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TRENDS AND RESEARCH FRONTIER IN GREEN INDUSTRY SUSTAINABILITY

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Abstract:

The growing urgency of addressing climate change and achieving sustainable development has positioned the green industry as a critical driver of environmental, social, and economic transformation. However, despite increasing scholarly interest, there remains a need to systematically map the intellectual landscape and research frontiers in green industry sustainability. This study employs a bibliometric approach to provide a comprehensive overview of global research trends in this field. Data were collected using Scopus advanced searching with the keywords "green industries," "green manufacturing," and "sustainability," yielding a total of 836 publications. The dataset was refined and harmonized using OpenRefine, analyzed statistically with the Scopus analyzer, and visualized through VOSviewer to identify co-authorship networks, keyword co-occurrence, and citation structures. The results reveal a steady growth in publications over the last decade, indicating the rising significance of green industry sustainability in academic discourse. Highly cited works predominantly focus on sustainable manufacturing practices, policy frameworks, and the integration of advanced technologies such as blockchain and Industry 4.0 for sustainable supply chain management. The United States, China, and European countries emerge as leading contributors, with extensive international collaboration shaping the field's development. Keyword analysis highlights the dominance of terms such as "sustainability," "green manufacturing," and "circular economy," reflecting the evolving thematic clusters that define the research frontier. These findings underscore the centrality of innovation, policy, and collaboration in advancing sustainable industrial practices while pointing toward emerging directions for future research. Overall, this bibliometric analysis maps the current state of knowledge and provides insights to guide policymakers, scholars, as well as practitioners in accelerating the transition toward sustainable green industries.

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Keywords:

Green Industry, Sustainability, Green Manufacturing, Green Growth

Introduction

The concept of green industry sustainability has gained substantial attention in recent years, driven by the pressing need to address environmental challenges such as climate change, resource depletion, and pollution (Hao et al., 2021). The green industry aims to harmonize industrial development with environmental sustainability, ensuring that economic growth is achieved without compromising the health of the planet. This approach involves the efficient and effective use of resources, the reduction of carbon emissions and the adoption of eco-friendly practices across various sectors (Adamowicz, 2022). As global awareness of environmental issues continues to grow, industries face increasing pressure to adopt sustainable practices that reduce their environmental impact and strengthen their long-term viability and competitiveness. This paper explores the frontiers in green industry sustainability, examining the latest advancements, challenges and opportunities in this critical field.

The role of green finance and private sector investment in promoting industry sustainability has become a central focus of recent research. Studies indicate that green finance plays a crucial role in advancing sustainability by encouraging eco-friendly investments and reducing carbon emissions. For example, a 1% increase in green finance has been shown to result in a 0.31% improvement in sustainability (Miao et al., 2025). Conversely, private sector investments tend to prioritize short-term financial gains, which can adversely affect sustainability, as a 1% increase in such investments has been associated with a 0.36% decline in sustainability (Miao et al., 2025). This dichotomy highlights the need for policies that incentivize long-term sustainable investments over short-term gains.

Other than that, green practices across various industries have also been extensively studied, revealing their positive impact on both environmental and economic sustainability. Businesses are increasingly implementing green practices such as sustainable supply chain management, green product innovation, and eco-friendly waste management to minimize their environmental footprint and ensure regulatory compliance (Surbakti et al., 2025). These practices improve operational efficiency, reduce costs, enhance corporate reputation, and align with the United Nations Sustainable Development Goals (SDGs) (Surbakti et al., 2025). However, the implementation of these practices varies across sectors, with some industries facing significant challenges due to resource constraints and high initial investment costs (Lubaba et al., 2025).

Technological advancements play a crucial role in promoting green industry sustainability. The integration of digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI) and digital twins has been shown to enhance green manufacturing practices by optimizing energy efficiency, reducing waste and improving resource management (Mahadevan et al., 2025). These technologies enable real-time monitoring and data analysis, facilitating more informed decision-making and efficient operations. Nevertheless, the adoption of these technologies is often constrained by high implementation costs and the requirement for substantial infrastructure investments. (Mahadevan et al., 2025) .

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The transition to a green economy presents considerable challenges, especially for emerging economies. For instance, implementing green manufacturing in Bangladesh's food and beverage industry faces hurdles such as difficulties in integrating eco-friendly design concepts, the lack of efficient recycling facilities, and high initial investment costs (Lubaba et al., 2025). Addressing these challenges requires a strategic framework that includes providing financial support, improving access to resources and training and simplifying certification processes (Adhi et al., 2023). Additionally, cross-sector collaboration and supportive policies are essential to overcoming these barriers and promoting sustainable practices (Surbakti et al., 2025).

