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EMERGING TECHNOLOGIES AND SUSTAINABILITY INTEGRATION IN INDUSTRY 4.0 MANUFACTURING: A BIBLIOMETRIC ANALYSIS

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ABSTRACT
The advancement of Industry 4.0 technologies has accelerated the transformation of manufacturing systems toward intelligent, interconnected, and sustainability-oriented industrial environments. Although numerous studies have explored smart manufacturing and digital transformation, limited bibliometric research has comprehensively examined the integration of intelligent manufacturing technologies with sustainability-driven production systems in the post-pandemic industrial era. This study aims to analyze the scientific development, intellectual structure, thematic evolution, and emerging research trends in smart and sustainable manufacturing research within the Industry 4.0 context. A bibliometric analysis was conducted using 616 English-language journal articles indexed in the Scopus database during the 2020–2025 period. Data were analyzed using Biblioshiny and VOSviewer to evaluate publication trends, country productivity, thematic structures, keyword co-occurrence networks, and topic evolution. The results reveal a substantial increase in research output after 2023, indicating growing global attention toward intelligent and sustainable industrial transformation. China becomes the most productive country, while smart manufacturing, Industry 4.0, and sustainable development were identified as the dominant research themes. The analysis demonstrates strong interconnections among artificial intelligence, machine learning, predictive maintenance, energy efficiency, and sustainable production systems. Emerging topics such as Industry 5.0, green manufacturing, carbon emission reduction, and green economy indicate a transition from automation-oriented manufacturing toward intelligent, human-centric, and environmentally sustainable industrial ecosystems. This study contributes to the literature by providing an updated bibliometric of the convergence between intelligent technologies and sustainability-oriented manufacturing research. The findings offer valuable insights for researchers, industrial practitioners, and policymakers in identifying future research directions and supporting sustainable industrial transformation strategies.

Keywords: Sustainable Manufacturing, Industry 4.0, Bibliometric Analysis, Artificial Intelligence, Industry 5.0

INTRODUCTION
The rapid advancement of Industry 4.0 technologies has fundamentally transformed modern manufacturing systems by enabling intelligent, interconnected, and data-driven industrial environments [1]. Technologies such as artificial intelligence (AI), the Internet of Things (IoT), cyber-physical systems (CPS), machine learning, big data analytics, and cloud computing have accelerated the transition from conventional manufacturing toward smart manufacturing systems characterized by automation, real-time monitoring, predictive decision-making, and adaptive

production capabilities [2]. These developments have significantly improved industrial productivity, operational flexibility, and manufacturing efficiency while reshaping global industrial competitiveness [3].

Alongside technological transformation, manufacturing industries are increasingly facing sustainability-related challenges associated with energy consumption, carbon emissions, resource depletion, environmental degradation, and global climate commitments [4], [5]. Consequently, sustainability has become a strategic priority within industrial transformation agendas worldwide. In this context, the integration of Industry 4.0 technologies with sustainability-oriented manufacturing practices has emerged as an important research area aimed at achieving both industrial efficiency and environmental responsibility simultaneously [6]. Smart and sustainable manufacturing is therefore increasingly viewed as a key approach for supporting resilient, energy-efficient, low-carbon, and environmentally responsible industrial systems [7].

The growing importance of this topic has led to a substantial increase in scientific publications related to Industry 4.0, intelligent manufacturing systems, digital transformation, green manufacturing, and sustainable industrial innovation [8], [9]. Previous studies have investigated various aspects of smart manufacturing, including AI-driven production systems, predictive maintenance, digital supply chains, energy-efficient manufacturing, and industrial automation technologies [10], [11]. In parallel, bibliometric analysis has become an increasingly important method for systematically evaluating scientific developments, mapping intellectual structures, identifying research trends, and exploring thematic evolution within rapidly growing research domains.

Several bibliometric studies related to Industry 4.0 and manufacturing technologies have been conducted in recent years. Existing studies mainly focus on specific areas such as Industry 4.0 implementation, digital transformation, smart factories, machine learning applications, or sustainability practices independently [12]. However, despite the increasing convergence between intelligent technologies and sustainability-oriented manufacturing systems, previous bibliometric studies remain fragmented in several important aspects. Most earlier studies primarily emphasize technological implementation and industrial automation while providing limited discussion regarding the integration of sustainability objectives, environmental performance, and intelligent manufacturing ecosystems [13].

In addition, many existing bibliometric studies rely mainly on descriptive publication analysis and basic keyword mapping techniques without comprehensively examining thematic evolution, emerging technologies, international collaboration patterns, and the transition toward Industry 5.0-oriented manufacturing systems [14]. This limitation is particularly important because manufacturing research has evolved rapidly after 2020 due to accelerated industrial digitalization, post-pandemic technological transformation, increasing sustainability pressures, and the growing adoption of AI-driven industrial systems [15]. As a result, earlier bibliometric studies may no longer fully represent the current research landscape and emerging directions of smart and sustainable manufacturing research. [16].

Furthermore, limited studies have specifically investigated how intelligent technologies such as artificial intelligence, machine learning, predictive analytics, and IoT are increasingly integrated with sustainability-oriented manufacturing strategies including energy efficiency, green manufacturing, carbon emission reduction, and sustainable industrial development. This indicates the existence of an important research gap concerning the intellectual structure and thematic evolution of integrated smart and sustainable manufacturing research within the recent Industry 4.0 and Industry 5.0 transition era.

To address these limitations, this study conducts a comprehensive bibliometric analysis of smart and sustainable manufacturing research within the Industry 4.0 context using publications indexed in the Scopus database during the 2020–2025 period. Unlike previous bibliometric studies that mainly focused on isolated technological themes, this study specifically examines the convergence between intelligent manufacturing technologies and sustainability-oriented industrial systems. In addition, this study integrates Biblioshiny and VOSviewer to perform complementary analyses involving publication trends, thematic mapping, keyword co-occurrence networks, international collaboration patterns, and topic evolution analysis.

Unlike previous bibliometric studies that mainly analyzed Industry 4.0 technologies or sustainability practices independently, this study provides a comprehensive bibliometric investigation of the convergence between intelligent manufacturing technologies and sustainability-oriented industrial transformation during the 2020–2025 period. The study further contributes by integrating Biblioshiny and VOSviewer to identify thematic evolution, emerging technologies, and Industry 5.0-related research trends within smart manufacturing ecosystems.

Accordingly, the objective of this study is to analyze the scientific development, intellectual structure, thematic evolution, and emerging research trends in smart and sustainable manufacturing research within the Industry 4.0 context. Specifically, this study aims to evaluate publication trends, influential countries and authors, thematic structures, keyword relationships, collaboration networks, and emerging technologies while identifying potential research gaps and future research opportunities related to intelligent and sustainable industrial transformation.

