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Bibliometric Mapping of Green Technology Innovation in the Manufacturing Industry

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ABSTRACT

This bibliometric mapping study provides a comprehensive analysis of green technology innovation within the manufacturing industry, employing quantitative methods to uncover thematic clusters, research trends, author collaborations, and research gaps. Three distinct thematic clusters—Sustainable Manufacture, Enterprise, and Challenge—emerge, each offering insights into prevalent terms and themes. The analysis of research trends reveals the evolution of key terms over time, highlighting emerging topics. Author collaboration mapping identifies influential researchers and collaborative networks, facilitating interdisciplinary partnerships. The study's implications extend to resource allocation, policy formulation, and industry best practices, emphasizing academia's pivotal role in sustainable manufacturing. Overall, this research serves as a roadmap for future endeavors, fostering collaboration, informing policy, and driving innovation in green technology within the manufacturing sector.

Keywords: *Bibliometric Mapping, Green Technology Innovation, Manufacturing Industry*

1. INTRODUCTION

In an era defined by the imperative to address environmental challenges and promote sustainable development, the manufacturing industry stands at the forefront of innovation. The integration of green technologies within manufacturing processes not only enhances operational efficiency but also contributes significantly to reducing ecological footprints [1]. As the global community intensifies its focus on mitigating climate change and fostering environmental stewardship, understanding the landscape of green technology innovation in the manufacturing sector becomes paramount [2].

This article delves into the intricate realm of green technology within the manufacturing industry through the lens of bibliometric mapping. Bibliometrics, as a quantitative analysis of publication patterns, citations, and collaborations, provides a systematic approach to navigating the vast and ever-expanding landscape of scholarly research [3]–[5]. By employing bibliometric techniques, we aim to unearth trends, identify key contributors, and map the intellectual structure of green technology innovation in manufacturing.

The manufacturing sector's quest for sustainability has given rise to a rich tapestry of research and development initiatives, spanning disciplines such as materials science, engineering, and environmental studies [6]–[8]. This article seeks to synthesize the wealth of knowledge dispersed across academic literature, journals, and conference proceedings, offering readers a comprehensive overview of the evolving discourse on green technology within manufacturing.

Through the exploration of bibliometric data, we endeavor to address critical questions such as the evolution of research themes, influential research groups, collaborative networks, and the impact of publications in shaping the trajectory of green technology innovation. By shedding light

on the intellectual landscape, this analysis not only provides valuable insights for researchers, policymakers, and industry professionals but also serves as a roadmap for future research directions.

2. LITERATURE REVIEW

2.1 Green Technology Innovation

In recent decades, the manufacturing industry has undergone a transformative shift propelled by the imperative to embrace sustainable practices and mitigate environmental impacts [1]. At the heart of this evolution lies the concept of green technology, a multifaceted approach that integrates environmentally friendly solutions into manufacturing processes [2]. The literature on green technology innovation within the manufacturing sector reflects a growing awareness of the need to balance industrial growth with ecological responsibility.

Green technology, often interchangeably referred to as clean technology or environmental technology, encompasses a spectrum of innovations aimed at reducing resource consumption, minimizing waste, and curbing emissions. From renewable energy sources to eco-efficient manufacturing processes, the literature highlights a broad array of technological advancements contributing to the greening of the manufacturing sector. Scholars emphasize the role of green technology as a catalyst for sustainable development, fostering economic growth while addressing the pressing challenges of climate change and environmental degradation [6].

Understanding the drivers and motivations behind the adoption of green technology in manufacturing is central to contextualizing the literature on innovation in this domain. Economic incentives, regulatory pressures, and a growing awareness of corporate social responsibility have been identified as key motivators for industries to invest in green technology [9]. The literature sheds light on how these external factors, coupled with internal organizational goals, influence the decision-making processes of manufacturing firms, steering them towards more sustainable and environmentally conscious practices.