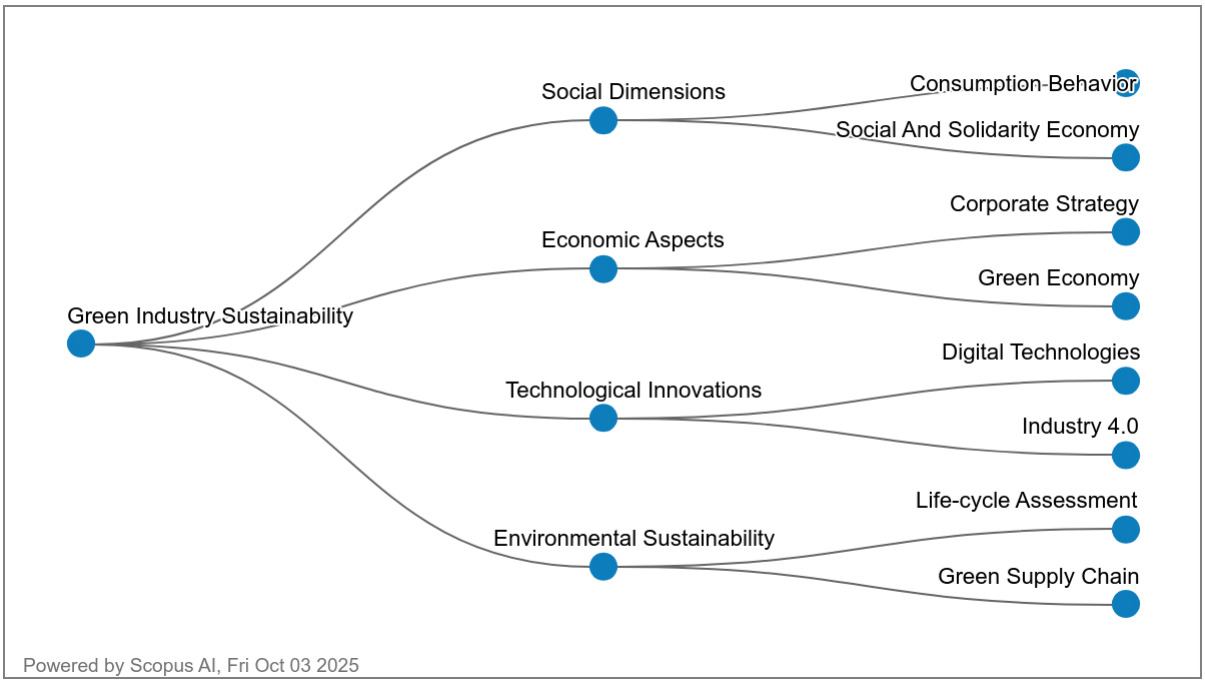

Figure 1: Green Industry Sustainability Concept Map

Figure 1 highlights the diverse yet interconnected research dimensions shaping the field of green industry sustainability. Four major clusters are identified: social dimensions, economic aspects, technological innovations and environmental sustainability. (1) Within the social sphere, studies emphasize the role of consumption behaviour and the social and solidarity economy in driving sustainable practices. (2) Economic perspectives focus on corporate strategies and the green economy, underscoring how market forces and policies can accelerate sustainability transitions. (3) Technological innovations, including digital technologies and Industry 4.0, are central to optimizing production processes and enabling smart, resource-efficient solutions. Meanwhile, (4) environmental sustainability research is grounded in life-cycle assessments and green supply chain management, reflecting the need to evaluate ecological impacts holistically. Together, these interconnected themes illustrate that advancing green industry sustainability requires a multidimensional approach that integrates social awareness, economic restructuring, technological advancement and environmental accountability. The frontier of research lies in bridging these domains to create synergies, enabling countries like Malaysia to leverage frameworks such as MADANI in fostering a more sustainable, inclusive and technologically advanced green industry.

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In conclusion, the frontier in green industry sustainability is marked by significant advancements in green finance, technological innovations and the adoption of sustainable practices across various sectors. However, challenges such as high implementation costs, limited resources, and the need for supportive policies must be addressed to fully unlock the potential of green industry sustainability. By promoting collaboration among industries, governments, and research institutions, and by harnessing technological advancements, a more sustainable and resilient future can be achieved.

