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Bibliometric Study on IoT Adoption in Smart Manufacturing: Trends, Challenges, and Opportunities

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ABSTRACT

This bibliometric study investigates the adoption of the Internet of Things (IoT) in smart manufacturing, examining the trends, challenges, and opportunities that have shaped this evolving field from 2000 to 2022. Utilizing data sourced exclusively from Scopus and analyzed through VOSviewer, the research identifies core themes, tracks their progression over time, and highlights the key contributors and collaborations across countries. The analysis reveals a significant shift from basic IoT applications towards more sophisticated integrations like machine learning, digital twins, and enhanced security protocols. The study also underscores the crucial role of international collaboration in advancing IoT research and addresses the pressing challenges such as interoperability, security concerns, and the workforce skills gap. Furthermore, it suggests future research directions, including the need for standardized IoT frameworks and the exploration of sustainable IoT practices. This study provides a comprehensive overview of the IoT landscape in manufacturing, offering insights into its future trajectory and the potential for transformative industry advancements.

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1. INTRODUCTION

The advent of the Internet of Things (IoT) has marked a transformative phase in the industrial sector, commonly referred to as Industry 4.0. This revolution is characterized by the integration of digital and physical systems, which facilitates the creation of smart and autonomous production environments [1], [2]. IoT, being at the forefront of this revolution, offers a myriad of opportunities to enhance manufacturing processes through improved connectivity, efficiency, and automation (Bi et al., 2018). As industries continuously strive for optimization, IoT technologies become pivotal in enabling real-time data collection and analysis, leading to more informed decision-making and increased operational efficiency [3], [4].

The scope of IoT adoption in manufacturing extends beyond mere technological upgrades; it redefines how manufacturers operate, innovate, and deliver products. The integration of IoT devices with traditional manufacturing processes creates a network of interconnected devices capable of communicating and making decentralized decisions. This network, powered by data-driven insights, can drastically reduce downtime, enhance product quality, and ensure a safer working environment [5], [6]. However, despite these advantages, the adoption of IoT in manufacturing is accompanied by significant challenges such as data security, interoperability between devices, and a high initial investment cost, which can impede its widespread implementation [1], [7].

Moreover, the literature on IoT adoption in manufacturing is vast and growing, making it increasingly difficult to capture and synthesize all relevant knowledge in this field [6]. This issue is compounded by the rapid pace of technological advancements, which often outstrips the ability of academic research to keep up. As a result, there exists a gap between the potential applications of IoT in manufacturing and the documented evidence of its impact and challenges [8]. This gap highlights the need for a comprehensive review and analysis of the existing research to understand the current trends, challenges, and future opportunities in the field of IoT-enabled smart manufacturing.

A bibliometric analysis serves as an effective method to address this need by quantitatively analyzing the vast body of literature available on the topic. By employing bibliometric techniques, researchers can identify not only the volume and growth trends of the literature but also the key themes, influential studies, and research gaps. Such an analysis can provide a structured overview of the state of research on IoT in manufacturing, highlighting the evolution of themes over time and pointing out under-researched areas that hold potential for future exploration [9].

Despite the recognized benefits of IoT in manufacturing, its adoption faces several barriers that are not sufficiently addressed in the literature. The primary issues include technological heterogeneity, security vulnerabilities, and substantial initial costs associated with IoT infrastructure development. Additionally, there is a lack of comprehensive studies that map out the evolution of IoT adoption in manufacturing, which could inform stakeholders about the maturity of research in this area and guide future studies. This research gap necessitates a bibliometric study that can consolidate existing knowledge, uncover emerging trends, and highlight persisting challenges and opportunities in IoT adoption within the smart manufacturing sector.

The main objective of this study is to conduct a comprehensive bibliometric analysis of the literature on IoT adoption in smart manufacturing. This will involve mapping the research landscape to identify and analyze trends, challenges, and opportunities that have been documented over the past decade. The analysis aims to elucidate the evolution of research themes, pinpoint seminal works and key researchers, and uncover areas that require further investigation. Through this systematic exploration, the study seeks to provide a detailed understanding of the field's development and offer insights into potential future directions for researchers and practitioners alike.