METHOD

1. Research Design

This study employed a bibliometric analysis approach to investigate the development, research trends, thematic evolution, and emerging technologies related to smart and sustainable manufacturing within the context of Industry 4.0 [17]. Bibliometric analysis is widely recognized as a quantitative research method for systematically evaluating scientific publications, identifying knowledge structures, mapping relationships among research topics, and exploring research evolution within a particular scientific domain [12], [18]. This approach enables researchers to analyze large volumes of scientific literature objectively and visualize the intellectual structure of a research field through bibliometric mapping techniques. To improve the comprehensiveness and reliability of the analysis, this study integrated two bibliometric tools, namely VOSviewer and Biblioshiny. VOSviewer was utilized for science mapping and visualization analysis, while Biblioshiny was employed for descriptive bibliometric analysis, thematic evolution, and research productivity analysis [19], [20]. Data retrieval was conducted at the beginning of 2026 to ensure complete indexing coverage for publications published in 2025.

2. Data Source and Search Strategy

The bibliographic data used in this study were retrieved from the Scopus database in early 2026. Scopus was selected because it is one of the largest and most comprehensive databases for peer-reviewed scientific publications, particularly in engineering, manufacturing, and technology-related disciplines. In addition, Scopus provides extensive bibliographic metadata suitable for bibliometric mapping and quantitative analysis.

The search strategy was designed to identify publications related to smart manufacturing, sustainability, and Industry 4.0 technologies. The search query was applied to titles, abstracts, and author keywords using the TITLE-ABS-KEY function in Scopus. The search string used in this study is presented as follows:

TITLE-ABS-KEY :

((("smart manufacturing" OR "intelligent manufacturing" OR "digital manufacturing" OR "advanced manufacturing") AND ("industry 4.0" OR "digital transformation" OR "industrial digitalization" OR "artificial intelligence" OR "internet of things" OR "machine learning" OR "cyber physical systems") AND (sustainab* OR "green manufacturing" OR "energy efficiency")))

AND (LIMIT-TO (DOCTYPE , "ar"))

AND (LIMIT-TO (LANGUAGE , "English"))
AND PUBYEAR >= 2020 AND PUBYEAR <= 2025.

To ensure dataset quality and relevance, several inclusion criteria were applied. The analysis was limited to journal articles published between 2020 and 2025 and written in English. Only peer-reviewed journal articles were included, while conference papers, review papers, editorials, book chapters, notes, and non-English publications were excluded from the analysis. The search strategy and filtering criteria applied in this study are summarized in Table 1.

Table 1. Search Strategy and Filtering Criteria

Item	Description
Database	Scopus
Search Field	Title, Abstract, Author Keywords
Publication Years	2020-2025
Language	English
Document Type	Journal
Analysis Tool	Vosviewer & Biblioshny
Final Dataset	616 Document

3. PRISMA flowchart diagram

To improve transparency and methodological rigor, this study adopted the PRISMA framework for dataset identification and selection. The initial search in the Scopus database retrieved 1,245 documents related to smart manufacturing, Industry 4.0, sustainability, and digital transformation.

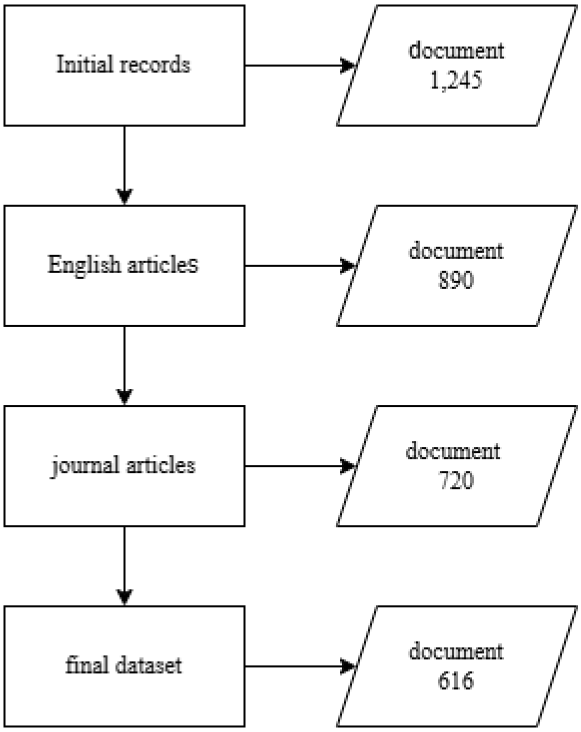

Figure 1. PRISMA flow diagram of publication selection process.

Subsequently, language filtering was applied, resulting in 890 English-language publications. Further refinement based on document type retained 720 journal articles, while conference papers, review papers, book chapters, editorials, and other non-article documents were excluded. Finally, duplicate and irrelevant records were removed through title and abstract evaluation, resulting in a final dataset of 616 journal articles for bibliometric analysis. The complete PRISMA flow diagram is presented in Figure 1.

4. Data Filtering and Screening Process

The initial search process identified a large number of publications related to smart manufacturing and Industry 4.0 technologies. To improve dataset relevance and consistency, filtering procedures were conducted based on publication year, document type, and language criteria. After the filtering process, a total of 616 journal articles were retained as the final dataset for bibliometric analysis. The bibliographic information, including titles, abstracts, author names, affiliations, citations, references, and author keywords, was exported in CSV format for further analysis and visualization. The overall filtering and bibliometric analysis workflow used in this study is illustrated in Figure 2.

