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Research Article

Bibliometric Analysis of Smart Manufacturing in Industry 4.0 Research Trends

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Abstract: Smart industry has become an important trend in the development of Industry 4.0, especially in promoting the creation of efficient systems in the manufacturing sector. Various countries and studies are encouraging the application of technologies such as IoT, digital twins, artificial intelligence, and smart factories to improve industrial efficiency and sustainability. Therefore, studies related to smart industry are important and necessary especially on the context of smart manufacturing in order to see the direction of future research trends. This study uses a qualitative approach with literature data from the Scopus database covering the period 2020 to 2025. Research trend analysis was conducted through data processing using Bibliometric analysis in R Studio and the VOSviewer applications. To identify the latest research trends regarding smart industry, particularly in the context of Industry 4.0 and smart manufacturing, this analysis can provide a comprehensive picture of future research developments and directions within a global context.

Keywords: Artificial Intelligence; Bibliometric; Industry 4.0; Smart Industry; Smart Manufacturing

1. Introduction

The Industrial Revolution 4.0 has brought fundamental changes to the global industrial landscape, particularly in the manufacturing sector. This transformation is characterized by the use of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, cloud computing, and automation, which enable the creation of more efficient, adaptive, and innovative production systems (Bi et al., 2022). The integration of this technology promotes automation, connectivity, and smarter data-driven decision-making in industrial processes. The concept of smart industry then emerged as a representation of the application of digital technology in industrial activities, with the aim of creating a smarter, more connected, and sustainable ecosystem. In the manufacturing industry, smart industry is realized through smart manufacturing, which is a real-time integrated production system that utilizes data access and analysis to meet customer needs more responsively. Various combinations of technologies such as machine learning, Big Data, predictive analytics, AI, and IoT are used not only to support the production process, but also for design, business strategy, and the development of innovative operating models (Hasibuan et al., 2024).

The implementation of smart manufacturing has a tangible impact on the supply chain. Digitalization, for example through the application of intelligent lots that store information in products or pallets, encourages the adoption of just-in-time manufacturing systems and increases supply chain flexibility. IoT integration strengthens data collection and analysis capabilities, while the application of AI and Big Data plays an important role in predictive maintenance, quality improvement, and production process optimization. As a result, the manufacturing sector has become more agile, responsive, and adaptive to changes in demand and market dynamics (Li et al., 2022). Historically, the manufacturing sector has always developed in line with technological advances to increase productivity and competitiveness. However, in the era of the Fourth Industrial Revolution, the increased integration of digital

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technology has provided a much more significant acceleration (Siska et al., 2023). The increasingly competitive business environment requires industries to continuously innovate and adopt new technologies. In addition, the emergence of sustainability and energy efficiency demands makes smart industry relevant not only for companies, but also in the context of green industry policies and the circular economy. This development shows that smart industry not only plays a role in improving operational efficiency, but also in supporting the sustainable development agenda at the global level. Thus, studying smart industry research trends in the manufacturing sector is crucial, not only to understand academic developments but also to provide strategic guidance for industry practitioners in effectively implementing technology.

In addition to boosting operational efficiency, technology integration in smart manufacturing also impacts the relationship patterns between companies, suppliers, and consumers. For example, the implementation of the Internet of Things (IoT) enables real-time tracking of raw materials, thereby maintaining product quality and minimizing delays in the supply chain. The impact of this transformation is felt not only by large companies but also by small and medium enterprises (SMEs) that are beginning to adopt smart industry principles. For SMEs, adopting digital technology can increase opportunities to enter the global supply chain through cost efficiency and increased product competitiveness. However, challenges arise from the relatively large initial investment required and the readiness of human resources. Therefore, research on smart manufacturing research trends also plays a role in answering how organizations of various sizes can capitalize on this opportunity while still maintaining sustainability aspects.

Literature on Industry 4.0 and smart manufacturing has indeed grown rapidly, but most research still focuses on the technical aspects of technology implementation or specific case studies at the company level. In fact, other dimensions such as international collaboration, human involvement, and industrial policy direction also play a major role in shaping a sustainable smart industry ecosystem. Relatively few studies have conducted comprehensive bibliometric analyses to map research trends in smart industry in the context of manufacturing. This study aims to identify publication trends and map key keywords to provide a deeper understanding of the development of smart industry research in the manufacturing sector, while also being relevant to practitioners and policymakers in formulating smart industry development strategies in the era of Industry 4.0.