Research Questions (5)

RQ1: How have publication trends in green industry sustainability developed over time?
RQ2: What are the ten most cited articles in this field?
RQ3: Which countries contribute the most publications on green industry sustainability?
RQ4: What are the most frequent keywords in related studies?
RQ5: How are countries connected through co-authorship collaborations?

Methodology

Bibliometrics is a powerful research tool that systematically collects, organizes and analyzes bibliographic data from scientific publications (Alves et al., 2021; Assyakur & Rosa, 2022; Verbeek et al., 2002). While it often begins with descriptive statistics such as identifying core journals, publication years and prolific authors (Wu & Wu, 2017), the true strength of bibliometrics lies in its advanced techniques, including document co-citation and network analysis, which uncover intellectual structures and research frontiers within a field. A rigorous literature review, therefore, requires a careful and iterative process that includes selecting precise keywords, conducting comprehensive searches, and applying thorough analytical procedures. Such an approach ensures the development of a reliable and well-structured bibliography and enhances the credibility of findings (Fahimnia et al., 2015). In line with this, the present research emphasizes high-impact publications, since they offer critical insights into the theoretical foundations shaping the discourse on sustainability. To maintain data accuracy and scholarly rigor, Scopus was selected as the primary database due to its extensive coverage and reliability (Al-Khoury et al., 2022; di Stefano et al., 2010; Khiste & Paithankar, 2017). Moreover, only peer-reviewed journal articles were incorporated, whereas lecture notes, books, and non-refereed sources were excluded to ensure methodological consistency and quality (Gu et al., 2019). In addition, publications spanning the period from 2020 to October 2025 were collected from Elsevier's Scopus database for analysis.

Data Search Strategy

This study employed the Scopus database as the primary source of bibliometric data because of its broad coverage of peer-reviewed journals and its reliability in citation analysis. Using the advanced search function, as per Table 1 the query *(TITLE-ABS-KEY ("green industr" OR "green manufacturing") AND TITLE-ABS-KEY ("sustainab*")) AND PUBYEAR > 2019 AND PUBYEAR < 2026 AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "SOCI")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar"))**, was applied to capture literature on the intersection of green industry, green manufacturing and sustainability. Truncation symbols ensured that variations, such as industries and sustainable development, were included, while the timeframe (2020–2025) reflected recent and emerging research aligned with global sustainability agendas. Table 2 presents clear screening criteria that were employed, limiting the dataset to English-language journal articles and excluding conference papers, books,

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reviews and non-English publications to maintain consistency and quality. Subject areas were restricted to Environmental Science, Energy and Social Sciences, given their relevance to sustainability. After applying these parameters, a total of 836 journal articles were retrieved (access date: October 2025), providing a comprehensive yet focused dataset suitable for bibliometric mapping of research clusters, leading authors and knowledge structures in green industry sustainability.

Table 1: The Search String

Scopus	**(TITLE-ABS-KEY ("green industr*" OR "green manufacturing") AND TITLE-ABS-KEY ("sustainab*")) AND PUBYEAR > 2019 AND PUBYEAR < 2027 AND (LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "SOCI")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar"))** **Access date: October 2025**

Table 2: Inclusion and Exclusion Criteria for Literature Selection

Criterion	Inclusion	Exclusion
Language	**English**	**Non-English**
Time line	**2020 – 2025**	**< 2020**
Literature type	**Journal (Article)**	**Conference, Book, Review**
Subject area	**Environmental science, Energy, Social Sciences**	**Other than Environmental Science, Energy, and Social Sciences**

Data Analysis

VOSviewer is a widely recognized bibliometric software established by Nees Jan van Eck and Ludo Waltman at Leiden University, Netherlands (van Eck & Waltman, 2010a, 2017). Known for its intuitive design and robust analytical capabilities, it has become a standard tool for visualizing and analyzing patterns in scientific literature. Moreover, the software is particularly effective in generating network visualizations, clustering related items and producing density maps that allow researchers to identify and interpret intellectual structures within a field. Its versatility extends to analyzing co-authorship, co-citation and keyword co-occurrence networks, offering a comprehensive understanding of research landscapes. With a continuously updated interface, customizable visualization options and compatibility across multiple bibliometric data sources, VOSviewer provides both novice and experienced scholars with a reliable and dynamic platform for bibliometric exploration.