2. LITERATURE REVIEW

2.1 Evolution of IoT in Smart Manufacturing

The concept of the Internet of Things (IoT) in manufacturing, commonly referred to as Industrial IoT (IIoT), represents a paradigm shift towards fully digitalized, intelligent production systems [10]. This transition is a key component of Industry 4.0, where manufacturing processes are enhanced through smart devices that collect and analyze data, enabling automated and optimized operations [11]. Several studies have identified the critical role of IoT technologies in improving manufacturing efficiency, product quality, and operational safety [12]. IoT devices are interconnected through a network that allows for real-time monitoring and decision-making, which is crucial for predictive maintenance, supply chain management, and energy consumption optimization [13].

2.2 *Technological Frameworks and Models*

The implementation of IoT in manufacturing requires robust technological frameworks that ensure seamless connectivity and interoperability among diverse devices and systems. As noted by [14] , such frameworks must support standard communication protocols and ensure data integrity and security. Several models have been proposed to address these needs, including the Reference Architectural Model Industrie 4.0 (RAMI 4.0) and the Industrial Internet Consortium (IIC) framework, which provide guidelines for implementing IoT technologies in a standardized, secure manner [15].

2.3 *Barriers to Adoption*

Despite the potential benefits, the adoption of IoT in smart manufacturing faces several barriers. These include the complexity of integrating IoT solutions with existing legacy systems, concerns about data privacy and security, and the significant initial investment required for IoT infrastructure [16]. Another significant challenge is the lack of skilled workforce capable of managing and operating IoT-enabled systems. This skills gap can hinder the effective deployment and utilization of IoT technologies in manufacturing environments [17].

2.4 *Security and Privacy Concerns*

Security is a major concern in IoT-enabled manufacturing due to the increased vulnerability to cyber-attacks that can disrupt manufacturing operations and compromise sensitive data [18]. Privacy issues arise from the extensive amount of data collected by IoT devices, which includes potentially sensitive information that must be protected from unauthorized access [19]. Studies have suggested the need for robust cybersecurity measures and frameworks to address these concerns, ensuring that data integrity and privacy are maintained.

2.5 *Economic and Operational Impacts*

The economic benefits of IoT in manufacturing are significant, as they include reductions in operational costs, improved asset utilization, and enhanced product quality [20]. IoT also enables better demand forecasting and inventory management, which can lead to more efficient supply chain operations [21]. However, the financial investment associated with implementing IoT technologies can be substantial, and the return on investment (ROI) may vary depending on the specific technologies adopted and the scale of implementation [22].

3. METHODS

This study employs a bibliometric analysis focused solely on scholarly articles indexed in the Scopus database to explore the domain of IoT adoption in smart manufacturing. The Scopus database is chosen for its extensive coverage of high-quality journals that publish research on industrial engineering, IoT applications, and smart technologies. The search strategy is designed to capture articles using keywords such as "Internet of Things," "IoT," "smart manufacturing," and "Industry 4.0," from January 2000 up to the present. The inclusion criteria are limited to peer-reviewed articles that explicitly discuss technological implementations, challenges, or advancements of IoT within the manufacturing sector. This approach ensures a comprehensive collection of data, which is critical for a detailed bibliometric study.

For the analysis of the retrieved literature, the study utilizes VOSviewer, a software tool specifically developed for constructing and visualizing bibliometric networks. This tool will be used to conduct co-citation analysis, bibliographic coupling, and to map the co-occurrence of keywords within the dataset. These analyses will help identify the most cited and influential papers, illustrate the structural connections between various research publications, and reveal the main themes and trends within the IoT in smart manufacturing research. Additionally, VOSviewer will enable the visualization of co-authorship networks, which will shed light on the collaborative patterns among scholars and research institutions in this field.