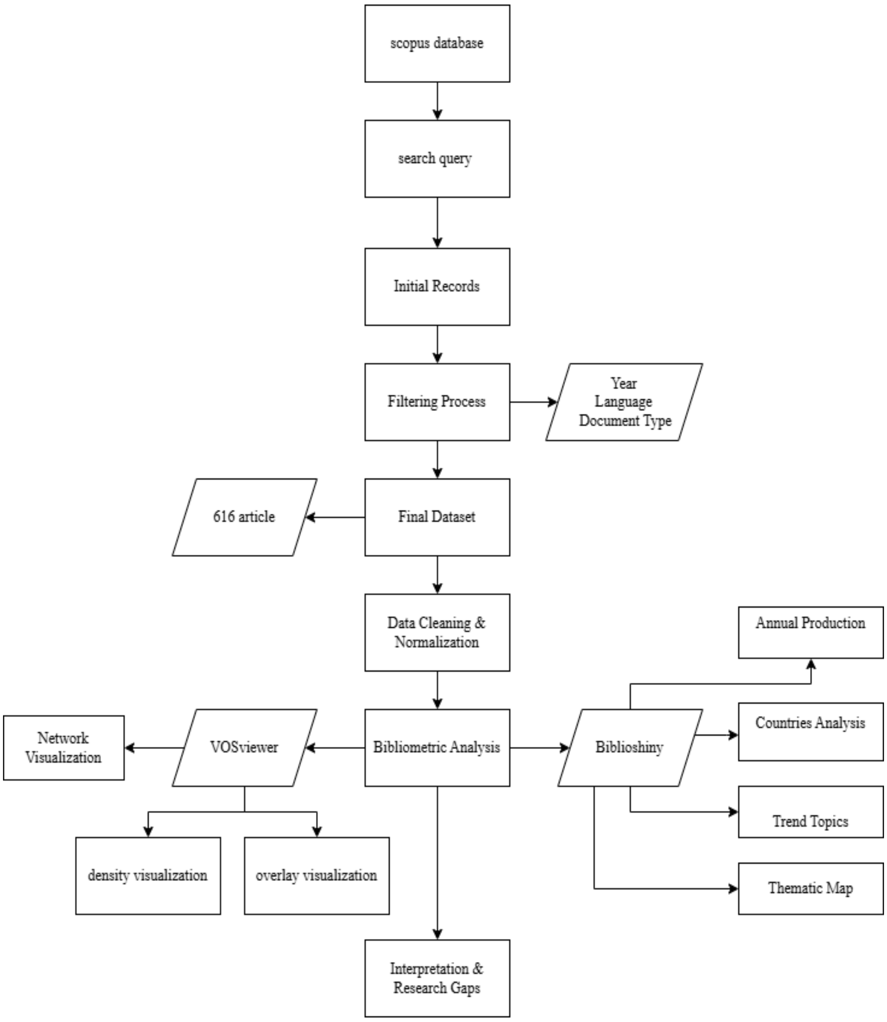

Figure 2. Research methodology workflow

5. Data Cleaning and Normalization

Prior to the analysis stage, data cleaning and keyword normalization procedures were conducted to improve the consistency and reliability of the bibliometric mapping results. Synonymous keywords, abbreviations, and variations of similar terms were standardized using a thesaurus file in VOSviewer.

For example, terms such as “AI” and “Artificial Intelligence” as well as “IoT” and “Internet of Things” were merged into unified terms to reduce redundancy and improve keyword consistency. In addition, irrelevant, duplicate, and overly generic keywords were manually removed to minimize visualization noise and improve analytical clarity.

6. Bibliometric Analysis

The bibliometric analysis was conducted using VOSviewer version 1.6.20 and Biblioshiny, which is a web-based interface of the bibliometrix package in R.
Biblioshiny was employed to perform descriptive bibliometric analysis, including:
1. Annual Scientific Production,
2. Country Scientific Production,
3. Author Productivity Analysis,
4. Thematic Mapping,
5. Trend Topic Analysis,
6. And International Collaboration Analysis.

Meanwhile, VOSviewer was utilized to construct and visualize keyword co-occurrence networks and thematic relationships within the dataset. The co-occurrence analysis was based on author keywords using the full counting method, in which each keyword occurrence was counted equally. A minimum occurrence threshold of five keywords was established to identify the most relevant research topics while reducing low-frequency keyword noise.
Three visualization techniques were generated using VOSviewer:
1. Network visualization, used to identify thematic clusters and relationships among research topics.
2. Overlay visualization, used to analyze the temporal evolution of research themes and identify emerging technologies.
3. Density visualization, used to examine the concentration and intensity of research topics based on keyword occurrence frequency.

Furthermore, the thematic map generated using Biblioshiny was utilized to classify research themes into motor themes, basic themes, niche themes, and emerging or declining themes. This analysis provided deeper insights into the maturity, relevance, and development of research topics within smart and sustainable manufacturing research.

7. Research Framework

The overall research framework consisted of five main stages:
1. Data Collection,
2. Data Filtering And Screening,
3. Data Cleaning And Normalization,
4. Bibliometric Mapping And Visualization,
5. Interpretation Of Research Trends And Research Gaps.

This framework was designed to ensure systematic, transparent, and reproducible bibliometric analysis for identifying the current state and future direction of smart and sustainable manufacturing research within Industry 4.0 environments.

RESULT AND DISCUSSION

1. Annual Scientific Production

Figure 3 presents the annual scientific production related to smart and sustainable manufacturing research during the 2020–2025 period. The publication trend shows a substantial increase in scientific output throughout the analyzed period, particularly after 2023, indicating growing global interest in intelligent and sustainability-oriented manufacturing systems.

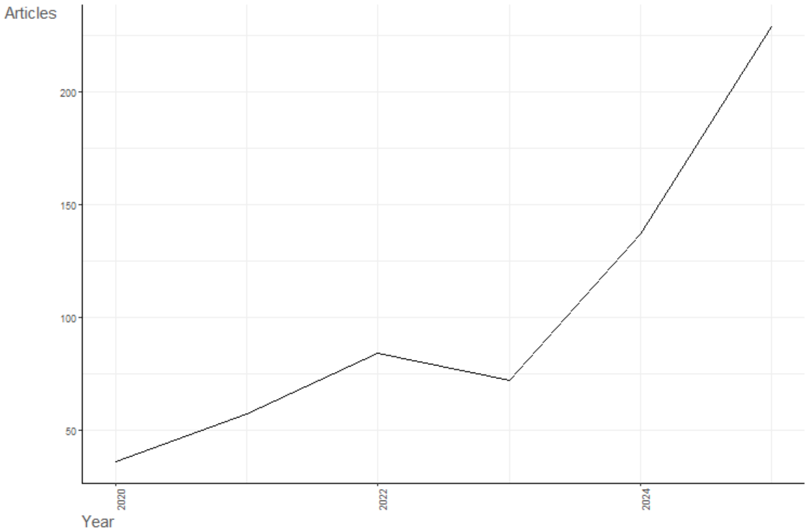

Figure 3. Presents the annual scientific production

The significant growth in publications after 2023 indicates the increasing global interest in integrating intelligent technologies and sustainability principles within manufacturing systems. This trend reflects the accelerated adoption of Industry 4.0 technologies such as artificial intelligence, IoT, machine learning, and data-driven automation to improve industrial efficiency, flexibility, and environmental performance.

These findings are consistent with previous bibliometric studies reporting rapid growth in Industry 4.0 and smart manufacturing research. Nevertheless, the current study demonstrates that recent publications increasingly emphasize sustainability-oriented manufacturing systems rather than focusing solely on industrial automation and digitalization. This shift suggests that future manufacturing research will increasingly prioritize environmentally responsible and intelligent production strategies.

The continuous increase in publication output also indicates that smart and sustainable manufacturing has evolved into a multidisciplinary research area involving engineering, industrial automation, sustainability management, and digital innovation. This development highlights the growing importance of integrating advanced digital technologies with sustainable industrial transformation strategies.

2. Countries Scientific Production

Figure 4 presents the geographical distribution of scientific publications related to smart and sustainable manufacturing research. The visualization indicates that China represents the most dominant contributor, followed by the United States, India, Germany, and several European countries.