As we navigate the expansive landscape of green technology innovation in manufacturing through this literature review, it becomes evident that scholarly discourse is pivotal in shaping the trajectory of sustainable industrial development. The next sections will build upon this foundation, employing bibliometric mapping to unravel the key themes, contributors, and collaborative networks driving innovation in the manufacturing sector's journey towards environmental sustainability.

2.2 Manufacturing Industry and Green Technology

The relationship between the manufacturing industry and green technology signifies a pivotal convergence where innovation intersects with environmental responsibility. In response to escalating challenges posed by climate change and resource depletion, the manufacturing sector is undergoing a transformative shift towards sustainable practices [10]. Green technology, characterized by cleaner production methods and resource-efficient processes, mitigates the environmental impact of industrial activities [10]. Technologies such as renewable energy integration, smart manufacturing through IoT and AI, and adherence to circular economy principles contribute to operational efficiency while reducing the carbon footprint. Beyond the factory floor, the adoption of green technology extends to creating sustainable supply chains, emphasizing ethical sourcing and

eco-friendly logistics [11]. Governments globally play a role in driving green manufacturing through regulatory frameworks, while corporate social responsibility initiatives further incentivize companies to embrace environmentally friendly practices. Despite technological challenges and initial costs, the integration of green technology presents economic opportunities, fostering a balance between ecological and economic objectives [6], [12]. This synergy between manufacturing and green technology heralds a new era of sustainable industrial practices, positioning industries as catalysts for positive environmental change on a global scale.

2.3 Important Role of Green Technology

Green technology plays a pivotal role in addressing pressing environmental challenges and advancing sustainable development across diverse sectors. This innovative approach, also known as environmental or clean technology, encompasses a spectrum of solutions designed to minimize environmental impact, conserve resources, and promote ecological balance. Its significance is underscored by the transformative shift toward renewable energy sources, such as solar, wind, hydropower, and geothermal technologies, ushering in a paradigm of energy independence and climate change mitigation [13]. Green technology also champions resource efficiency and conservation through circular economy practices, waste-to-energy solutions, and sustainable agricultural methods. In the context of climate change, it stands as a crucial ally, offering carbon capture and storage, sustainable transportation solutions, and eco-friendly building materials to reduce greenhouse gas emissions and foster climate resilience. Embracing circular economy principles, green technology facilitates a transition from linear resource consumption to a circular model, promoting reuse, recycling, and regeneration [14]. Moreover, it extends its influence to sustainable agriculture, precision farming, and environmentally conscious practices, reshaping our food systems for long-term resilience. In the realm of construction and infrastructure, green technology fuels sustainable architecture and design, yielding energy-efficient buildings and eco-friendly materials. Beyond its environmental benefits, green technology stimulates economic growth by fostering innovation, creating jobs, and attracting investments in sustainable industries. As societies worldwide increasingly prioritize sustainability, the role of green technology continues to expand, influencing various facets of our lives, industries, and the global pursuit of a harmonious coexistence with the planet [15].

3. RESEARCH METHOD

The methodological approach for this study involved a systematic data collection and analysis process. Academic databases such as PubMed, Scopus, IEEE Xplore, and Web of Science were extensively searched using a carefully designed search strategy encompassing keywords related to green technology, innovation, and manufacturing. Inclusion criteria were established to focus on peer-reviewed articles, conference papers, and reviews written in English, while exclusion criteria were applied to filter out non-English publications and non-peer-reviewed sources. We employ a tool for handling the searching process namely Publish or Perish, this tool is used to collect and produce research data metrics as displays on the Table 1.

Bibliometric analysis, a key component of the study, was conducted using bibliometric software, namely VOSviewer. This allowed for the exploration of quantitative indicators like

publication counts, citation counts, and co-authorship networks. The data extracted from the selected publications, including publication year, authorship details, keywords, and citation information, formed the basis for constructing visual bibliometric maps and identifying prominent themes and influential authors within the field.