4. RESULTS AND DISCUSSION

4.1 Keyword Co-Occurrence Network

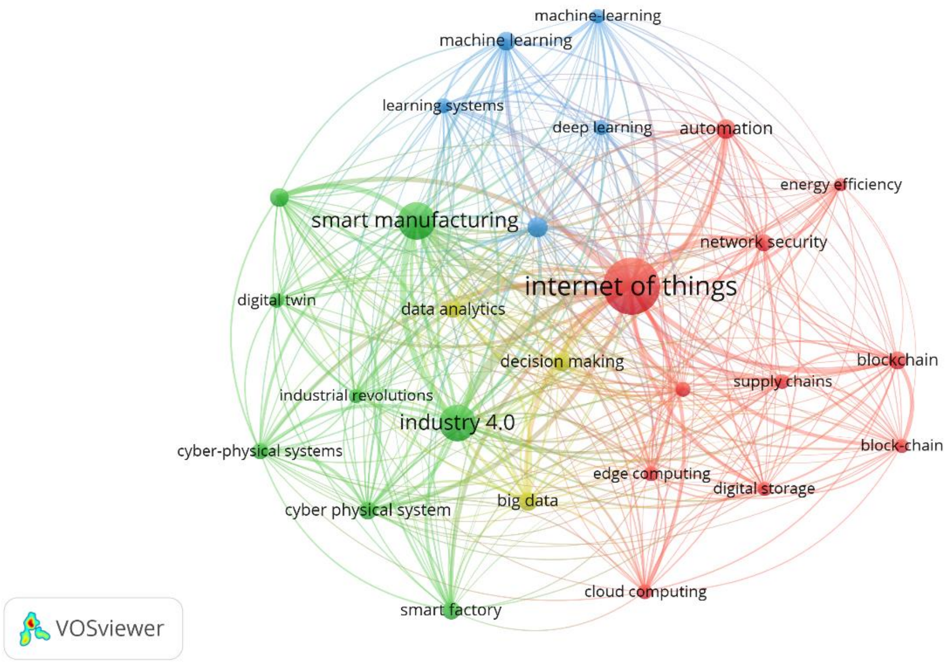

Figure 1. Network Visualization

Source: Data Analysis Result, 2025

This VOSviewer network visualization presents a rich landscape of research areas interconnected through the overarching themes of the Internet of Things (IoT) in the context of smart manufacturing and Industry 4.0. The network is segmented into several clusters, each represented by a different color indicating the concentration of topics that share a common research focus. The most prominent cluster, centered around "Internet of Things," illustrates its pivotal role in linking various technological and operational aspects within the manufacturing industry. At the heart of the network, the "Internet of Things" node acts as a central hub, with dense connections to other major nodes like "smart manufacturing," "industry 4.0," "big data," and "cyber-physical systems." This centrality underscores IoT's integral role in advancing manufacturing technologies, where it serves to integrate data-driven systems and enhance connectivity between machines and processes. The links to "big data" and "cyber-physical systems" highlight the importance of data management and real-time information processing in optimizing manufacturing operations.

The visualization also emphasizes the significance of "machine learning," "cloud computing," and "edge computing" as essential components of IoT implementations in manufacturing. These technologies support the processing and analysis of large volumes of data generated by IoT devices, facilitating more efficient decision-making processes and automation. "Machine learning" and its associated nodes like "deep learning" suggest a focus on predictive analytics and intelligent automation, which are crucial for predictive maintenance and quality control. Adjacent to the technological advancements are nodes concerned with "network security" and "energy efficiency," indicating a growing research focus on protecting IoT environments and optimizing energy use in manufacturing processes. The presence of "blockchain" in the network points towards an emerging interest in securing IoT transactions and data exchanges, which is essential for maintaining integrity and trust in fully digitalized manufacturing environments.

Lastly, the network shows emerging trends through nodes like "digital twin" and "supply chains," suggesting that future research is moving towards more integrated and holistic approaches to smart manufacturing. Digital twins represent a significant advancement in simulating and optimizing manufacturing processes, while enhanced supply chain integration focuses on the broader implications of IoT for logistics and distribution. These trends indicate a shift towards comprehensive systems that not only focus on production but also encompass the entire product lifecycle management.