The strong contribution from China reflects the country’s extensive investment in Industry 4.0 implementation, artificial intelligence, industrial automation, and smart factory development. In addition, national policies promoting digital transformation and sustainable industrial modernization have significantly accelerated research productivity in advanced manufacturing technologies

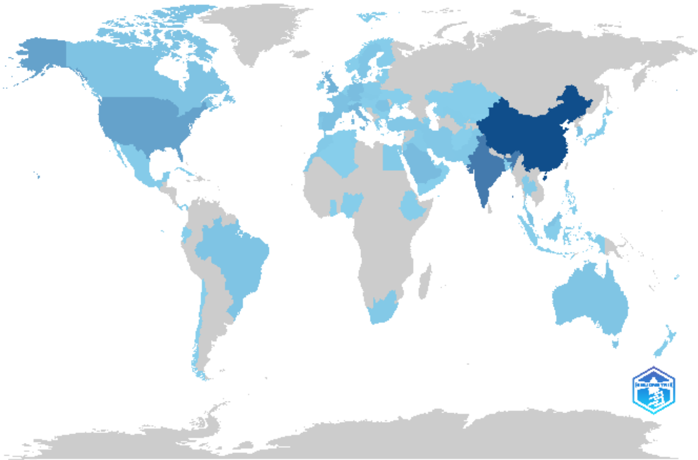

Figure 4. Presents the geographical distribution of scientific publications

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The United States and Germany also demonstrate substantial research contributions due to their strong technological infrastructure and long-standing involvement in industrial innovation. Germany's contribution is closely associated with its pioneering role in the development of the Industry 4.0 concept, while the United States remains highly influential in artificial intelligence, machine learning, and intelligent manufacturing systems.

Compared with previous bibliometric studies on Industry 4.0, the current findings indicate a broader global participation in sustainability-oriented manufacturing research. Emerging economies such as India are increasingly contributing to this research area, suggesting that sustainable industrial transformation has become an important global concern rather than a topic limited to highly industrialized countries.

Despite the increasing global research distribution, scientific productivity remains concentrated within countries possessing strong technological readiness and industrial infrastructure. This finding highlights the continuing disparity in research capability and digital manufacturing adoption between developed and developing regions. Therefore, future international collaboration may play an important role in supporting more inclusive and globally balanced manufacturing innovation.

3. Most Relevant Authors

Figure 5 presents the most relevant authors contributing to smart and sustainable manufacturing research during the analyzed period. The results indicate that Liu Y emerged as the most productive author with 10 publications, followed by Li C with 9 publications, while several other authors, including Wang J, Wang Y, and Wang Z, each contributed 8 publications.

The dominance of these authors reflects the growing concentration of research activities in areas related to intelligent manufacturing systems, artificial intelligence integration, industrial automation, and sustainability-oriented production technologies. The findings also indicate that research in smart manufacturing is increasingly driven by interdisciplinary collaboration involving manufacturing engineering, digital technologies, and sustainability management.

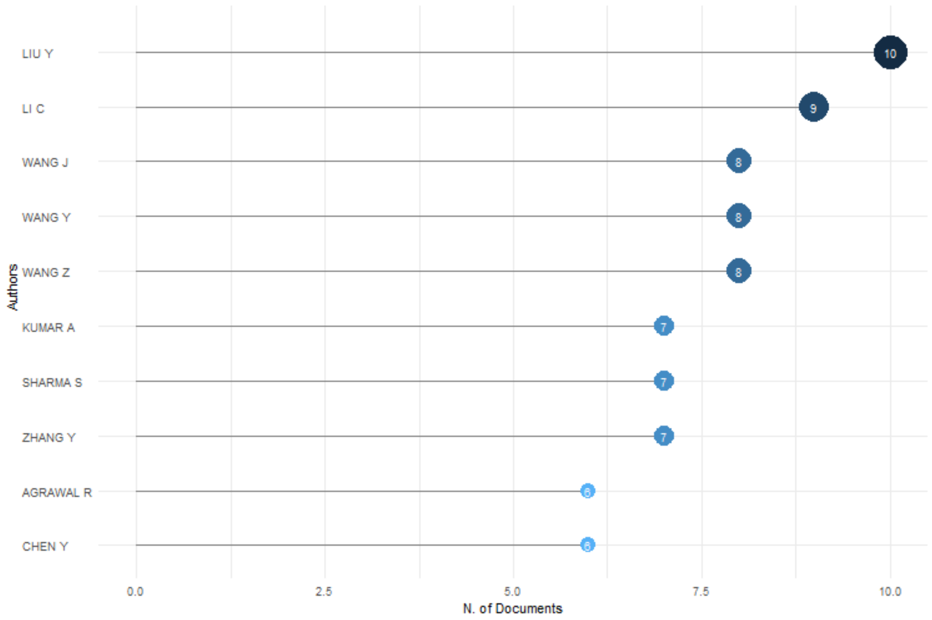

Figure 5. presents the most relevant authors contributing

The strong contribution from Asian researchers, particularly from China, aligns with the country's dominant scientific production identified in the previous analysis. This pattern suggests that China has established a strong research ecosystem supporting Industry 4.0 implementation, intelligent manufacturing, and industrial digitalization. Similar trends have also been reported in previous bibliometric studies on Industry 4.0 and smart manufacturing research.

In addition, the distribution of publications among multiple productive authors demonstrates that the research field remains highly collaborative rather than being dominated by a limited number of scholars. This condition reflects the rapidly evolving nature of smart and sustainable manufacturing research, where continuous technological developments encourage broader academic participation and interdisciplinary knowledge integration.

The increasing involvement of researchers from different scientific backgrounds further indicates that future manufacturing studies will likely focus on integrating artificial intelligence, predictive analytics, sustainable production systems, and intelligent decision-making technologies to support adaptive and environmentally responsible industrial operations.

4. Thematic Map Analysis

Figure 6 presents the thematic map of smart and sustainable manufacturing research based on keyword co-occurrence analysis. The thematic structure is categorized into four quadrants, namely motor themes, basic themes, niche themes, and emerging or declining themes, according to their centrality and density levels. The analysis identifies *smart manufacturing*, *Industry 4.0*, and *sustainable development* as the dominant basic themes. These themes demonstrate high relevance within the research field but relatively lower developmental maturity, indicating that they remain fundamental topics that continue to evolve across various manufacturing studies. Their strong centrality also confirms that sustainability and digital manufacturing transformation have become core research directions in modern industrial systems.