A major strength of VOSviewer lies in its capacity to transform large and complex bibliometric datasets into clear, visually interpretable charts and maps. By emphasizing network visualization, it enables the detection of keyword co-occurrence patterns, the clustering of

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related themes and the mapping of knowledge domains. In this study, bibliometric datasets containing publication years, titles, author names, citations, journals, and keywords were exported in PlainText format from the Scopus database, covering the period from 2020 to October 2025. Correspondingly, these datasets were assessed utilizing VOSviewer version 1.6.20, which applies clustering and mapping techniques to establish knowledge maps. Unlike traditional Multidimensional Scaling (MDS), which calculates similarity metrics such as cosine and Jaccard indices, VOSviewer adopts a appropriate suitable normalization approach utilizing Association Strength (AS_{ij}) to ensure that the spatial distance between items precisely demonstrates their degree of relatedness (van Eck & Waltman, 2010b), (Appio et al., 2014), (Van Eck & Waltman, 2007a). This methodological rigor reinforces VOSviewer's position as a powerful and indispensable tool for advancing bibliometric research.

$$AS_{ij} = \frac{C_{ij}}{w_i w_j}.$$

This measure is defined as "proportional to the ratio between, on the one hand, the observed number of co-occurrences of i and j and on the other hand, the expected number of co-occurrences of i and j under the assumption that their co-occurrences are statistically independent" (Van Eck & Waltman, 2007b).

Findings and Discussion

Publication Trend

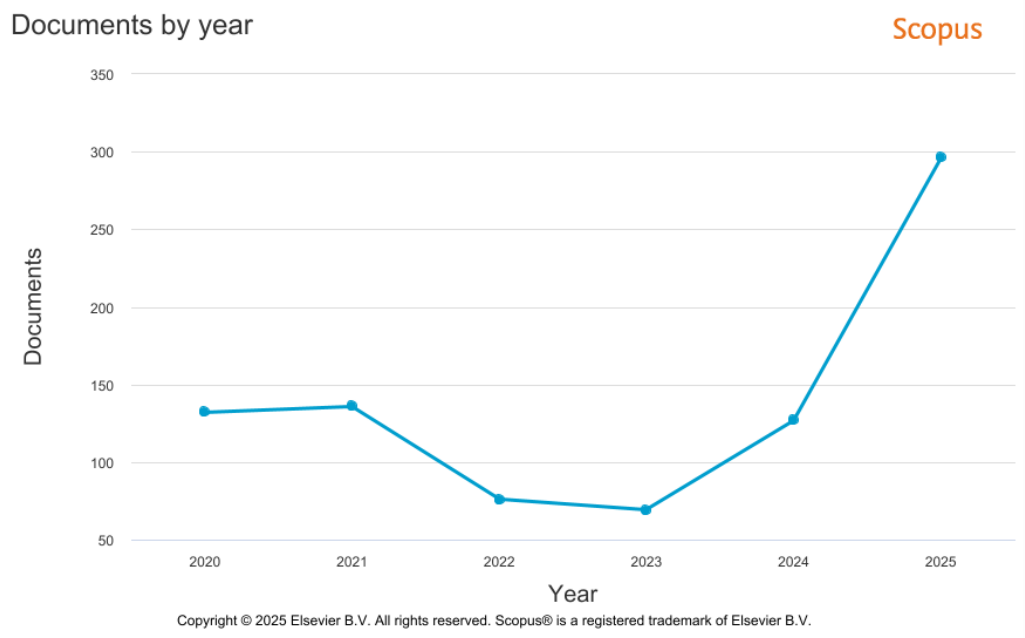

Figure 2: Number Of Documents Based on the Year of Publication

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Figure 2 illustrates the publication trend from 2020 to 2025, demonstrating a dynamic yet steadily increasing scholarly interest in green industry sustainability. In the early years, 2020 (132 documents) and 2021 (136 documents) show a relatively stable output, reflecting the initial consolidation of sustainability-related research within industrial and environmental studies. However, a dip is observed in 2022 with only 76 publications, possibly due to shifting academic priorities and research disruptions during the height of the COVID-19 pandemic, which redirected global research attention toward public health and economic recovery. A gradual rebound occurs in 2023 (69 documents), indicating that while research in this field persisted, it remained comparatively limited as global economies were still adapting to post-pandemic transitions.