Table 1. Research Data Metrics

Publication years	: 1984-2023
Citation years	: 39 (1984-2023)
Paper	: 979
Citations	: 126773
Cites/year	: 3250.59
Cites/paper	: 129.49
Cites/author	: 67225.32
Papers/author	: 451.74
Author/paper	: 2.83
h-index	: 121
g-index	: 353
hI,norm	: 103
hI,annual	: 2.64
hA-index	: 68
Papers with ACC	: 1,2,5,10,20:618,488,323,195,123

The provided table presents bibliometric data for a researcher or a group of researchers from the years 1984 to 2023. Over this period, a total of 979 papers have been published, accumulating a substantial 126,773 citations with an impressive average of 129.49 citations per paper. The citation impact is notably high, with an average of 3,250.59 citations per year. Each author associated with these publications has contributed to an average of 451.74 papers and has received an average of 67225.32 citations, indicating a prolific and influential body of work. The h-index stands at 121, demonstrating the significance of 121 papers that have each been cited at least 121 times. The g-index is 353, reflecting the cumulative impact of the top 353 papers. The hI,norm is 103, suggesting that the researcher's h-index is normalized for career length. The hI,annual is 2.64, indicating an average increase of 2.64 in the h-index each year. The hA-index is 68, representing the highest number of papers that have been cited hA times. Additionally, there is information about the number of papers with specific citation counts (1, 2, 5, 10, 20), revealing the distribution of impact across different thresholds. Overall, these metrics collectively portray a highly productive and influential scholarly profile.

4. RESULTS AND DISCUSSION

The first stage in this section is to analyze how previous research related to the topic Green Technology Innovation in the Manufacturing Industry is classified according to the themes they have. To analyze this, we utilized the main feature in VOS Viewer, namely the Network Visualization section. In this feature, it will illustrate how scientific mapping is related to this topic and how the relationships between terms are found. Figure 1 below shows the mapping of these terms.