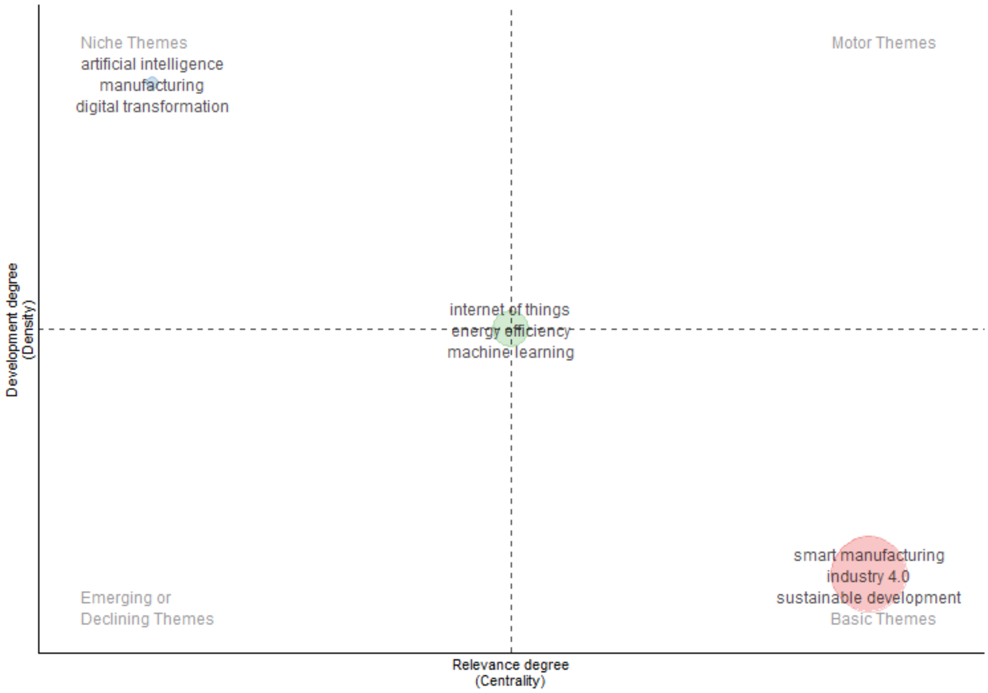

Figure 6. presents the thematic map

In contrast, *artificial intelligence*, *digital transformation*, and *manufacturing* appear within the niche theme quadrant. This finding suggests that these topics are highly developed internally but remain relatively specialized and less connected to broader research themes. The increasing presence of artificial intelligence within this quadrant reflects the rapid advancement of intelligent manufacturing technologies, particularly in areas related to predictive analytics, autonomous systems, and data-driven decision-making. Meanwhile, keywords such as *internet of things*, *machine learning*, and *energy efficiency* are positioned near the center of the thematic map, indicating their growing importance and strong interconnection with multiple research domains. These technologies increasingly function as enabling components that support both industrial digitalization and sustainable manufacturing implementation.

Compared with previous bibliometric studies that primarily emphasized Industry 4.0 adoption and industrial automation, the current findings demonstrate a stronger integration between intelligent technologies and sustainability-oriented manufacturing systems. This trend indicates a gradual transition from conventional automation toward adaptive, data-centric, and environmentally sustainable production ecosystems [21], [22], [23], [24].

The thematic evolution identified in this study also highlights several future research opportunities, particularly in integrating artificial intelligence, machine learning, and energy-efficient production strategies within smart manufacturing environments. Therefore, future studies may focus more extensively on intelligent sustainability frameworks, low-carbon manufacturing systems, and autonomous industrial optimization technologies to support long-term industrial transformation.

5. Trend Topic Analysis

Figure 7 presents the evolution of research topics in smart and sustainable manufacturing during the 2020–2025 period. The analysis demonstrates a clear transition in research focus from conventional industrial automation toward intelligent and sustainability-oriented manufacturing systems.

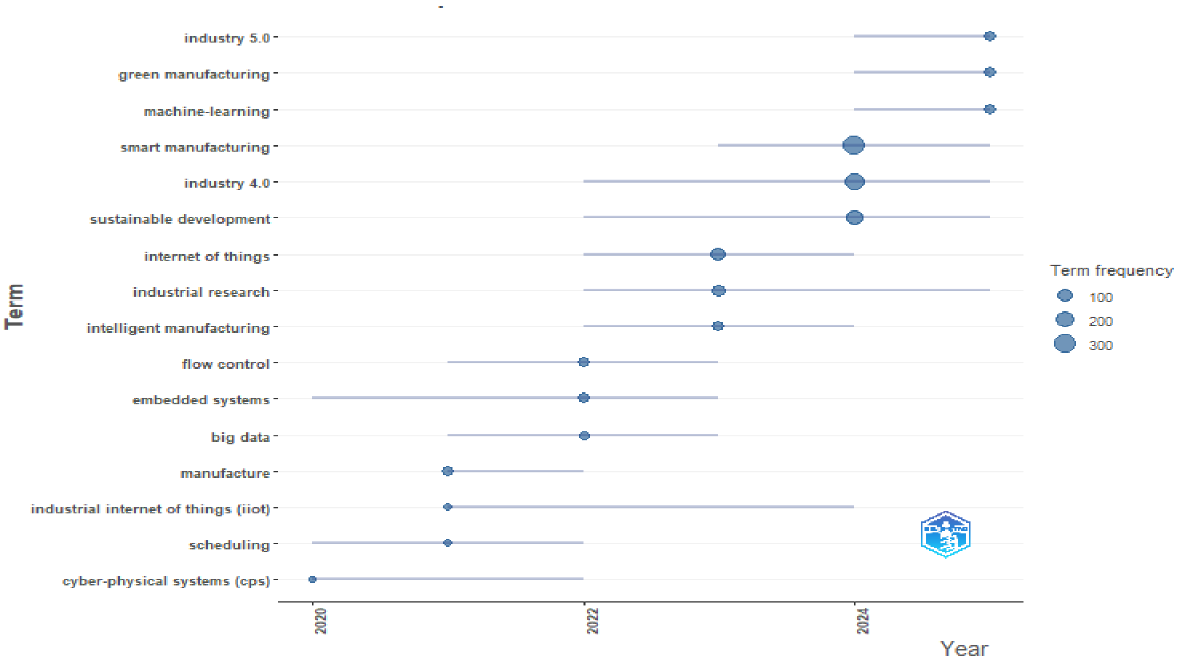

Figure 7. presents the evolution of research topics

Early research trends were primarily associated with cyber-physical systems (CPS), industrial internet of things (IIoT), embedded systems, and big data, which became dominant topics between 2020 and 2022. These technologies formed the technological foundation of Industry 4.0 implementation and enabled the initial development of interconnected manufacturing environments**.**

From 2023 onward, research attention increasingly shifted toward *internet of things*, *intelligent manufacturing*, *smart manufacturing*, and *sustainable development*. This transition indicates that manufacturing research has evolved beyond basic automation and connectivity toward integrated intelligent production systems capable of improving operational efficiency and sustainability performance simultaneously. More recent topics, including *machine learning*, *green manufacturing*, and *Industry 5.0*, emerged prominently in 2024–2025. The appearance of these themes reflects the growing emphasis on human-centric, sustainable, and AI-driven manufacturing systems. In particular, the emergence of Industry 5.0 suggests a new research direction focusing not only on technological advancement but also on environmental sustainability, human collaboration, and resilient industrial ecosystems.

Compared with previous bibliometric studies that mainly emphasized Industry 4.0 technologies, the current findings demonstrate a stronger integration between artificial intelligence and sustainability-oriented manufacturing strategies. This evolution indicates that future manufacturing systems will increasingly rely on adaptive intelligence, predictive analytics, and environmentally responsible production models.