A significant surge is evident from 2024 (127 documents) to 2025 (296 documents), highlighting a renewed momentum and heightened focus on sustainability in green industries. This sharp increase can be attributed to several factors: the global push for achieving climate commitments under the Paris Agreement, stronger policy frameworks such as the EU Green Deal and national sustainability agendas and the rising influence of circular economy and clean technology discourses. In Malaysia and similar developing economies, frameworks like MADANI further underscore the growing alignment between national policies and global sustainability trends, fueling academic attention. Moreover, the sharp increase in 2025 suggests not only a growing urgency around decarbonization and sustainable industrial transformation but also reflects advancements in funding opportunities, international collaborations and technological innovations that have made sustainability-oriented research more prominent and publishable. Overall, the data confirms that green industry sustainability has moved from being a niche academic concern to a mainstream, urgent research frontier.

Analysis of Most Cited Authors

Table 3: Most cited article

No	Authors	Title	Year	Source title	Cited by
1	(Esmaeilian et al., 2020)	Blockchain for the future of sustainable supply chain management in Industry 4.0	2020	Resources, Conservation and Recycling	705
2	(Cai et al., 2020)	Can direct environmental regulation promote green technology innovation in heavily polluting industries? Evidence from Chinese listed companies	2020	Science of the Total Environment	582
3	(Bag et al., 2021)	Key resources for Industry 4.0 adoption and its effect on sustainable production and circular economy: An empirical study	2021	Journal of Cleaner Production	347
4	(Yusliza et al., 2020)	A structural model of the impact of green intellectual capital on sustainable performance	2020	Journal of Cleaner Production	330

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5	(Raihan et al., 2022)	Nexus between carbon emissions, economic growth, renewable energy use, urbanization, industrialization, technological innovation and forest area towards achieving environmental sustainability in Bangladesh	2022	Energy and Climate Change	240
6	(Meng et al., 2021)	Pricing policies of dual-channel green supply chain: Considering government subsidies and consumers' dual preferences	2021	Sustainable Production and Consumption	240
7	(Amankwah-Amoah, 2020)	Stepping up and stepping out of COVID-19: New challenges for environmental sustainability policies in the global airline industry	2020	Journal of Cleaner Production	229
8	(Zahoor et al., 2022)	Clean energy investment and financial development as determinants of environment and sustainable economic growth: evidence from China	2022	Environmental Science and Pollution Research	213
9	(Khan et al., 2023)	Green capabilities, green purchasing and triple bottom line performance: Leading toward environmental sustainability	2023	Business Strategy and the Environment	204
10	(Appolloni et al., 2022)	Green recovery in the mature manufacturing industry: The role of the green-circular premium and sustainability certification in innovative efforts	2022	Ecological Economics	185

Table 3 indicates the citation analysis highlights how highly cited works in green industry sustainability are driven by the intersection of technological innovation, policy and sustainable business practices. The most influential paper (Esmaeilian et al., 2020), with 705 citations, explores blockchain's role in sustainable supply chains under Industry 4.0, reflecting the research community's strong interest in digital transformation for sustainability. Similarly, Cai et al. (2020), with 582 citations, underscore the importance of environmental regulation in fostering green innovation in heavily polluting industries, particularly in the Chinese context, where rapid industrialization has necessitated regulatory interventions. Other notable contributions, such as (Bag et al., 2021) and (Yusliza et al., 2020), both emphasized organizational as well as intellectual resources as drivers of the circular economy and sustainable performance. It shows how firm-level capabilities complement policy and technology in advancing sustainability goals.

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The subsequent cluster of works from 2021 to 2023 demonstrates a shift toward applied and contextual studies, often focusing on emerging economies. Raihan et al., (2022) and Zahoor et al., (2022) investigated sustainability linkages in Bangladesh and China, respectively, revealing the role of renewable energy, financial development and urbanization in shaping green growth trajectories. Likewise, (Meng et al., 2021) highlighted government subsidies and consumer preferences as crucial levers for green supply chains, while (Khan et al., 2023) extended the discussion to green capabilities and triple bottom line performance. The diversity of topics from clean energy investment to green certification in manufacturing (Appolloni et al., 2022) reflects an expanding research frontier where sustainability is approached through environmental science, management, economics and innovation. Collectively, the results suggest that the most impactful studies integrate interdisciplinary approaches and respond to urgent global challenges, such as carbon emissions, industrial pollution and the post-COVID-19 recovery, explaining their rapid accumulation of citations and scholarly influence.