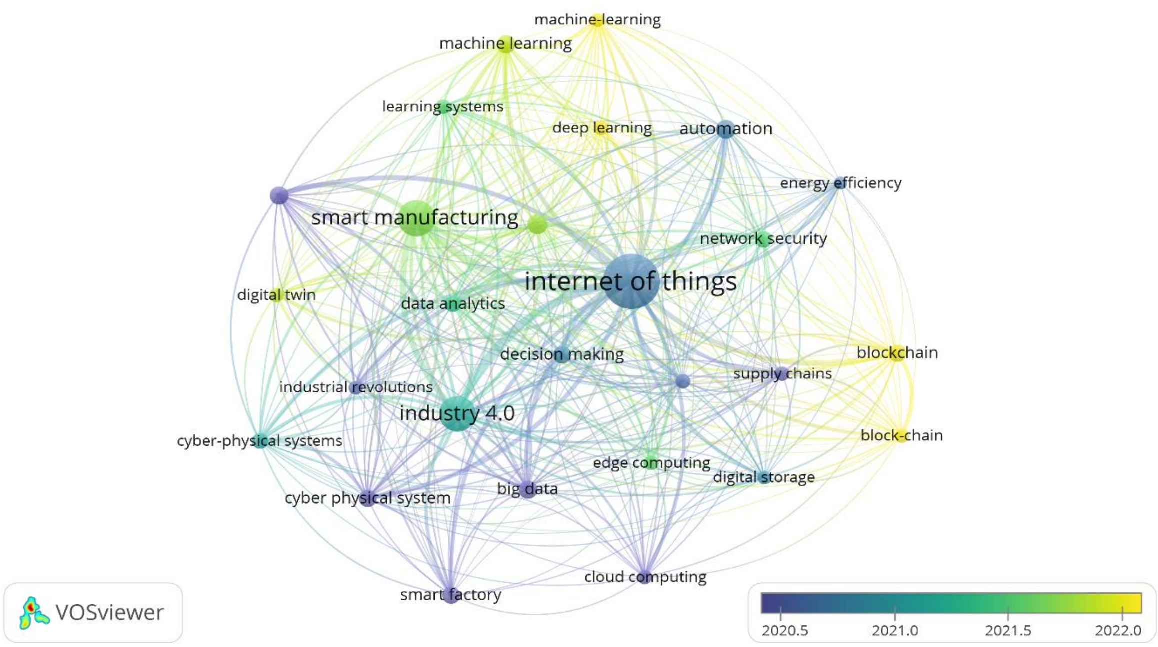

Figure 2. Overlay Visualization

Source: Data Analysis Result, 2025

This overlay visualization illustrates the temporal development of research themes within the field of IoT in smart manufacturing from mid-2020 to late 2022. The color gradient from yellow to blue across nodes denotes the evolution of research focus over time, with yellow indicating more recent research activities. This temporal coding highlights that topics such as "digital twin," "edge computing," and "blockchain" have received increasing attention in the more recent parts of the timeline, reflecting the industry's push towards more sophisticated and secure IoT implementations. Conversely, foundational concepts like "big data" and "cloud computing" display a shift from a more concentrated early focus (shown in blue), indicating these areas have mature and well-established research bases.

Recent themes showing a marked increase in research activity, denoted by yellow hues, include "machine learning" and "energy efficiency." This suggests a significant shift towards optimizing IoT systems for better energy management and leveraging advanced machine learning techniques to improve automation and predictive maintenance within manufacturing processes. The presence of yellow in "supply chains" indicates a growing recognition of the impact of IoT on enhancing supply chain transparency and efficiency, likely spurred by recent global supply chain challenges. In contrast, older, more established areas like "industry 4.0" and "cyber-physical systems" appear in cooler tones, suggesting that while they remain central to IoT discussions, the explosive growth in these areas may have plateaued as the focus shifts towards newer applications and challenges.

The increasing emphasis on "network security" and "blockchain" in more recent studies (indicated by their transition towards warmer colors) underscores the critical importance of securing IoT networks as they become more complex and integral to manufacturing operations. Additionally, the emerging focus on "digital twin" technology indicates a promising area for further exploration, particularly in its capacity to enhance real-time monitoring and simulation of manufacturing processes. This trend towards integrating cutting-edge technologies suggests a continued evolution towards more autonomous, efficient, and secure manufacturing environments, providing a roadmap for academic and industrial research priorities.