2. Literature Review

Industry 4.0 was first introduced in 2011 in Germany through the "Industrie 4.0" initiative as part of the High-Tech Strategy 2020, which aims to increase manufacturing competitiveness through technological innovation. This concept marks a comprehensive transformation in production systems by integrating digital technology and the internet into conventional industries, giving rise to smart, connected, and largely autonomous manufacturing (Oztemel & Gursev, 2020). These changes not only bring automation to a higher level, but also enable the creation of intelligent, interconnected production systems capable of operating autonomously. To achieve this transformation, it is important to understand the main pillars of Industry 4.0, such as digitization, connectivity, and the application of advanced technology. From this foundation, the idea of smart industry or smart manufacturing was born, which is a production system that utilizes advanced technology to improve efficiency, flexibility, and sustainability. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), data analytics, robotics, cloud computing, and automation systems play a crucial role in creating factories that are adaptive and responsive to changes in market demand. Furthermore, the implementation of Industry 4.0 is not only oriented towards increasing productivity, but also supports mass customization, predictive maintenance, and reduction of environmental impact through the concept of green manufacturing (Nugrowibowo & Muslimin, 2023).

Smart manufacturing, as the tangible implementation of Industry 4.0, focuses on integrating digital technology to address the challenges of modern production complexity. The main factors in daily manufacturing operations are achieving throughput, quality, and cost targets while maintaining workplace safety. However, increasing product variety, changing customer demands, and global competitive pressures make these goals increasingly difficult to achieve. In this context, the use of cutting-edge technology is crucial. Artificial intelligence (AI) and its derivatives, such as machine learning and deep learning, play an important role in supporting data-driven decision making, improving quality, flexibility, and cost efficiency. Other technological advances such as the Internet of Things (IoT), cloud computing, big data, edge computing, robotics, and blockchain further strengthen the implementation of smart manufacturing through predictive maintenance, production automation, and more responsive supply chain management. One notable innovation is the digital twin, which is a virtual representation of a physical system that utilizes historical and real-time data for simulation, prediction, and optimization of manufacturing processes. This technology also strengthens the role of cyber-physical systems in improving communication, monitoring, and real-time control of production processes, thereby creating a more adaptive and sustainable system (Lee et al., 2020). It's important to understand that the technological advantage in smart manufacturing lies not in individual implementations, but rather in the integrated synergy between them. A digital twin, for example, cannot function optimally without the massive data streams provided by Internet of Things (IoT) sensors embedded throughout the production floor. This raw data is then processed by algorithms, Artificial Intelligence (AI) and machine learning to analyze performance, predict potential failures, and virtually simulate various production scenarios before they are implemented in the real world. This ecosystem enables companies to achieve unprecedented levels of optimization, where physical and cyber systems work in a continuous feedback loop to ensure every decision is based on accurate and relevant data.

As Industry 4.0 technology matures, global discourse is shifting toward a more advanced concept, Industry 5.0, which puts humans back at the center of the manufacturing process (human-centric manufacturing). While Industry 4.0 focused on automation and system efficiency, Industry 5.0 emphasizes collaboration between humans and intelligent machines. The goal is not to completely replace humans, but rather to empower them with technology. This includes the use of cobots (collaborative robots) working alongside human operators for high-precision tasks, as well as the use of augmented reality (AR) to provide guidance on machine assembly or maintenance directly before workers' eyes. As Industry 4.0 technology matures, global discourse is moving toward a more advanced concept, Industry 5.0, which puts humans back at the center of the manufacturing process (human-centric manufacturing). While Industry 4.0 focused on automation and system efficiency, Industry 5.0 emphasizes collaboration between humans and intelligent machines. The goal is not to replace humans entirely, but rather to empower them with technology. This includes the use of cobots (collaborative robots) working alongside human operators for high-precision tasks, as well as the use of augmented reality (AR) to provide guidance on machine assembly or maintenance directly before workers' eyes.

