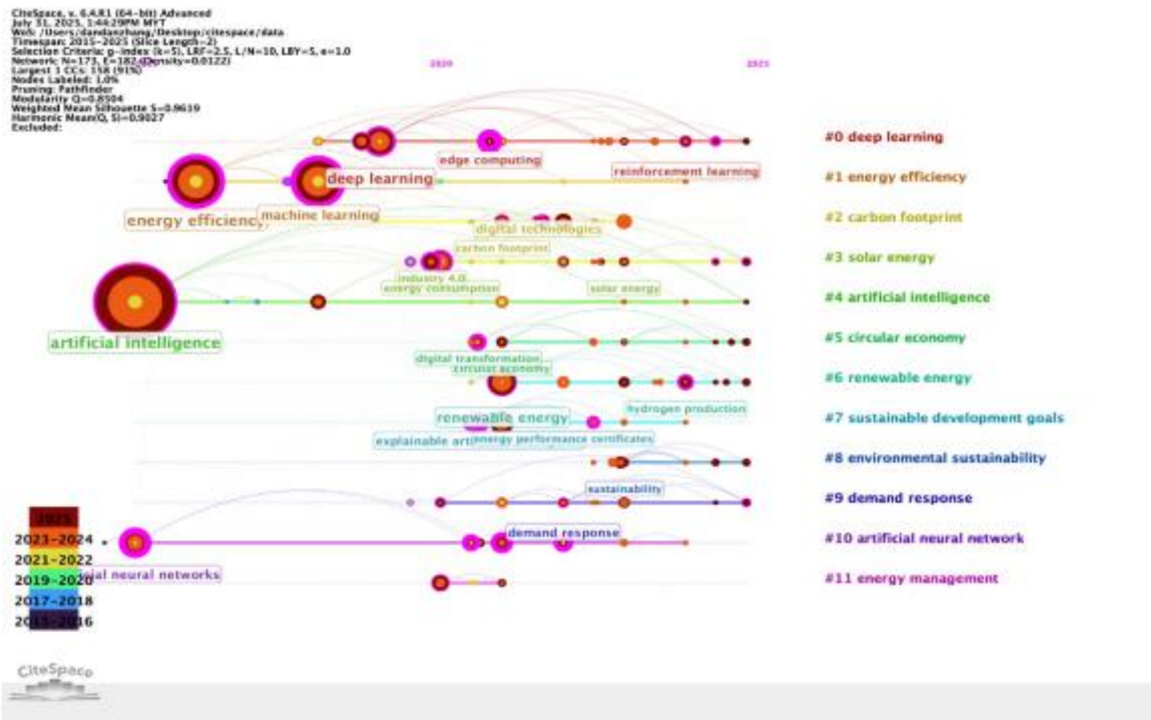


Figure 7. Timeline view of keywords

Table 4

Top 18 Keywords with the Strongest Citation Bursts

Keyword	Year	Strength	Begin	End	2015-2025
artificial neural networks	2015	1.35	2015	2018	
big data	2018	4.76	2018	2022	
wind turbines	2019	1.28	2019	2020	
neural nets	2019	1.28	2019	2020	
particle swarm optimization	2019	1.28	2019	2020	
wind speed	2019	1.28	2019	2020	
asset management	2019	1.28	2019	2020	
solar thermal collector	2019	1.28	2019	2020	
smart grid	2021	3.22	2021	2024	
energy storage	2022	2.28	2022	2024	
thermal comfort	2021	1.72	2021	2022	
energy saving	2021	1.5	2021	2022	
transfer learning	2021	1.5	2021	2022	

smart energy	2021	1.5	2021	2022	
smart building	2021	1.5	2021	2022	
decision support systems	2021	1.5	2021	2022	
in-memory computing	2021	1.5	2021	2022	
climate change	2023	3.73	2023	2025	

The first stage (2015-2018) was an exploratory phase focused on the application of technologies. Scholars primarily discussed the development of AI and its early applications in environmental fields. The number of related studies was relatively small, and the distribution of literature was sparse, with interdisciplinary applications of AI in the environmental sector not yet forming a broad research network. During this period, research was still at a foundational stage, with fewer keywords and relatively low intensity. Large-scale cross-disciplinary research had not yet emerged. Keywords such as “artificial neural networks” appeared as early as 2015, becoming one of the earliest research hotspots. The focus was mainly on the application of machine learning methods, such as artificial neural networks, in specific and localized problems like building energy consumption prediction and optimization, and carbon emissions assessment (Paudel et al., 2017; Wang & Srinivasan, 2017; Nabavi-Pelesaraei et al., 2018). These early applications of AI in environmental research mainly targeted small-scale scenarios and had not yet formed a systematic, interdisciplinary framework. During this stage, the academic community focused more on the establishment of AI’s foundational theories and methods and its preliminary applications in specific fields, laying the groundwork for future interdisciplinary research.