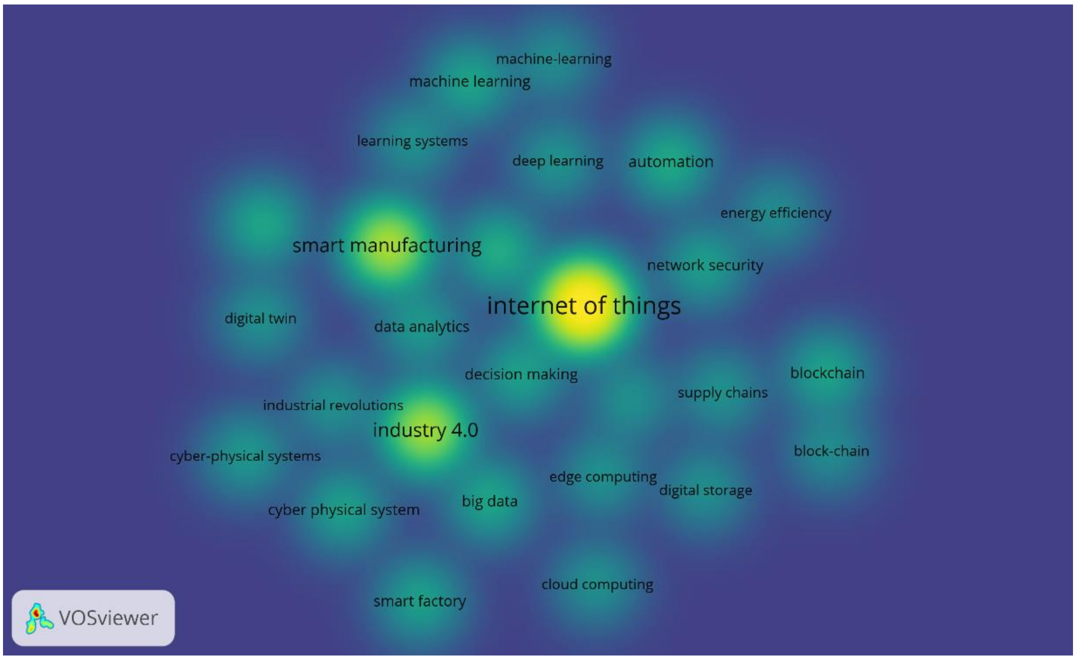

Figure 3. Density Visualization

Source: Data Analysis, 2025

The density visualization provides a vivid representation of the concentration of research interest within the field of IoT in smart manufacturing. In this visualization, areas with higher densities are indicated by brighter colors, revealing the core themes that have accumulated substantial scholarly attention. The bright concentration around "Internet of Things" at the center signifies it as the focal point of research activity, acting as a nexus connecting various subfields like "smart manufacturing," "data analytics," and "network security." This central positioning underscores the fundamental role of IoT as the backbone of Industry 4.0 innovations, impacting diverse aspects of manufacturing from operational efficiency to cybersecurity. Adjacent to the central node, the areas highlighted in green such as "machine learning," "automation," and "digital twin" reflect emerging trends that are garnering increasing focus within the academic community. The visual prominence of "machine learning" and its connection to "deep learning" suggests a robust interest in advancing IoT applications through intelligent algorithms that enhance predictive capabilities and automation within smart manufacturing setups. Furthermore, the relatively significant focus on "network security" and "blockchain" reflects the growing recognition of the importance of secure data handling and transaction systems in IoT frameworks, which are crucial for protecting sensitive industrial operations from cyber threats.