Along with this, research on smart manufacturing has continued to show significant growth in recent years. Early studies tended to focus on technical aspects, but recently the direction of research has expanded to broader themes, including energy efficiency, green manufacturing, and the circular economy. X. Li et al. (2021) even introduced the concept of Greentelligent Manufacturing (GIM), which is the integration of smart technology with environmentally friendly practices to reduce emissions and improve energy efficiency. With this approach, smart manufacturing serves a dual purpose: as a driver of productivity and as an instrument for responding to sustainability demands in the global era. In addition, smart manufacturing is also closely related to the development of the circular economy. Travaglioni et al. (2020) emphasize that digital transformation in industry, through the use of technologies such as artificial intelligence (AI), additive manufacturing, and cyber-physical systems, contributes to a more sustainable production model. The implementation of these technologies helps reduce production waste, extend product life cycles, and improve energy efficiency in the supply chain. Thus, smart manufacturing becomes an important foundation for integrating sustainability principles into modern production systems.

The use of big data in smart industries also strengthens the role of smart manufacturing in creating smarter and more sustainable production systems. Large-scale data analysis enables companies to optimize resource allocation, reduce energy consumption, and lower carbon emissions. This model also supports faster and more accurate decision-making, especially in the context of complex supply chain management (Gao et al., 2023). Thus, smart manufacturing is seen not only as the application of advanced technology to increase productivity but also as a comprehensive strategy that integrates digital innovation with environmental sustainability and industrial competitiveness in the global era and the future. Furthermore, the integration of big data with AI enables predictive models to anticipate market fluctuations and potential disruptions in real time. This capability ensures smart manufacturing systems remain resilient, adaptive, and aligned with economic and environmental goals.

3. Research Method

This research method was conducted in three main stages as shown in Figure 1. The first step was to collect bibliographic data from the Scopus database using the keyword "smart manufacturing" for the period 2020–2025, including titles, abstracts, keywords, authors, affiliations, publishers, and document types. The next step was to export the data in .csv format and process it using VOSviewer and R Studio (Bibliometrix–Biblioshiny) software to perform bibliometric analysis and information visualization, including mapping collaborations between authors, countries, and keywords. The final stage is to analyze the results of the visualization to identify publication trends, collaboration patterns, and dominant research topics in smart manufacturing, which are then further interpreted through a literature review to map the direction of future research.