Top 10 Countries based on Publication

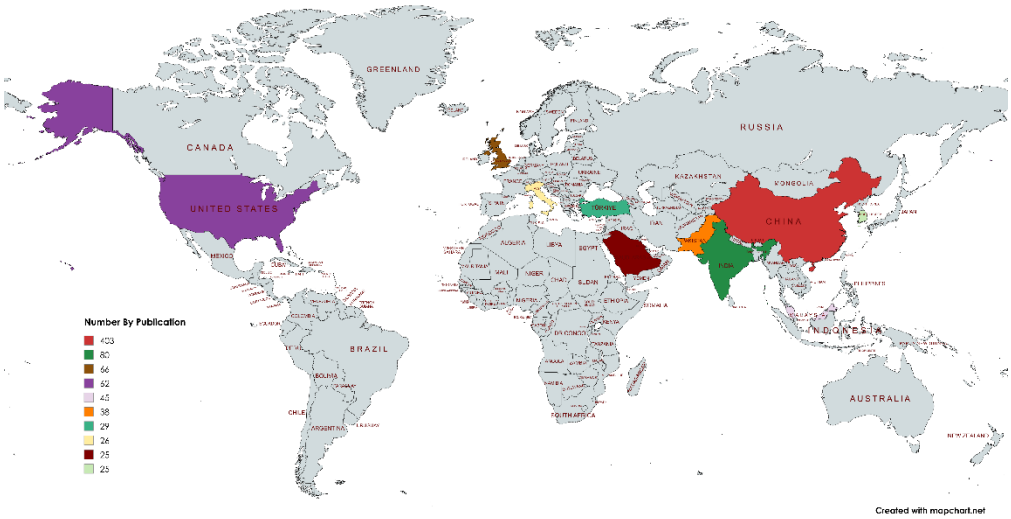

Figure 3: Top 10 Countries Based on the Number of Publications

Figure 3 illustrates the distribution of publications across countries and reveals clear regional disparities, with **China** dominating the field at 403 documents, far ahead of all other contributors. This overwhelming lead can be explained by China's rapid industrial growth, strong state-driven sustainability policies and substantial investment in renewable energy, circular economy initiatives and green manufacturing technologies. Countries like **India (80)** and the **United Kingdom (UK) (66)** follow at a considerable distance, reflecting their active engagement in sustainable industrial development. India's performance is likely tied to its dual focus on balancing industrialization with environmental management, while the UK's contribution can be attributed to its strong research infrastructure and policy frameworks aligned with the European Union's sustainability agenda (prior to Brexit) and subsequent national climate commitments. The **United States (62)**, while recognized as a global leader in research, shows comparatively lower output in this specific area, which may reflect its more fragmented approach to sustainability policy at the federal versus state levels.

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Among emerging economies, **Malaysia (45)**, **Pakistan (38)** and **Turkey (29)** demonstrated growing academic contributions, signaling increased regional attention to sustainable industrial transformation in the Global South. Malaysia's performance is particularly notable given its smaller research base compared to larger economies, reflecting government-driven initiatives such as the MADANI framework and green growth policies that have stimulated scholarly interest. Similarly, **Saudi Arabia (25)** and **South Korea (25)** highlighted distinct motivations: Saudi Arabia's diversification under *Vision 2030* and investments in renewable energy and South Korea's emphasis on high-tech, eco-friendly manufacturing. European representation, seen in **Italy (26)**, further underscored the integration of sustainability into industrial practices within EU policy frameworks. Collectively, the data suggest that while developed countries maintain strong academic infrastructures, the sharp rise in contributions from Asian economies reflects a shift in global research leadership. In this context, sustainability in green industries is increasingly prioritized in regions undergoing rapid industrialization and energy transition.