4.2 Co-Authorship Network

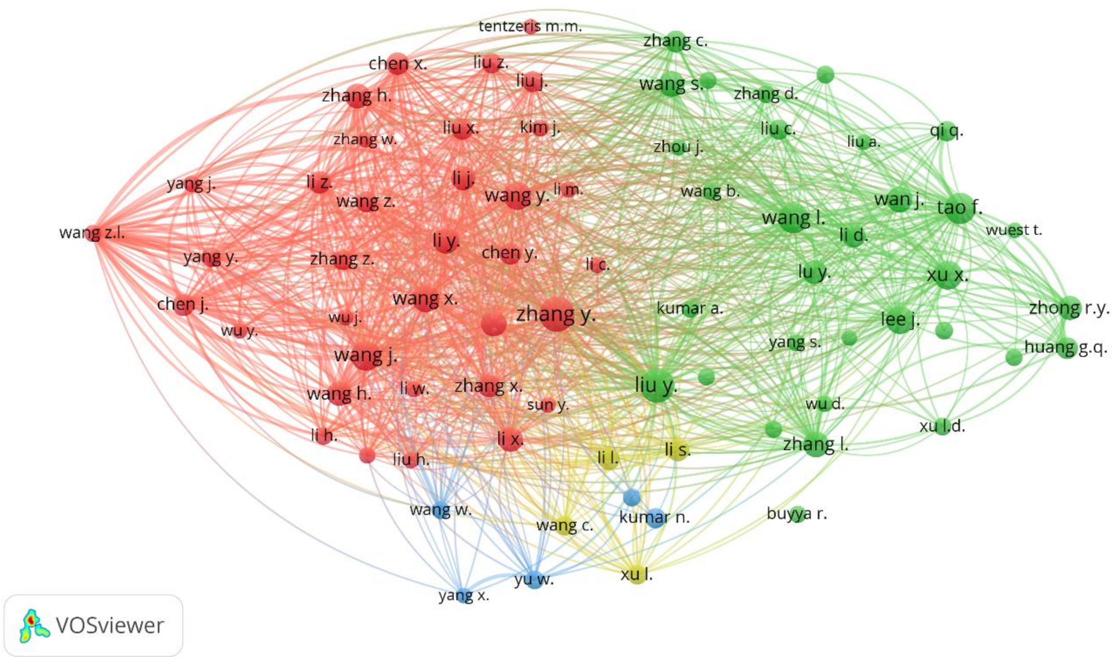

Figure 4. Author Collaboration Visualization

Source: Data Analysis, 2025

This VOSviewer visualization represents a co-authorship network among researchers in the field of IoT and smart manufacturing. The various clusters, distinguished by different colors, signify groups of researchers who frequently collaborate on scholarly papers. The size of each node (representing individual researchers such as "Wang," "Zhang," "Liu," among others) indicates the volume of publications or prominence of the researcher in the network, with larger nodes signifying more prolific authors. The lines between the nodes denote co-authorship links, with thicker lines suggesting more frequent collaboration between the connected authors. The red cluster in the center, densely packed with interconnected nodes, likely represents a core group of researchers who are central to the development of this field and collaborate extensively. The green cluster, on the other hand, might represent an emerging group or a specialized sub-domain within the broader research community.

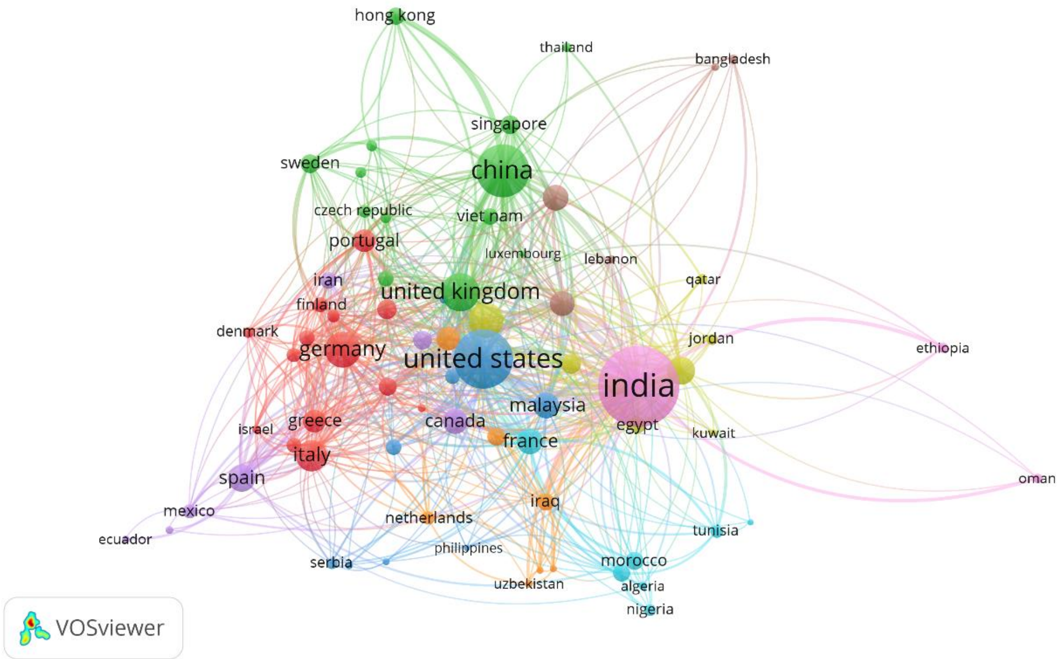

Figure 5. Country Collaboration Visualization
Source: Data Analysis, 2025

This VOSviewer visualization depicts a country co-authorship network, illustrating the international collaboration in research related to IoT and smart manufacturing. Each node represents a country, with the node size indicating the volume of publications or intensity of research activity from that country. The various colors symbolize different clusters or groups of countries that frequently collaborate on research projects. Lines between nodes show co-authorship links, where thicker lines suggest stronger or more frequent collaborations. Notably, countries like the United States, China, and India are prominent, reflecting their significant contributions to the field and central roles in global research networks. The visualization also highlights active research collaborations between countries in Europe such as Germany, the United Kingdom, and France, as well as between Asian countries like China, India, and Singapore.