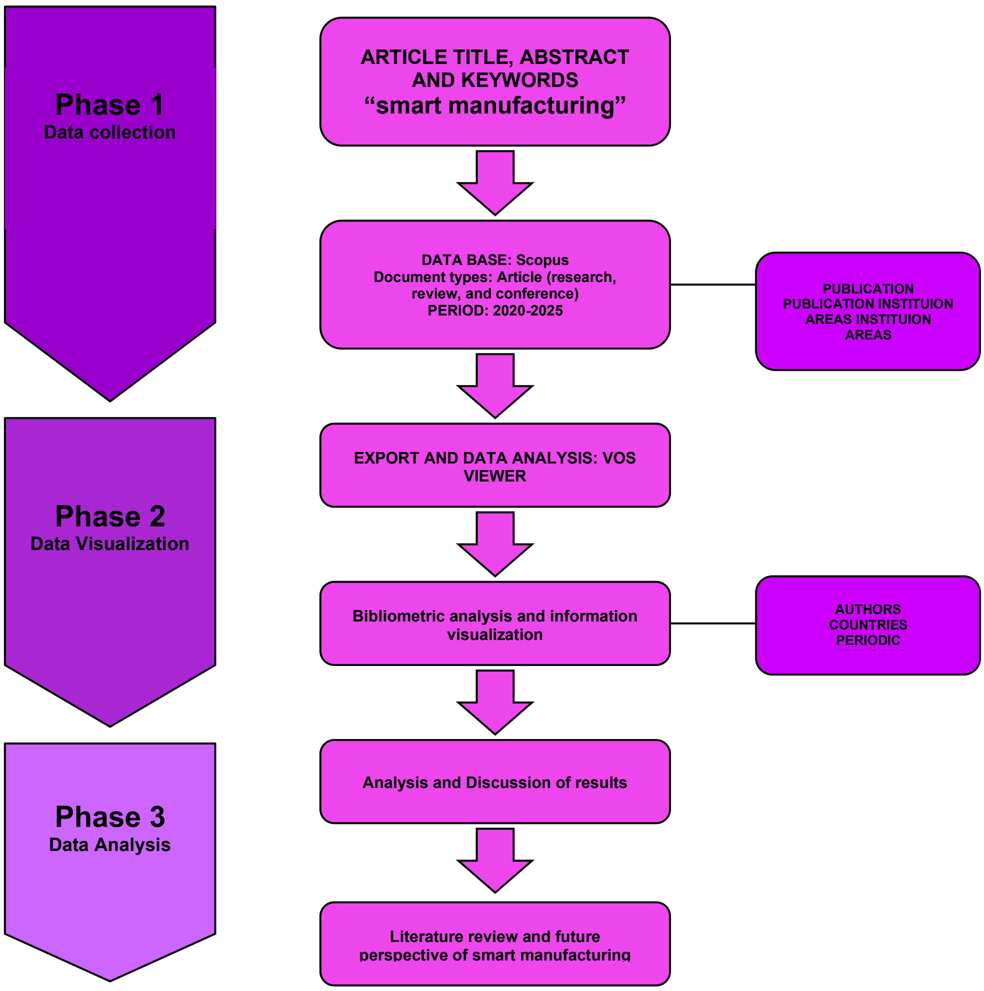

Figure 1. Methodology Phases Applied to the Present Work

This study utilizes bibliographic data from articles indexed in the Scopus database for the period 2020–2025 (Figure 1). The sampling technique used is total sampling, with variables analyzed including publication title, author, abstract, keywords, year of publication, journal publisher, type of publication, and institutional affiliation. Data were extracted from Scopus using Mendeley Desktop with the English search keyword "smart manufacturing" The search results were downloaded in .csv format through the Scopus export feature, then synchronized with Mendeley Desktop. Descriptive analyses, such as the distribution of annual publications, the number of publications per author, and journal publishers, were processed using Microsoft Excel. Next, topic trend mapping was carried out using the VOSviewer version 1.6.20 application using .csv data. The analysis used included country-based co-authorship to identify the largest contributions, as well as co-occurrence analysis on keywords to produce a visualization of the topic map and keyword network.

4. Results and Discussion

This section presents the results of a bibliometric analysis obtained from Scopus data for the period 2020–2025. The analysis includes an overview of publication metrics, annual scientific production trends, the most relevant publication sources, and a mapping of collaboration networks and keywords to comprehensively identify the smart manufacturing research landscape. Bibliometric analysis based on the main information related to research outputs published between 2020 and 2025. The dataset comprises 441 distinct sources with a total of 2,412 documents, reflecting an annual growth rate of 11.96%, indicating that smart industry is one of the fastest growing and most consistent areas of research. In total, 10,336 authors contributed to these publications, with no records of single-authored works. International collaboration is visible, with 29.06% of the studies involving co-authorship across countries, while the overall average reaches 10.1 authors per document. The collection includes 11,485 author-provided keywords and 17,749 cited references. On average, the documents are 1.98 years old and have received 17.76 citations each. This number reflects the significant attention given by academics to the issues of digital technology integration, smart manufacturing, and industrial sustainability.

Figure 2. Main Information Overview (Using R Studio)

This dataset includes 11,485 keywords provided by authors, demonstrating the diversity of topics explored in this field. A total of 17,749 references were cited, reflecting strong engagement with previous studies and the cumulative development of the literature. The relatively young average age of the documents, 1.98 years, indicates that this field is developing rapidly, with research results dominated by recent contributions. In addition, the average number of citations of 17.76 per document indicates that these publications have attracted significant academic attention, highlighting the relevance and impact of research in this field.