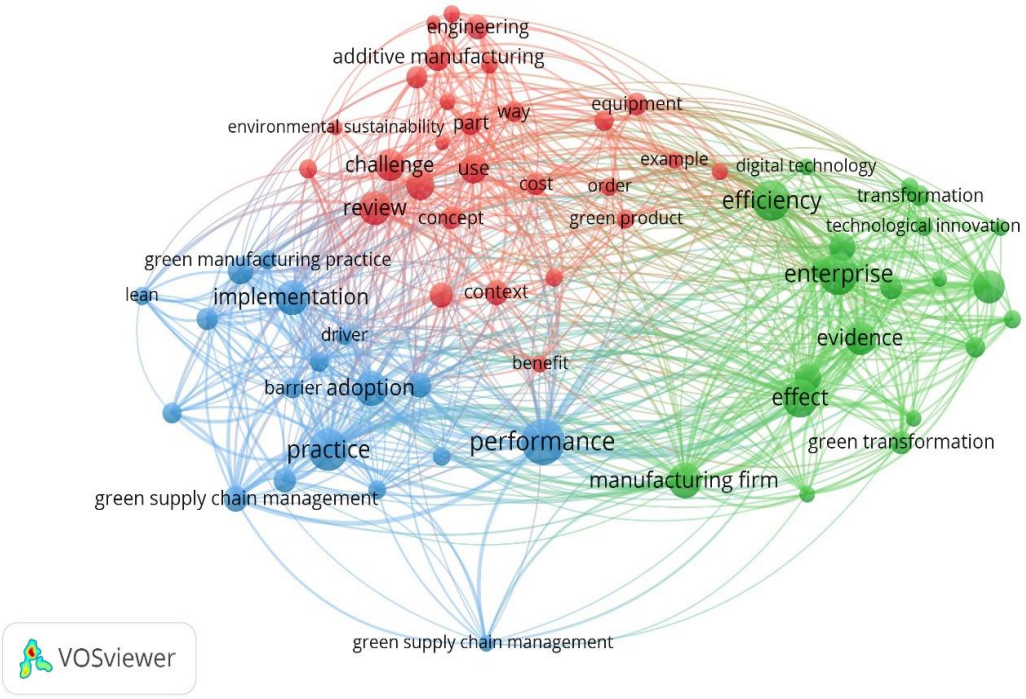

Figure 1. Network Visualization

Based on Figure 1 above, there is a network visualization depicted in three different colors, namely red, green and blue. These different colors indicate different classifications or groups. In bibliometric analysis, we usually call them clusters. Thus, it can be stated that previous research related to Green Technology Innovation in the manufacturing industry is divided into three theme groups, each group consisting of various items. The first cluster is shown in blue which consists of 18 different items, the second cluster is shown in green which consists of 16 items, and the third cluster is shown in red with a composition of 11 different items. Specifically, Table 2 below shows the composition of items in each cluster.

Table 2. Cluster and Terms

Cluster	Most Occurrence	Terms
1	Sustainable manufacture	Automative industry (16), barrier (21), benefit (15), driver (16), green design (16), green manufacturing practice (19), green practice (19), green supply chain (28), Indian manufacturing industry (20), lean (15), organization (26), relationship (28), smart manufacturing (15), smes (23), supply chain (16), sustainable manufacture (39).

2	Enterprise	Chinese manufacturing (13), digital technology (12), efficiency (75), enterprise (77), environmental regulation (20), green development (15), green innovation (36), green technological innovation (13),
3	Challenge	Additive manufacturing (31), challenge (45), cost (24), energy efficiency (13), engineering (26), environmental sustainability (10), equipment (23), green chemistry (14), green product (16), sustainable development (19).

The table presents a clustering analysis of terms related to three distinct topics: Sustainable Manufacture (Cluster 1), Enterprise (Cluster 2), and Challenge (Cluster 3). In the context of sustainable manufacture (Cluster 1), the most frequently occurring terms include "sustainable manufacture" itself (39 occurrences), emphasizing a focus on environmentally conscious manufacturing practices. Other key terms within this cluster encompass aspects such as green design, green manufacturing practices, smart manufacturing, and the integration of sustainability within the supply chain, particularly in the context of the Indian manufacturing industry. The second cluster, centered around the theme of enterprise, highlights terms like "efficiency" (75 occurrences) and "enterprise" (77 occurrences), underscoring the importance of streamlined and effective business operations, with a notable emphasis on Chinese manufacturing and green technological innovation. Lastly, the challenge cluster (Cluster 3) emphasizes terms such as "challenge" (45 occurrences), "additive manufacturing" (31 occurrences), and "sustainable development" (19 occurrences), reflecting a discussion around obstacles and considerations within manufacturing processes, including cost, energy efficiency, and environmental sustainability. Overall, the clustering analysis provides insights into the prevalent themes and key terms within each category, offering a structured view of the diverse facets encompassed by sustainable manufacturing, enterprise dynamics, and associated challenges.

Next, after the discovery of terms is carried out, we will analyze research trends in this field from year to year. This will be very interesting because the trends and interest of researchers in this field continue to grow along with the issue of global warming and climate change. This research trend analysis is carried out using the overlay visualization feature which can provide complete research trends each year. Terms and networks that are dark in color indicate that these terms appeared earlier and more recently, while terms that appeared more recently or in a more recent time are marked in bright color.