Popular Keywords Related to this Study

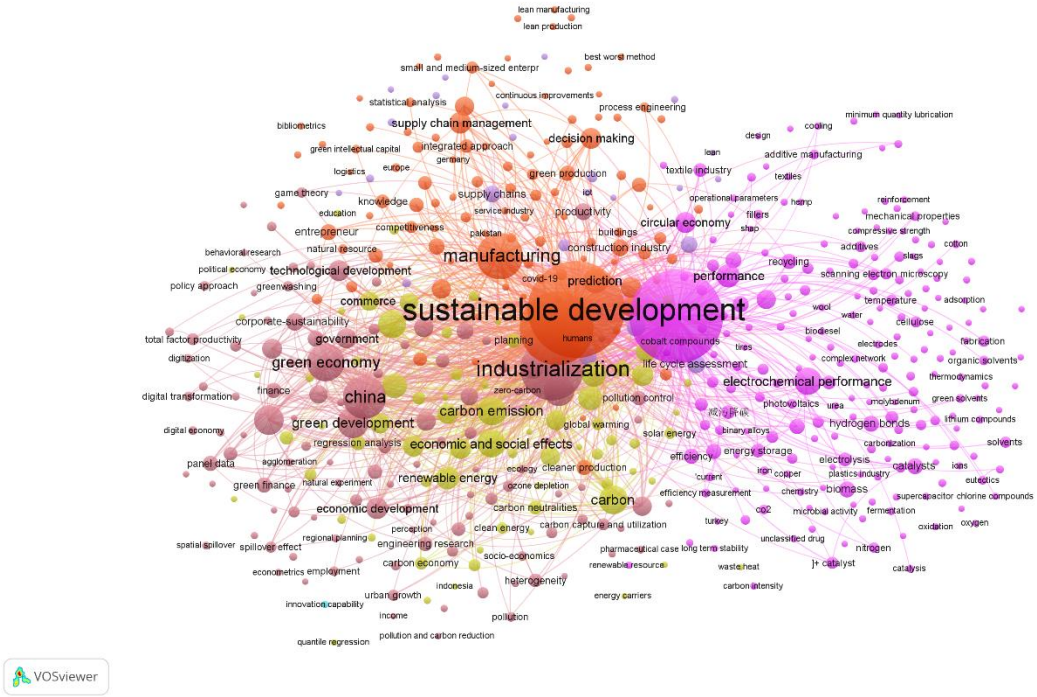

Figure 4: Network Visualization Map Regarding Keywords' Co-Occurrence

Figure 4 initiates the co-occurrence analysis of author keywords in VOSviewer, a bibliometric method that maps the relationships between frequently used keywords in academic publications, illustrating how research topics are conceptually connected. By analyzing how often keywords appear together across studies, this approach helps identify central themes, knowledge structures, and evolving trends within a research field. Here, the settings applied include the full counting method, where each occurrence of a keyword is fully considered. A minimum threshold of 5 occurrences out of a total of 4,517 keywords results in 538 meeting the criteria. With the minimum cluster size set at 5, the software generated six distinct clusters, each representing a thematic grouping of research focus areas, such as sustainable

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development, green manufacturing, environmental protection, industrialization, and the role of China in green economic transformation.

The results contribute to the body of knowledge by highlighting sustainability-related concepts as dominant drivers in current scholarship. Keywords such as "sustainable development" and "green manufacturing" demonstrate high occurrence and link strength, reflecting their central role in bridging diverse themes like innovation, renewable energy, supply chain management, and environmental policy. The six clusters reveal an interdisciplinary structure, connecting economics, technology, and environmental sciences, and suggest that the discourse is moving towards integrated approaches to address climate change and industrial transformation. This co-occurrence analysis maps the intellectual landscape and offers evidence of the evolving focus on green industry and low-carbon development, providing valuable insights for future research directions and policy formulation.