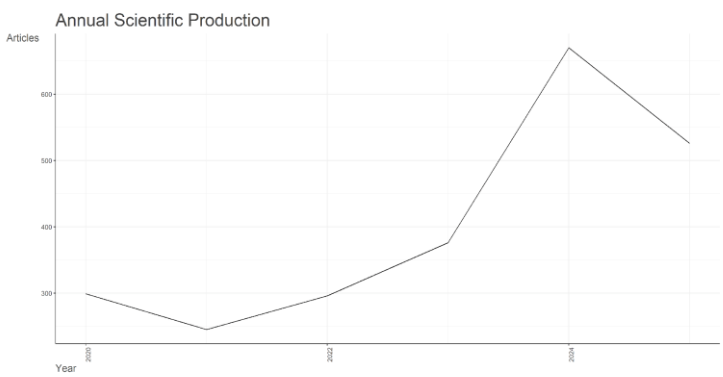

Figure 3. Annual Scientific Production (Using R Studio)

In the image, we can see how the number of scientific articles published has grown over a period of five years. In terms of scientific productivity, the number of publications in 2021 has decreased slightly, falling below 300. However, overall, the number of publications has increased consistently since 2020 and will peak in 2024 with more than 600 publications. Although there was a decline in the number of publications in 2025, the overall trend continues to show positive growth, reflecting that smart manufacturing remains a focus of global research. The slight decline recorded in 2021 is likely a lingering effect of the global disruption caused by the COVID-19 pandemic, which may have slowed some research projects and international collaborations. However, the sharp surge toward a peak in 2024 can be interpreted as an accelerated response by the research and industry community to the fragility of global supply chains exposed during the pandemic. The crisis has awakened many to the urgency of building more resilient, flexible, and decentralized manufacturing systems, directly driving investment and publications in the field of smart manufacturing.

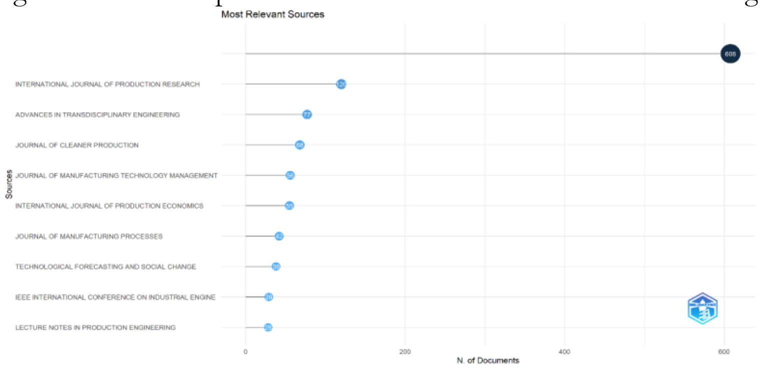

Figure 4. Most Relevant Sources (Using R Studio)

This image (figure 4) shows the number of authors who cite the most relevant scientific publication sources, sorted by the number of documents they have contributed. The results of bibliometric analysis show that research on smart manufacturing in the context of Industry 4.0 is spread across various leading publication sources. International Journal of Production Research is the journal with the largest contribution, publishing 120 articles, followed by the Advances in Transdisciplinary Engineering with 77 articles, Journal of Cleaner Production with 68 articles, and other journals. Each source has a corresponding circle that shows the number of documents it has contributed, and the further down the source name is, the lower the numbers are for each source. The presence of journals like the Journal of Cleaner Production in the top list also quantitatively confirms the findings from the keyword analysis. This indicates that sustainability is no longer a side theme but has become a central pillar of the smart manufacturing discourse, published in highly reputable journals.

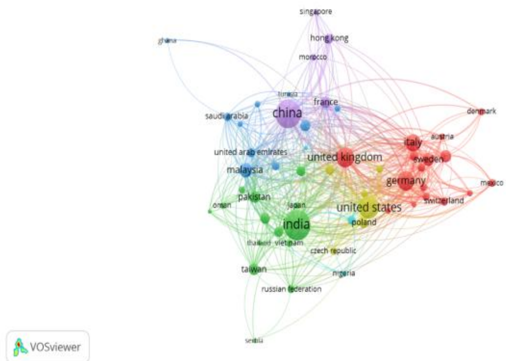

Figure 5. Network Visualization Co-Authorship Based on the Countries (Using Vos Viewer)

The image of figure 5 shows a network of authors based on the countries with the highest publication contributions in the field of smart manufacturing. Larger nodes, such as the United States, United Kingdom, India, China, Germany, and Italy, indicate high productivity and a central position in the global research network. The connecting lines between nodes illustrate the intensity of collaboration, showing that smart manufacturing research is driven by close international collaboration, especially between developed and developing countries.