Overall, the trend topic analysis highlights the dynamic evolution of manufacturing research and confirms that sustainability, artificial intelligence, and intelligent automation are becoming central components of future industrial transformation.

6. Most Cited Documents

Citation analysis is an important component of bibliometric studies because highly cited publications represent the intellectual foundation and major research contributions within a scientific field. Identifying the most cited documents helps reveal influential studies, dominant research themes, and theoretical developments that shape the evolution of smart and sustainable manufacturing research within the Industry 4.0 context.

Figure 8 presents the top 10 most globally cited documents in the analyzed dataset, while Table 2 summarizes the authors, publication years, sources, and total global citations of each document.

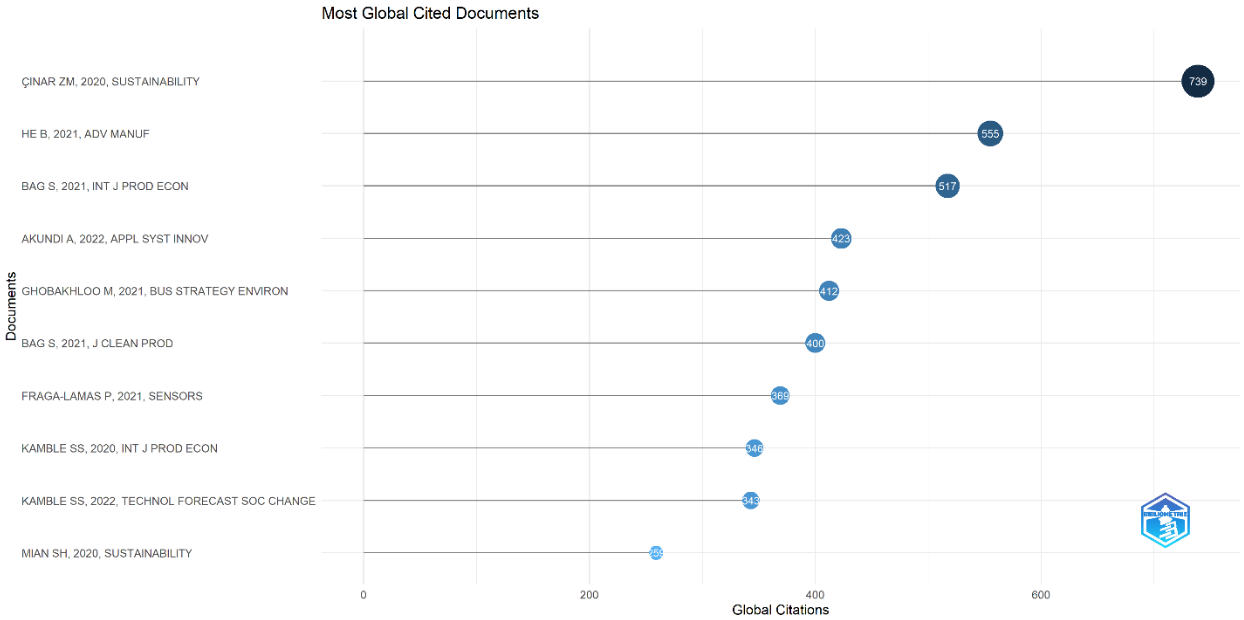

Figure 8. presents the top 10 most globally cited documents

Table 2. Top 10 Most Globally Cited Documents

Rank	Author	Year	Source	Global Cited
1	Cınar, Z. M.	2020	Sustainability	739
2	He, B.	2021	Advanced Manufacturing	555
3	Bag, S.	2021	International Journal of Production Economics	517
4	Akundi, A.	2022	Applied System Innovation	423
5	Ghobakhloo, M	2021	Business Strategy and the Environment	412
6	Bag, S.	2021	Journal of Cleaner Production	400
7	Fraga-Lamas, P.	2021	Sensors	369
8	Kamble, S. S.	2020	International Journal of Production Economics	346
9	Kamble, S. S.	2022	Technological Forecasting and Social Change	343
10	Mian, S. H.	2020	Sustainability	259

The most cited publication is the study by Çınar (2020) with 739 global citations, indicating the strong research interest in sustainability-oriented Industry 4.0 transformation. Other highly cited studies mainly discuss smart manufacturing, digitalization, big data analytics, and sustainable industrial systems.

Overall, the citation analysis shows that research in this field is strongly driven by the integration of Industry 4.0 technologies and sustainability objectives. The highly cited publications also demonstrate the multidisciplinary nature of smart and sustainable manufacturing research involving engineering, sustainability, and technology management perspectives.

7. Keyword Co-occurrence Network Analysis

Figure 9 presents the keyword co-occurrence network generated using VOSviewer. The visualization illustrates the conceptual relationships among major research topics within smart and sustainable manufacturing studies. The size of each node represents keyword frequency, while the connecting lines indicate the strength of relationships between research themes.

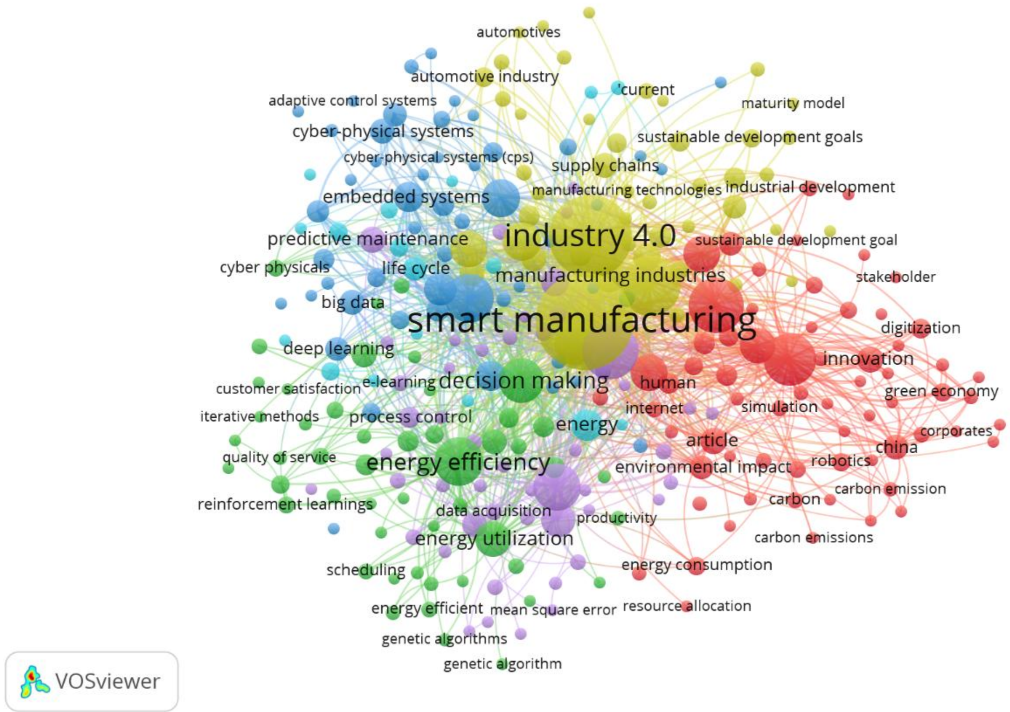

Figure 9. Presents the keyword co-occurrence network

The analysis identifies *smart manufacturing* and *Industry 4.0* as the most dominant and highly connected keywords, indicating their central role in the current manufacturing research landscape. These keywords are strongly associated with several technological and sustainability-related topics, including *energy efficiency*, *decision making*, *predictive maintenance*, *internet of things*, and *sustainable development*. This finding demonstrates that intelligent manufacturing systems are increasingly integrated with sustainability-oriented industrial strategies.