Co-Authorship based on Countries' Collaboration

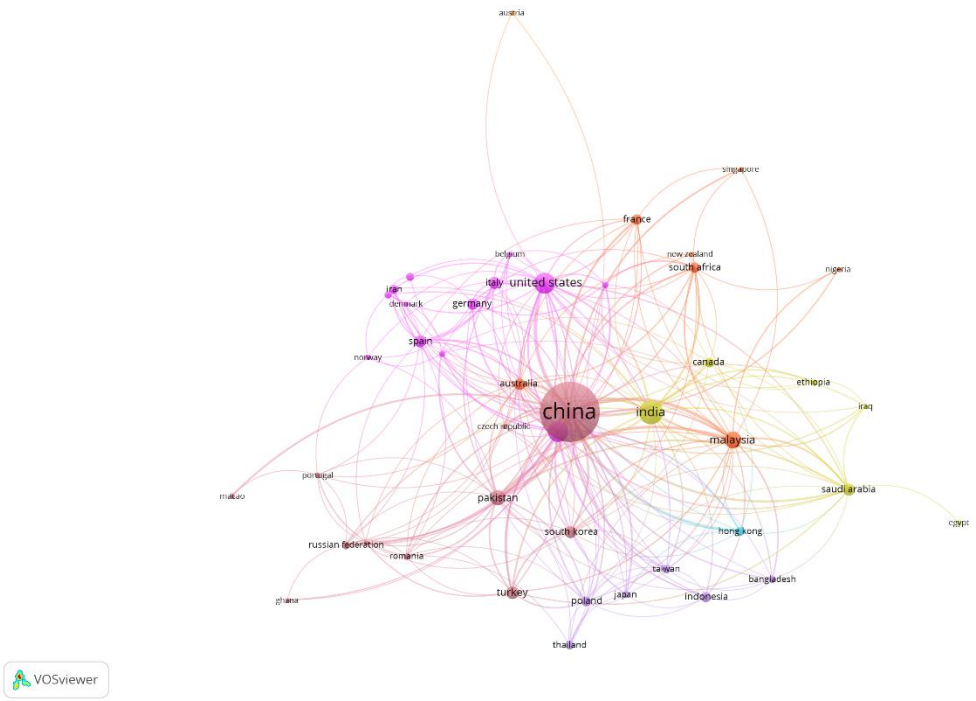

Figure 5: Network Visualization Map regarding Co-authorship by Countries

Co-authorship by countries in VOSviewer is a bibliometric technique that visualizes the research collaboration network among nations in Figure 5, showing how frequently scholars from different countries publish together. This method highlights the strength of international linkages, the volume of joint publications, and the extent of scholarly influence through citations. In this analysis, the full counting method was applied, with a minimum threshold of five publications per country. Out of 86 countries, 45 met the threshold. With a minimum cluster size of five, seven distinct clusters were generated, each representing collaborative groups of countries engaged in related research activities. Note that these clusters illustrate both strong regional partnerships and global linkages, mapping how countries interact within the broader research landscape.

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The findings revealed China as the leading contributor with 399 documents and the highest citation count, underscoring its dominance in research output and collaborations. Other countries, such as the United Kingdom, the United States, India, Malaysia, and Pakistan, also demonstrate a significant presence, with strong total link strengths indicating active collaboration networks. The distribution of seven clusters suggests that international collaboration is concentrated among developed nations and increasingly involves emerging economies, particularly in Asia. This adds to the body of knowledge by showing the global interconnectedness of sustainability-related research, highlighting the importance of cross-border partnerships in addressing complex issues. The visualization provides evidence that international collaboration enhances research impact, strengthens knowledge transfer, and accelerates advancements in global sustainability efforts.

Conclusion

This study was undertaken to map research trends and frontiers in green industry sustainability through bibliometric analysis, aiming to identify key publication patterns, influential works, leading contributors, and collaborative networks. By analyzing 836 Scopus-indexed articles published between 2020 and 2025, the study addressed research questions relating to publication growth, most cited articles, country contributions, keyword co-occurrence, as well as international co-authorship.

The analysis revealed that scholarly attention to green industry sustainability has grown significantly, particularly in recent years, with a notable surge in 2025. The most cited works emphasized themes such as sustainable manufacturing, environmental regulation, clean energy, and advanced technologies like blockchain and Industry 4.0. China emerged as the most productive contributor, followed by India, the United Kingdom, and the United States, whereas Malaysia and other emerging economies also demonstrated rising participation. Keyword mapping highlighted the prominence of concepts that include sustainability, circular economy, and renewable energy, underscoring the multidisciplinary nature of this research area. Co-authorship analysis further demonstrated the importance of international collaboration in advancing sustainability knowledge.

This study contributes to the field by providing a structured overview of knowledge development in green industry sustainability, highlighting emerging clusters that connect technological innovation, environmental management, and policy frameworks. The outcomes provide useful insights for policymakers, industry stakeholders, and academics to align future strategies with global sustainability goals.

Nonetheless, the analysis is constrained by its dependence on a single database, language limitations, as well as the exclusion of non-article publications, which may have overlooked relevant perspectives. Future studies could expand coverage to multiple databases, include non-English literature, or adopt longitudinal approaches to track thematic evolution more comprehensively.

Overall, this bibliometric study underscores the significance of green industry sustainability as a rapidly expanding research frontier, where innovation, policy support, and collaboration are central to achieving industrial transformation. The results highlight the importance of bibliometric mapping as a tool for understanding intellectual landscapes and guiding future research in advancing sustainable industrial practices worldwide.

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