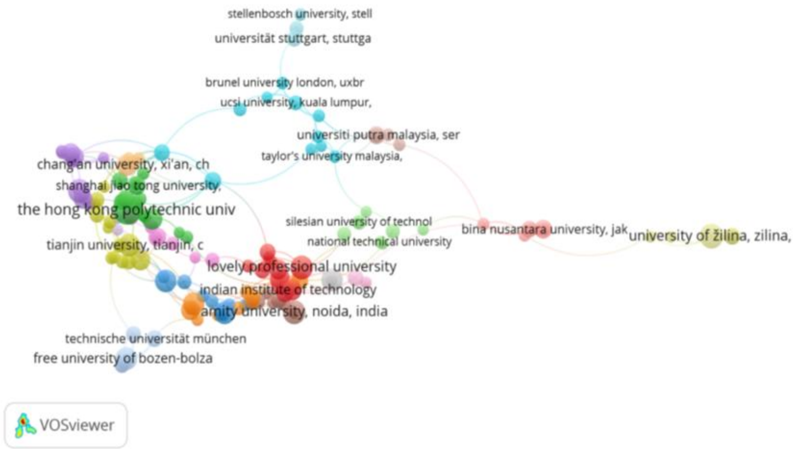

Figure 6. Network Visualization Co-authorship Based on the Organizations (Using Vos Viewer)

The visualization of co-authorship by organization shows the pattern of collaboration among universities and research institutions active in the field of smart manufacturing. The Hong Kong Polytechnic University, Shanghai Jiao Tong University, and Tianjin University are key nodes with a strong collaboration network, reflecting the dominant role of Chinese universities in driving related research. Similarly, Chang'an University and Technische Universitat Munchen appear prominently in the network, indicating significant contributions from European institutions in synergy with Asia. Furthermore, Indian universities such as Lovely Professional University, Amity University, and the Indian Institute of Technology also form a distinct cluster, demonstrating the active involvement of the Indian academic community in developing smart manufacturing studies. Universities from Southeast Asia, including University Putra Malaysia, Taylor's University, and BINUS University in Indonesia, are also included in the collaboration map, demonstrating the growing role of developing countries in the global discourse on Industry 4.0. This collaboration pattern confirms that smart manufacturing research is not only concentrated in developed countries but also involves institutions from developing economies.

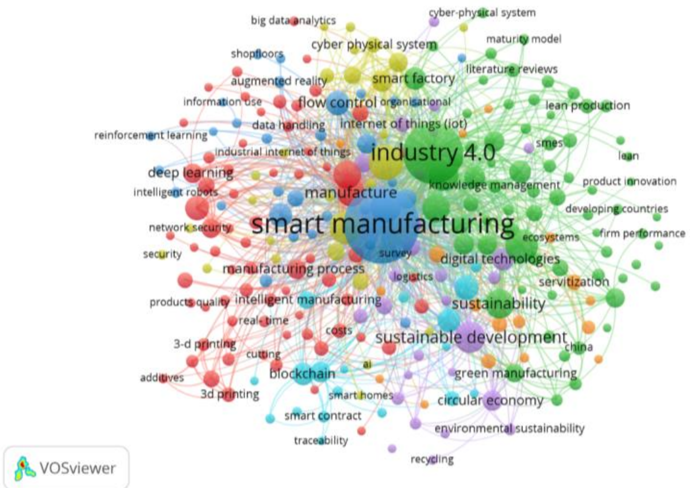

Figure 7. Network Visualization Keyword (Using Vos Viewer)