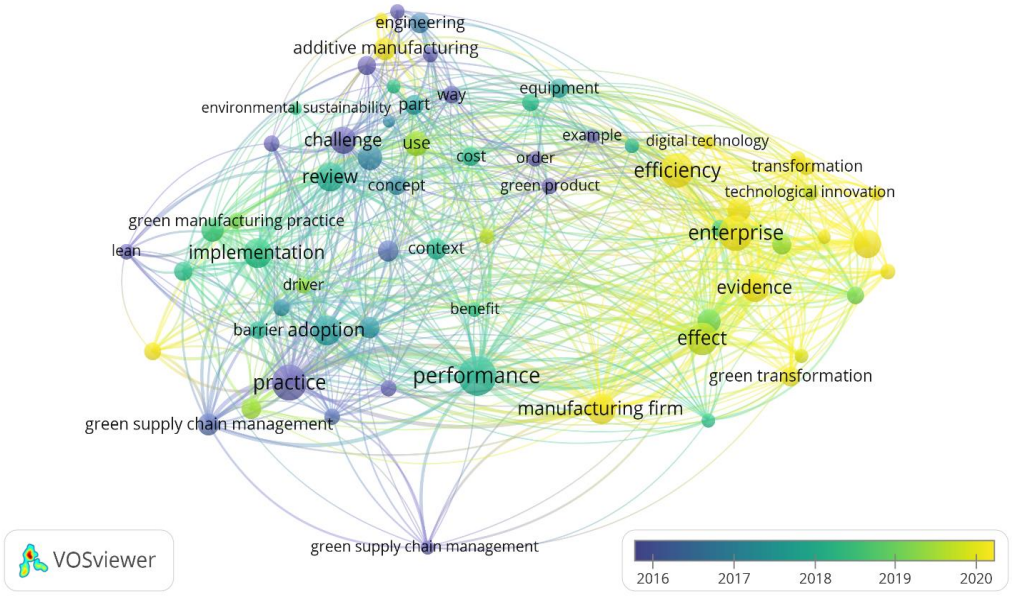

Figure 2. Overlay Visualization

The image shows three main color gradations, namely dark purple, turquoise green and bright yellow. Terms such as challenge, lean, practice, and green supply chain management are some of the terms that have appeared for a long time, namely since 2016, indicating that these terms are very common and often used among researchers. Researchers in the future can utilize newer and more interesting terms such as transformation, technological innovation, green transformation, and digital technology which in the picture above is shown starting to appear in 2020. Research trends can also be identified by identifying some significant articles in this area. With the help of the Publish or Perish software, we have collected the 10 articles with the highest number of citations available which are believed to have had a large and significant impact on scholarship related to this topic. These 10 articles can be used as a basis for future research.

Table 3. Top Cited Document

Citations	Authors and year	Title
5402	SK Srivastava (2007)	Green supply-chain management: a state-of-the-art literature review
3461	Q Zhu, J Sarkis (2004)	Relationships between operational practices and performance among early adopters of green supply chain management practices in Chinese manufacturing
2786	AK Mohanty, M Misra, LT Drzal (2002)	Sustainable bio-composites from renewable resources: opportunities and challenges in the green materils world
2615	M Lieder, A Rashid (2016)	Towards circular economy implementation: a comprehensive review in context of manufacturing industry
2072	P Shrivastava (1995)	Environmental technologies and competitive advantage
2061	P Duxson, JL Provis, GC Lukey (2007)	The role of inorganic polymer technology in the development of 'green concrete'
2056	S Vachon, RD Klassen (2008)	Environmental management and manufacturing performance: The role of collaboration in the supply chain
1958	Q Zhu, J Sarkis, Y Geng (2005)	Green supply chain management in China: pressures, practices and performance
1894	SB Brunnermeier, MA Cohen (2003)	Determinants of environemtal innovation in US manufacturing industries
1811	E Oztemen, S Gursev (2020)	Literature review of industry 4.0 and related technologies

Furthermore, in an effort to help develop science in the future, we also carry out an analysis of what topics are suggested to be used as research material in the future. We carried out this analysis with the Density Visualization feature which graphically takes the form of circles with certain color intensities. The more intense and brighter the color indicates that the term is frequently used and it is not recommended to be used again in future research because it does not represent a very important research gap.