The second stage (2019-2022) was a phase of diverse exploration, with research topics becoming increasingly diversified, particularly in energy efficiency optimization, carbon management, and sustainable development. The emergence of numerous new keywords during this period reflected the multidimensional exploration in the field. Between 2019 and 2020, keywords like “wind turbines”, “wind speed”, “solar thermal collector”, and “particle swarm optimization” emerged, with AI applications in renewable energy fields such as wind and solar energy gaining significant attention. AI was widely used to optimize wind energy efficiency, predict wind speed, and improve solar thermal energy collection efficiency (Brahimi, 2019; Bublitz et al., 2019; Sadeghi et al., 2020).

Between 2021 and 2022, more research hotspots emerged, focusing more on areas like smart energy and building energy efficiency. Keywords such as “smart grid”, “energy storage”, “smart energy”, and “energy saving” became more prominent, reflecting the increasing application of AI in smart grids and energy storage, especially in the optimization of energy prediction, scheduling, and storage. Al-Fattah & Aramco (2021) discussed the application of the AI GANNATS model in forecasting crude oil demand in Saudi Arabia and China, showcasing AI’s potential in energy management. Simultaneously, the appearance of keywords like “thermal comfort”, “smart building”, and “decision support systems” signaled growing attention to AI’s application in building energy efficiency and comfort regulation. AI was used to predict and optimize environmental parameters such as temperature and humidity within buildings, improving energy efficiency and comfort to meet the demands for environmental control in smart buildings (Halhoul Merabet et al., 2021).

Analyzing the keyword timeline (Figure 7), a large number of high-frequency keywords appeared during this phase, with “energy efficiency”, “carbon footprint”, and “energy consumption” emerging as core themes. The focus shifted to addressing practical issues, particularly how AI could enhance energy efficiency and reduce carbon emissions. Ahmad et al.(2021) emphasized that AI, through intelligent energy management systems, can improve energy production, distribution, and consumption, helping businesses and governments reduce their carbon footprints and increase sustainability. Farahzadi & Kioumarsi (2023) found that machine learning applications in building energy efficiency not only improved energy use but also successfully reduced carbon emissions, providing technological support for achieving environmental sustainability goals.

Research during the second stage gradually transitioned from theoretical exploration to practical application, focusing on real environmental benefits and solutions. AI technologies were further developed in energy systems, carbon emission control, building energy efficiency, and sustainable development, providing new technological pathways and solutions for achieving global environmental sustainability goals.

The third stage (2023-2025) is characterized by an explosive growth phase, particularly in addressing global climate change issues, where AI’s application has become a core research theme. The keyword “climate change” persisted with high strength (3.73) through to 2025, becoming a central topic across multiple research directions. As the climate change issue continued to worsen, AI was recognized as a potential solution to address climate change problems(Chen et al., 2023)

At this stage, with the continuous maturation of AI technology, research focus gradually shifted toward more complex and advanced technical methods and practical applications. Keywords such as “deep learning”, “reinforcement learning”, “edge computing,” and “explainable AI” have emerged, with AI technology achieving deep development in both algorithms and applications, particularly in handling large-scale data, optimizing decision-making processes, and enhancing algorithm transparency. Advanced algorithms like deep learning and reinforcement learning, which have developed in recent years, have shown great potential across multiple fields, especially in applications related to optimizing energy systems, intelligent decision support, and complex environmental governance (Hussein et al., 2025). Meanwhile, the research on “explainable AI” has gained widespread attention, which not only improves the transparency of AI decision-making processes but also enhances users' and decision-makers' trust in AI systems, especially in complex environmental management and climate policy formulation, where understanding the rationale behind AI’s decisions is crucial (Leuthe et al., 2024).

As technological breakthroughs continue, AI’s application areas have further expanded to new emerging topics, especially in renewable energy scheduling, carbon market monitoring, and environmental governance. AI is beginning to play a pivotal role in these areas. In carbon emissions monitoring and carbon market management, AI’s capabilities in big data analysis and pattern recognition allow for real-time predictions of carbon emissions trends, optimizing carbon trading mechanisms, and supporting countries in formulating flexible and forward-looking climate policies (Chen et al., 2023; Tao et al., 2023; Hua et al., 2025). Furthermore, keywords such as “sustainability” and “digital transformation” have gained prominence, highlighting AI's vital role not only in optimizing energy systems but also in driving digital transformation and sustainability across various sectors. In this phase, AI has been widely applied to promote green transformation in enterprises and achieve sustainable development goals, such as optimizing supply chain management, reducing energy consumption, and lowering carbon footprints (Ali et al., 2025; Zhang et al., 2025).

As new algorithms continue to emerge, the research in this third phase not only focuses on optimizing energy production and consumption but also delves into cutting-edge areas such as carbon markets and environmental governance, providing innovative technological paths to achieve global climate change response goals and environmental sustainability.

Conclusion

Research Findings

Based on a bibliometric and visualization analysis of 930 papers on the environmental effects of AI in the Web of Science Core Database from 2015 to 2025, this study draws the following key conclusions:

Firstly, the collaboration network exhibits a multi-center structure. China is the leading country in terms of publication volume, while the United States and the United Kingdom play a significant bridging role within the international collaboration network due to their high intermediary centrality. At the institutional level, organizations such as the Egyptian Knowledge Bank, the Chinese Academy of Sciences, and Tsinghua University are among the top contributors. Despite increasing collaboration in recent years, the overall density of the network remains relatively low, suggesting ample room for international collaboration. On the author's level, the network structure remains loose, and there is still a need for enhanced communication and exchange among scholars.