The following image shows a visualization map of research keywords related to smart manufacturing for the period 2020–2025 using VOSviewer co-occurrence analysis. Keywords that appear more frequently are visualized with larger node sizes, while the relationship between topics is shown through connecting lines. From this visualization, it can be seen that smart manufacturing is the main focus of scientific discussion, with close links to the concepts of industry 4.0, sustainability, and digital technologies. The colors in the network represent clusters of interrelated research themes. The blue cluster focuses on the core concepts of smart manufacturing and Industry 4.0, including the integration of digital technologies, manufacturing processes, and real-time data. The green cluster highlights links to sustainability aspects, such as sustainable development, green manufacturing, circular economy, and knowledge management, indicating a shift in research towards energy efficiency and green industry issues. The red cluster emphasizes supporting technologies such as artificial intelligence, deep learning, 3D printing, blockchain, and network security, signaling a push for technological transformation in smart factory operations. The yellow cluster is related to the topics of production management and innovation, including lean production, SMEs, and product innovation, which focus on the adaptation of small and medium-sized industries to digital transformation. The purple cluster is related to aspects of systems, such as cyber-physical systems, smart factories, and environmental sustainability, which demonstrate physical-digital integration in achieving sustainability. Overall, this map shows that smart manufacturing research not only addresses technical aspects, but also touches on the dimensions of sustainability, management, and cross-sector innovation.

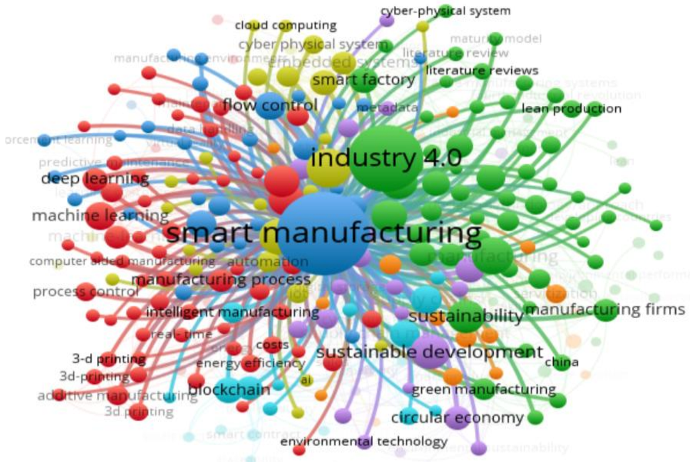

Figure 8. Overlay Visualization of Smart Manufacturing (Using Vos Viewer)

This image is a co-occurrence network map that visualizes the interrelationships between keywords in the field of smart manufacturing research. Larger nodes indicate higher frequency of occurrence, and in this case, "smart manufacturing" is the largest node and the main center of the network, confirming its position as the dominant focus in academic studies. Keywords that are closest to smart manufacturing indicate a very strong connection, including industry 4.0, manufacturing process, intelligent manufacturing, automation, machine learning, and deep learning. This illustrates that research on smart manufacturing focuses not only on the concept of technology integration, but also on the application of smart technology and automation to improve production processes. In addition, the emergence of keywords such as real-time, process control, and computer-aided manufacturing confirms that issues of efficiency, response speed, and quality control are important aspects in the development of smart manufacturing.

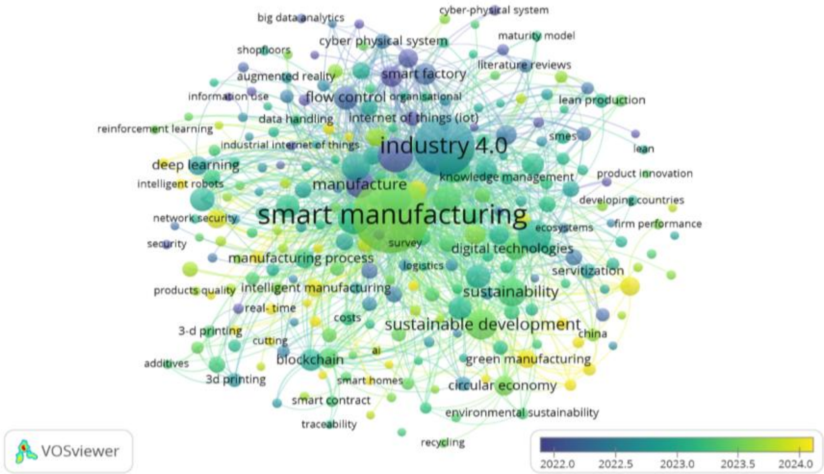

Figure 9. Overlay Visualization of Smart Manufacturing (Using Vos Viewer)