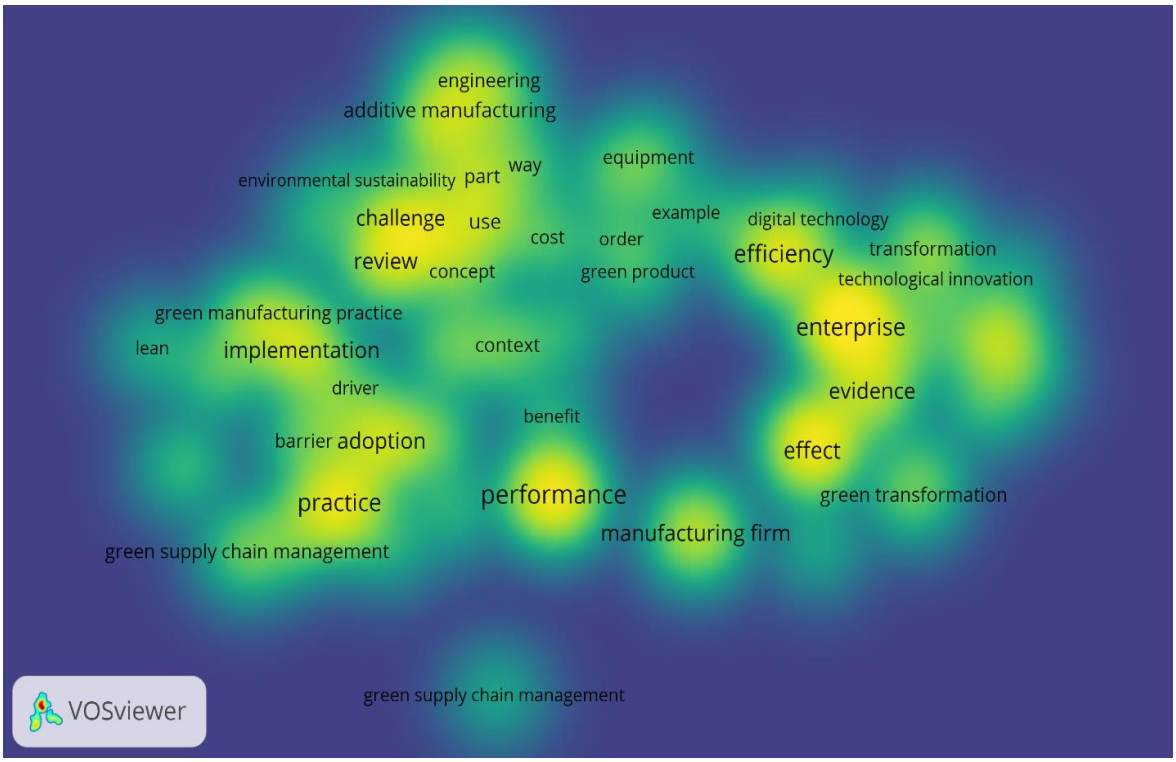

Figure 3. Density Visualization

Terms such as green transformation, digital technology, and green supply chain management are some terms that rarely appear so they are interesting to reproduce and research in the future. We also carefully identified each of the 10 terms with the highest occurrences and the 10 terms with the lowest occurrences in order to provide insight to future researchers in building research gaps.

Table 4. Most Frequented and Fewest Occurrence

Most Frequented		**Fewest**	
Term	**Occurrence**	**Term**	**Occurrence**
Enterprise	77	Environmental sustainability	10
Manufacturing firm	58	Green manufacturing process	10
Green Technology Innovation	50	Digital technology	12
Challenge	45	Chinese manufacturing industry	13
Sustainable Manufacturing	39	Energy Efficiency	13
Green Innovation	36	Green chemistry	14
Additive manufacturing	31	Lean	15
Green supply chain management	30	Green total factor productivity	15
Organization	26	Green development	15
Enggineering	26	Technological Innovation	16