Secondly, the volume of research has experienced rapid growth, with distinct stages of development. From 2015 to 2018, the research was in an exploratory phase, with slow growth and a focus on the preliminary application of core AI technologies, such as artificial neural networks, in specific scenarios. The period from 2019 to 2022 marked the stage of diversified exploration, with a notable increase in research topics, including smart grids, energy storage, building energy efficiency, renewable energy utilization, and carbon footprint assessment. The focus gradually shifted from theoretical exploration to practical applications, with increasing attention to environmental benefits and solutions. From 2023 to 2025, the field entered an explosive growth phase, with addressing climate change through AI becoming a central issue, alongside the application of advanced technologies such as deep reinforcement learning, explainable AI, and edge computing.

Thirdly, research hotspots center on three main areas. The first is the application of core AI technologies, including deep learning, machine learning, and artificial neural networks, which form the technical foundation of the research. The second focus is the impact of AI technologies on energy and carbon management, with ongoing emphasis on improving energy efficiency, controlling carbon emissions and footprints, and promoting renewable energy. Finally, the role of AI in sustainable development is a key focus, with topics such as sustainable development goals and environmental sustainability closely intertwined with AI applications.

Fourthly, the development of technologies and the scope of application are continuously expanding. New technologies, such as explainable AI and edge computing, are gaining attention, and the application areas are extending into emerging fields like smart cities, smart buildings, and clean energy.

Theoretical Contributions and Practical Implications

This study makes several theoretical contributions to the knowledge system of research on the environmental effects of artificial intelligence. First, it constructs a comprehensive research landscape based on a large-scale sample of literature and systematically outlines the knowledge structure of the field. By applying CiteSpace and VOSviewer to visualize 930 English-language publications from 2015 to 2025, this study maps the collaboration networks at the national, institutional, and author levels, and presents keyword clusters and temporal evolution patterns. These visualizations offer a clear perspective on the overall research landscape of the field. Second, this study identifies the knowledge evolution logic of AI-related environmental research. The findings show that research has progressed from improving energy efficiency and controlling carbon emissions to addressing broader sustainability goals, forming a complete technological chain. Moreover, the research focus has shifted from early single-purpose predictive models to system-level optimization and integrated governance, filling a gap in existing literature that has paid limited attention to technological evolution. Third, this study reveals the stage-based evolution of research hotspots and expands the theoretical boundaries of AI's environmental effects. We divide the development of the field into three phases—an exploratory period (2015–2018), a diversified expansion period (2019–2022), and a rapid growth period (2023–2025)—and identify emerging themes such as "climate change," "smart grid," "energy storage," and "explainable AI." These findings illustrate how research attention has gradually shifted from technical applications to broader sustainability concerns, offering valuable references for future interdisciplinary integration between AI and environmental research.

This study also provides practical implications for governments and enterprises. First, the findings offer data support and decision-making references for energy and carbon management policies. Governments and regulatory authorities can leverage AI models to build dynamic carbon emission monitoring systems, improve energy allocation efficiency, and achieve more precise environmental governance throughout the implementation of carbon neutrality and carbon peaking strategies. Additionally, the results demonstrate that AI offers direct benefits in enhancing resource utilization, reducing energy consumption, and lowering carbon footprints across various sectors, including smart buildings, intelligent manufacturing, and green supply chains. Enterprises may adopt AI technologies to promote digital and green transformation, thereby strengthening their sustainable competitiveness. Besides, the technological evolution trends identified in this study provide meaningful guidance for enterprises in selecting AI application directions and gaining advantages in green innovation.

Potential Challenges

While numerous studies demonstrate that AI has significant benefits in carbon emission control, energy efficiency optimization, and environmental sustainability, its development also entails environmental costs that cannot be overlooked. With the increasing computational demands of AI, its energy consumption and environmental footprint are rising. Several studies indicate that training modern machine learning models results in substantial carbon emissions (Strubell et al., 2020; Bouza et al., 2023), and data centers storing vast amounts of training data also require considerable energy and water for cooling (Bolón-Canedo et al., 2024). Moreover, while AI plays a crucial role in enhancing efficiency across various industries, a potential "rebound effect" may occur. That is, the efficiency gains driven by AI applications could stimulate additional energy demand, leading to an overall increase in resource consumption, thus negating the initial environmental benefits and hindering sustainable development (Mhlanga, 2025). Therefore, to maximize the environmental benefits of AI, scholars are emphasizing the integration of environmental considerations into AI practices, promoting concepts such as "green AI" and "sustainable AI," which aim to reduce the environmental footprint of AI and foster more eco-friendly, energy-efficient AI development (Bolón-Canedo et al., 2024).

The dual role of AI in the environment suggests that researchers and policymakers should address the sustainability of AI alongside its application. The balance between "AI for Sustainability" and "Sustainability of AI" has become a crucial issue in the current research field (Van Wynsberghe, 2021).

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