The image shows an overlay visualization of research keywords smart manufacturing for the period 2020–2025. This visualization displays different colors on keyword nodes to indicate the temporal development of publications, with color gradients from dark blue to bright yellow. Dark blue represents keywords at the beginning of the research period until around 2022. In this phase, topics such as industry 4.0, cyber-physical systems, and deep learning appeared frequently, indicating an initial research focus on technical aspects and the foundations of industrial digitization.

Furthermore, green nodes indicate keywords that frequently appeared in the middle of the period, around 2023. Topics in this group include digital technologies, knowledge management, intelligent manufacturing, and logistics. These keywords confirm the shift in research towards technology integration in operational management, manufacturing process optimization, and supply chain efficiency improvement. Meanwhile, bright yellow nodes represent newer keywords that are trending in 2024, such as sustainable development, green manufacturing, circular economy, blockchain, and environmental sustainability. The emergence of these keywords indicates the latest direction of research, which increasingly emphasizes sustainability, energy efficiency, and the adoption of cutting-edge technologies such as blockchain to support transparency and traceability in the supply chain.

Upon further examination, the color distribution on this map also shows a correlation between the early, middle, and latest phases. Topics that emerged earlier, such as IoT or deep learning, served as the basis for developing further themes in the middle of the period, such as intelligent manufacturing and knowledge management. Furthermore, the results of the integration of these technologies became the foundation for addressing sustainability challenges, thereby encouraging the emergence of current keywords related to the circular economy and sustainable development. This demonstrates the logical continuity in the evolution of smart manufacturing research.

Overall, this overlay visualization shows the dynamics of smart manufacturing research, from its beginnings focusing on digitization and automation, continuing to the integration of technology in manufacturing systems, to the most advanced stage emphasizing sustainability and the transformation towards a green industry. This indicates that the field of smart manufacturing is not only developing technically, but is also increasingly connected to the global agenda related to sustainable innovation and environmentally friendly industrial policies.

5. Conclusions

Bibliometric analysis shows that research on smart manufacturing has experienced steady growth between 2020 and 2025, with over 2,400 papers published and an annual growth rate of 11.96%. The United States, China, India, Germany, and the United Kingdom are the countries with the highest contributions, forming a strong international collaborative network for knowledge exchange. At the institutional level, universities such as Hong Kong Polytechnic University, Shanghai Jiao Tong University, and Technische Universität München play a central role as hubs for global research partnerships. These findings confirm that both countries and organizations are actively shaping the global discourse on Industry 4.0.

Keyword mapping further confirms that core terms such as smart manufacturing, Industry 4.0, the internet of things (IoT), and AI remain a key focus, indicating the importance of digitalizing manufacturing processes. However, temporal analysis reveals significant thematic evolution. While early research was dominated by technical aspects such as cyber-physical systems and automation, current research trends show a marked shift towards sustainability, the circular economy, and green manufacturing.

Overall, the study confirms that smart manufacturing is evolving beyond technical integration into a more holistic concept that connects technology, sustainability, and global collaboration. The overlay visualization further demonstrates this dynamic, where earlier research focused on cyber-physical systems and IoT, then shifted to intelligent manufacturing and logistics, and most recently toward sustainable development and green innovation. These findings highlight that smart manufacturing is not only a tool for efficiency and productivity but also a strategic enabler of sustainable development and global industrial transformation.

The results of this study indicate that developing smart manufacturing requires synergy between academics, practitioners, and policymakers. Academics should focus their research not only on technical aspects but also on sustainability and social impact. Industrial practitioners are encouraged to utilize smart technology as a strategy to increase efficiency while supporting green industry. Meanwhile, regulatory support from the government is needed to expand technology adoption, particularly in the SME sector, and to ensure that digital transformation is inclusive and sustainable.

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