The table provides a comparative analysis of the most and least frequently occurring terms within a given context, shedding light on the emphasis and prevalence of certain concepts. At the forefront, the term "Enterprise" stands out with the highest occurrence, appearing 77 times in the dataset, underscoring a significant focus on business operations and organizational dynamics. Following closely is "Manufacturing firm" with 58 occurrences, highlighting a strong emphasis on the entities engaged in production processes. The term "Green Technology Innovation" follows with 50 occurrences, indicative of a substantial focus on environmentally conscious technological

advancements. On the other end of the spectrum, terms such as "Environmental sustainability" and "Green manufacturing process" occur the least frequently, both with only 10 instances, suggesting a potential gap in the discussion or perhaps a lower level of emphasis on these specific aspects. Similarly, "Digital technology" and "Chinese manufacturing industry" appear with 12 and 13 occurrences, respectively, indicating a comparatively lower emphasis on these topics. The table also illustrates a range of terms associated with challenges and sustainable practices, with "Challenge" and "Sustainable Manufacturing" featuring 45 and 39 occurrences, respectively, while terms like "Energy Efficiency," "Lean," and "Green chemistry" are less frequently mentioned. Overall, the table provides a nuanced view of the key terms, emphasizing the varying degrees of attention and importance assigned to different concepts within the specified context.

Finally, we carry out an analysis of the authors in this field to find out how they are also grouped and how they are associated with others.

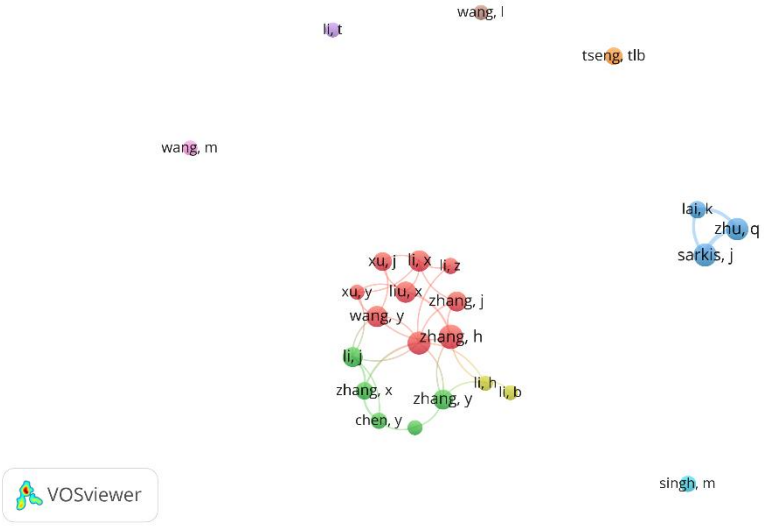

Figure 4. Author's Maping

From Figure 4 above, it can be seen that there are 9 author clusters, each cluster has a different color. The first cluster is represented in red, the second cluster is represented in green, the third cluster is dark blue, the fourth cluster is yellow, the fifth cluster is a single item in purple, the sixth cluster is light blue, the seventh cluster is orange, the eighth cluster is pink, and the last klister is brown.

Table 5. Author Cluster

Cluster	Most Occurrence	Author
1	Zhang, h	Li x (10), li, y (12), liu, x (10), wang y (10), xu, j (8), xu, y (5), zhang, h (13), zhang, j (9).
2	Li, j and zhang, y	Chen j (5), chen, y (6), li, j (9), zhang, x (7), zhang, y (9)
3	Sarkis, j	Lai, k (7), sarkis, j (12), zhu, q (11)
4	Li b, li h	Li b (5), li h (5)
5	Li, t	Li, t (5)
6	Singh, m	Singh, m (5)
7	Tseng, tlb	Tseng, tlb (7)
8	Wang, l	Wang, l (5)
9	Wang, m	Wang, m (5)