Several major thematic clusters can also be identified within the network. The first cluster mainly focuses on intelligent manufacturing technologies, including cyber-physical systems, embedded systems, deep learning, and predictive maintenance. This cluster reflects the growing importance of intelligent automation and real-time industrial monitoring in modern manufacturing environments.

The second cluster is closely related to sustainability and energy management themes, including energy efficiency, energy utilization, carbon emissions, and environmental impact. The strong interconnection between these keywords suggests that sustainable manufacturing has become an important research priority alongside industrial digitalization. Another significant cluster emphasizes industrial innovation and digital transformation topics, including innovation, digitization, robotics, and green economy. This cluster indicates that manufacturing research is increasingly oriented toward achieving industrial competitiveness while simultaneously supporting environmental sustainability objectives. Compared with previous bibliometric studies that mainly emphasized Industry 4.0 technologies and automation systems, the present findings reveal stronger integration between intelligent technologies and sustainability-oriented manufacturing approaches. The network structure demonstrates that manufacturing research has evolved from isolated technological implementation toward interconnected intelligent and environmentally responsible industrial ecosystems.

Overall, the co-occurrence network confirms that future manufacturing research will increasingly depend on the integration of artificial intelligence, sustainable production systems, digital transformation, and energy-efficient industrial operations to support adaptive and resilient manufacturing environments.

8. Overlay Visualization Analysis

Figure 10 illustrates the temporal evolution of research themes in smart and sustainable manufacturing during the 2020–2025 period. The visualization indicates a clear transition from foundational Industry 4.0 technologies toward sustainability-oriented and intelligent manufacturing systems.

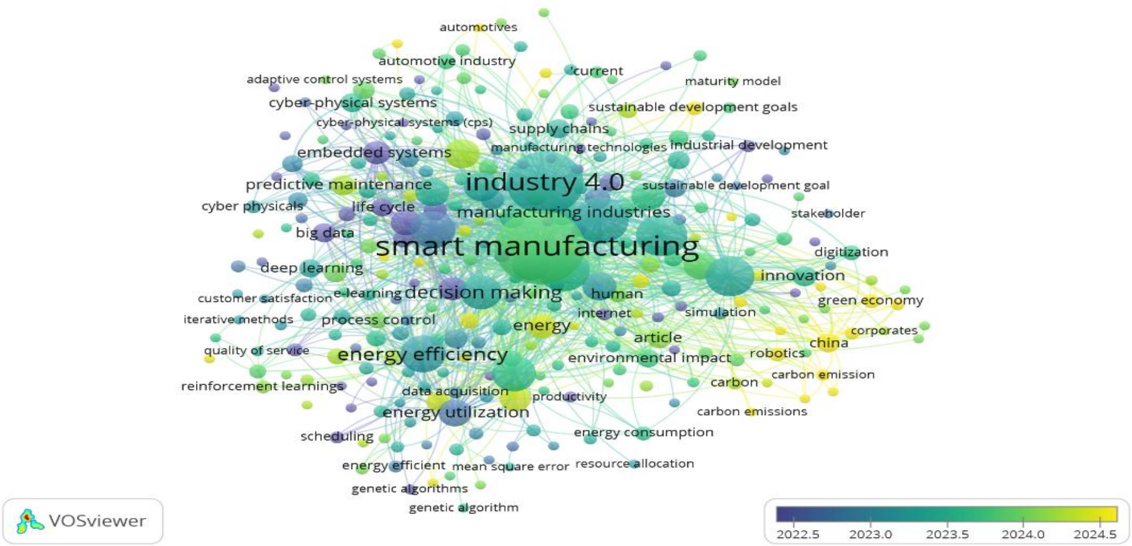

Figure 10. Overlay Visualization Analysis

Earlier studies were dominated by topics such as *cyber-physical systems*, *embedded systems*, *big data*, and *adaptive control systems*, reflecting the initial focus on industrial connectivity and automation infrastructure. In contrast, recent keywords including *green economy*, *carbon emission*, *sustainable development goals*, and *robotics* appear in brighter colors, indicating increasing research attention after 2023.

The strong and central position of smart manufacturing and Industry 4.0 confirms that both themes remain the core structure linking digital technologies and sustainability strategies. Meanwhile, the growing prominence of energy efficiency, decision making, and predictive maintenance suggests that current research is increasingly oriented toward intelligent optimization and operational sustainability rather than basic automation alone. Compared with earlier bibliometric studies that primarily emphasized industrial digitalization and IoT implementation, the present findings demonstrate a broader research shift toward low-carbon manufacturing, intelligent energy management, and sustainable industrial transformation. This indicates that sustainability is no longer treated as a secondary objective but has become structurally integrated into smart manufacturing research.

The emergence of keywords related to environmental performance and innovation also implies that future manufacturing systems will increasingly depend on AI-driven optimization, energy-efficient production, and sustainability-based industrial policies. These findings highlight an important research direction toward adaptive and environmentally responsible manufacturing ecosystems.

9. Density Visualization Analysis

Figure 11 presents the density visualization of keyword co-occurrence in smart and sustainable manufacturing research. In this visualization, brighter yellow areas indicate topics with the highest occurrence frequency and strongest interconnections, while green and blue areas represent less explored themes.