The table presents a clustering analysis based on the most frequently occurring authors within different clusters. Each cluster is associated with a specific researcher or group of researchers, and the most prevalent authors within each cluster are highlighted. In Cluster 1, Zhang, H emerges as the most frequent author, with co-authors such as Li, X, Li, Y, Liu, X, Wang, Y, Xu, J, Xu, Y, Zhang, J, and Zhang, H itself. Cluster 2 is represented by Li, J, and Zhang, Y, with prominent co-authors including Chen, J, Chen, Y, Li, J, Zhang, X, and Zhang, Y. Cluster 3 is associated with Sarkis, J, featuring co-authors like Lai, K and Zhu, Q. Clusters 4 to 9 highlight individual authors or smaller groups, with Li, B and Li, H in Cluster 4, Li, T in Cluster 5, Singh, M in Cluster 6, Tseng, TLB in Cluster 7, Wang, L in Cluster 8, and Wang, M in Cluster 9. The table effectively organizes authors into distinct clusters based on their collaborative patterns, offering a snapshot of the most prominent researchers within each identified group.

Comparison with Previous Studies

Bibliometric analysis has been used to study the impact of environmental regulation on green technology innovation in the manufacturing industry. A bibliometric analysis by [16] examined the impact of environmental regulation on green technology innovation. The study analyzed the annual number of publications, authors, publishing institutions, and countries (regions) with research findings. The results showed that environmental regulations can effectively promote green technological innovation. A bibliometric analysis by [17] focused on green manufacturing in the context of achieving carbon neutrality goals. The study found that future research may continue following the trend of developing innovative technologies for green manufacturing. [5] aimed to visually research map and identify research trends in green technology on an international level. The study provided insights into the evolving field of green technology and highlighted the importance of bibliometric analysis in understanding research trends. Another bibliometric analysis provided insights into the evolving field of green manufacturing by mapping the literature and critically identifying research frontiers. The study highlighted the importance of understanding the literature and research trends in green manufacturing to guide future research and development [3]. A study by [18] explored and analyzed research trends in green innovation using bibliometric analysis. The literature review revealed that green innovation is a growing field with increasing research interest and potential for further development.

Study Implication

The bibliometric mapping of green technology innovation in the manufacturing industry yields significant implications for various stakeholders. By identifying research gaps, scholars can focus on understudied aspects, ensuring a more comprehensive understanding of sustainable practices. The clustering of authors reveals collaboration opportunities, fostering interdisciplinary partnerships and enhancing the impact of research. Institutions and funding agencies can strategically allocate resources based on prevalent themes, guiding advancements in green technology innovation. Policymakers can draw on the study to formulate regulations that encourage sustainable practices, while industry professionals can glean insights into best practices and emerging trends, ensuring competitiveness and environmental responsibility. The study also informs academic curricula, enriching education on green technology innovation. Furthermore, the identification of collaborative networks across regions promotes international collaboration, contributing to a global perspective on sustainability. In essence, this bibliometric analysis provides a roadmap for advancing research, fostering collaboration, shaping policies, and driving innovation in green technology within the manufacturing industry, with far-reaching implications for sustainable development.

CONCLUSION

In conclusion, this bibliometric mapping study provides a comprehensive exploration of green technology innovation in the manufacturing industry, revealing thematic clusters, research trends, author collaborations, and research gaps. The identified clusters—Sustainable Manufacture, Enterprise, and Challenge—offer insights into prevalent themes, while the analysis of research trends illuminates the evolving landscape. Author collaboration mapping exposes influential researchers and collaborative networks, fostering interdisciplinary partnerships. The study's implications extend to resource allocation, policy formulation, and industry best practices, emphasizing the pivotal role of academia in shaping sustainable manufacturing. This research serves as a roadmap for future endeavors, promoting collaboration, informing policy, and driving innovation in green technology within the manufacturing sector, contributing to global efforts for environmental sustainability.

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