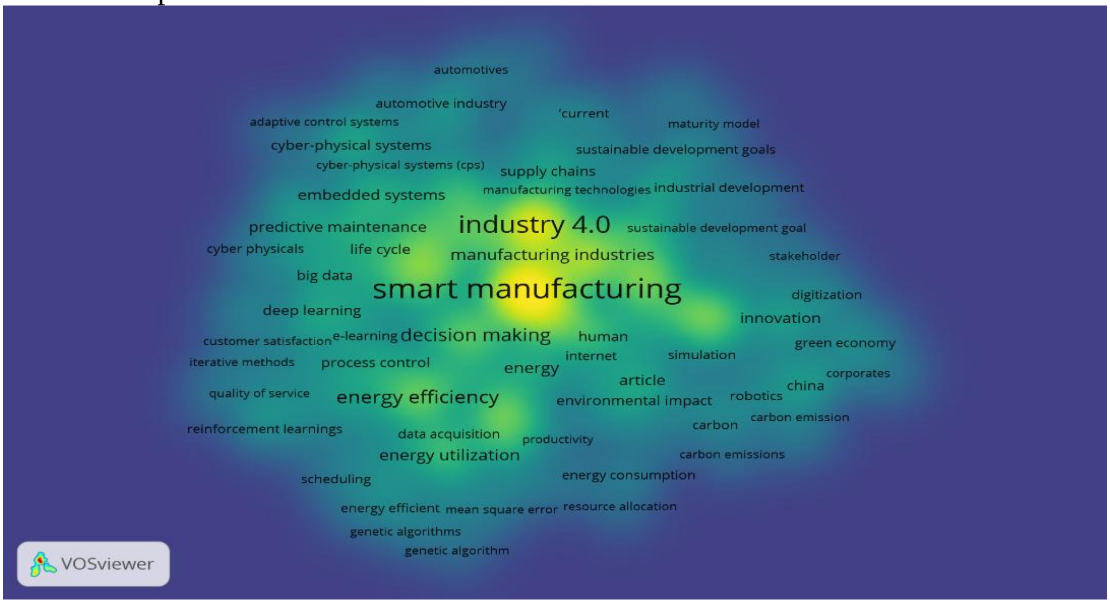

Figure 11. Presents the density visualization

The visualization shows that *smart manufacturing* and *Industry 4.0* form the main research concentration, confirming their dominant role as the central foundation of current manufacturing studies. Their high density indicates that most recent studies are strongly connected to digital manufacturing transformation and intelligent production systems.

High-density concentrations are also observed around energy efficiency, decision making, and manufacturing industries. This finding suggests that current research is increasingly focused on operational optimization, intelligent decision-support systems, and sustainable industrial performance. Unlike earlier Industry 4.0 studies that mainly emphasized automation and connectivity, recent research demonstrates stronger integration between intelligent technologies and energy-oriented sustainability strategies. Meanwhile, topics such as carbon emission, green economy, robotics, and environmental impact appear in medium-density areas. Although these themes are becoming increasingly relevant, their lower density compared with the core cluster indicates that sustainability-oriented implementation research is still developing and has not yet become fully mature within the manufacturing literature.

Several topics including genetic algorithm, reinforcement learning, resource allocation, and adaptive control systems appear in lower-density regions. This pattern indicates that advanced AI optimization methods and autonomous industrial intelligence remain relatively underexplored despite their high future potential. The limited concentration of these topics suggests opportunities for future research, particularly in AI-driven sustainable manufacturing systems and intelligent resource optimization. Compared with previous bibliometric studies that primarily concentrated on IoT and industrial automation, the present density analysis reveals a broader shift toward energy efficiency, environmental sustainability, and intelligent industrial decision-making. This finding indicates that manufacturing research is evolving toward more adaptive, low-carbon, and sustainability-centered industrial ecosystems.

Overall, the density visualization confirms that smart manufacturing research is currently dominated by the integration of Industry 4.0 technologies and sustainability objectives, while emerging AI-based optimization and environmental management themes continue to offer important directions for future investigation.

10. Research Implications and Future Directions

The findings of this study provide several important theoretical and practical implications for the development of smart and sustainable manufacturing research. From a theoretical perspective, the bibliometric analysis demonstrates that manufacturing research is evolving from conventional automation-oriented systems toward intelligent and sustainability-driven industrial ecosystems. The strong interconnection between Industry 4.0 technologies, artificial intelligence, energy efficiency, and sustainable development indicates that future manufacturing frameworks increasingly require integrated approaches combining digital intelligence with environmental sustainability.

The results also highlight the growing importance of interdisciplinary collaboration in manufacturing research. The integration of machine learning, predictive analytics, IoT, and sustainable production strategies suggests that future industrial systems will depend heavily on data-driven decision-making and adaptive manufacturing technologies. Therefore, researchers are encouraged to develop more comprehensive models that integrate technological innovation, operational efficiency, and sustainability performance within smart manufacturing environments.

From a practical perspective, the study indicates that manufacturing industries are increasingly prioritizing intelligent and environmentally responsible production systems to improve industrial competitiveness and operational resilience. Technologies such as predictive maintenance, energy-efficient manufacturing, and AI-driven optimization systems may support industries in reducing operational costs, improving resource utilization, and minimizing environmental impact. Consequently, policymakers and industrial stakeholders should strengthen investments in digital manufacturing infrastructure, sustainable industrial innovation, and intelligent production technologies.

The analysis further reveals several promising future research directions. Emerging topics such as Industry 5.0, green manufacturing, carbon emission reduction, sustainable development goals, and intelligent energy management systems remain relatively underexplored and require deeper investigation [25]. Future studies may also focus on integrating artificial intelligence with circular economy principles, low-carbon manufacturing systems, and human-centric industrial ecosystems to support long-term sustainable industrial transformation.

In addition, future bibliometric studies may expand the dataset by incorporating multiple scientific databases such as Web of Science and Dimensions to obtain broader research coverage and improve comparative analysis across disciplines and regions. Combining bibliometric analysis with systematic literature review approaches may also provide deeper conceptual understanding regarding the evolution of intelligent and sustainable manufacturing research.

CONCLUSION

This study conducted a bibliometric analysis of smart and sustainable manufacturing research within the Industry 4.0 context using 616 journal articles indexed in the Scopus database during the 2020–2025 period. The findings indicate a significant increase in scientific publications, reflecting the growing global interest in integrating intelligent technologies with sustainable manufacturing systems.

The analysis identified smart manufacturing, Industry 4.0, and sustainable development as dominant research themes, while emerging topics such as machine learning, green manufacturing, Industry 5.0, and energy efficiency demonstrate the evolving direction of future manufacturing research. The VOSviewer network analysis further revealed strong interconnections between artificial intelligence, industrial digitalization, and sustainability-oriented production strategies, indicating a transition toward adaptive and environmentally responsible industrial ecosystems. This study contributes to the existing literature by providing a comprehensive overview of the intellectual structure, thematic evolution, and emerging trends in smart and sustainable manufacturing research. The findings may support researchers, industrial practitioners, and policymakers in understanding the current research landscape and identifying future development opportunities for intelligent and sustainable industrial transformation.

Despite these contributions, the study has several limitations. First, the dataset was limited to the Scopus database and English-language journal articles, which may exclude relevant studies indexed in other databases. Second, the analysis relied primarily on bibliometric mapping techniques, which focus on publication metadata rather than in-depth content evaluation. In addition, the selected time period (2020–2025) may limit the representation of earlier foundational studies related to Industry 4.0 and sustainable manufacturing. Future research may expand the analysis by integrating multiple databases such as Web of Science or Dimensions and combining bibliometric methods with systematic literature review approaches to obtain deeper conceptual insights. Further studies are also recommended to explore emerging themes related to Industry 5.0, low-carbon manufacturing systems, circular economy integration, and AI-driven sustainable industrial optimization.

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