4.3 Citation Analysis

Table 2. Top Cited Research

Citations	Authors and year	Title
2064	[23]	Intelligent Manufacturing in the Context of Industry 4.0: A Review
1359	[24]	Literature review of Industry 4.0 and related technologies

Citations	Authors and year	Title
1255	[25]	Digital Twin: Enabling Technologies, Challenges and Open Research
888	[26]	Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges
880	[27]	Internet of things and supply chain management: a literature review
847	[28]	Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison
740	[29]	INDUSTRY 4.0: THE INDUSTRIAL INTERNET OF THINGS
716	[30]	China's manufacturing locus in 2025: With a comparison of “Made-in-China 2025” and “Industry 4.0”
548	[31]	Blockchain for the future of sustainable supply chain management in Industry 4.0
513	[32]	Edge Computing in Industrial Internet of Things: Architecture, Advances and Challenges

Source: Publish or Perish Output, 2025

Discussion

The bibliometric analysis conducted in this study offers a comprehensive overview of the research landscape in IoT adoption within smart manufacturing, revealing key themes, influential contributors, and collaborative networks. The dense interconnectivity between terms like "Internet of Things," "smart manufacturing," "machine learning," and "Industry 4.0" underscores the integral role of IoT technologies in driving advancements in manufacturing. These technologies are not isolated in their application; rather, they are part of a synergistic ecosystem aimed at enhancing efficiency, quality, and sustainability in manufacturing processes. The temporal progression of research themes from foundational concepts such as "big data" and "cloud computing" to more recent focuses on "digital twins" and "edge computing" indicates a shift towards more sophisticated, real-time processing and analysis capabilities. This evolution reflects the industry's response to the increasing demand for more agile and responsive manufacturing systems that can adapt to changing market conditions and complexities.

1. Key Research Themes

The prominence of "machine learning" and "automation" in recent research highlights the trend towards autonomous systems that can predict failures, optimize operations, and personalize production through advanced data analytics. The integration of machine learning with IoT devices facilitates these capabilities, offering significant improvements over traditional manufacturing approaches. Similarly, the focus on "energy efficiency" and "network security" points to an increasing awareness of the need for sustainable and secure manufacturing practices. As IoT devices proliferate across the manufacturing sector, ensuring the security of these devices and the data they handle becomes paramount. Furthermore, the visualization of country collaborations reveals that research in IoT and smart manufacturing is a global endeavor, with significant contributions from the United States, China, and India. These countries not only lead in terms of volume of research but also in influencing the research directions of the global community. The strong networks between countries in Europe and Asia highlight the collaborative nature of modern research, where cross-border partnerships help pool resources, knowledge, and expertise to tackle complex technological challenges.

2. Challenges and Opportunities

Despite the advancements depicted in the bibliometric analysis, several challenges remain. The integration of IoT technologies with existing manufacturing infrastructures often requires substantial upfront investment and poses interoperability issues. Additionally, the sheer volume of data generated by IoT devices necessitates robust data management and analysis capabilities, which can be a barrier for smaller manufacturers with limited technical and financial resources. Moreover, as the technology advances, the skill gaps within the workforce become more pronounced. There is a pressing need for education and training programs that can equip workers with the necessary skills to operate and maintain sophisticated IoT-enabled systems. Addressing these challenges is crucial for the widespread adoption and optimization of IoT technologies in manufacturing.

3. Future Research Directions

Based on the findings of this study, several areas for future research can be identified. First, there is a need for more focused research on the development of standardized protocols and frameworks to enhance the interoperability of IoT devices across different platforms and manufacturers. This could facilitate more seamless integration of new technologies into existing systems, reducing implementation costs and complexities. Second, exploring the potential of artificial intelligence and machine learning in predictive maintenance and quality assurance could yield significant benefits for manufacturers. These technologies have the potential to revolutionize the way manufacturing processes are monitored and controlled, by predicting equipment failures before they occur and ensuring product quality meets the required standards. Third, the ethical implications of widespread IoT adoption in manufacturing need to be addressed. This includes concerns related to surveillance, data privacy, and the potential displacement of workers by automated systems. Research into developing ethical guidelines and policies that govern the use of IoT in manufacturing could help mitigate these issues.

5. CONCLUSION

This bibliometric study has systematically mapped the landscape of IoT adoption in smart manufacturing, revealing a robust and dynamic field characterized by rapid technological advancements and extensive international collaboration. The findings underscore the pivotal role of IoT technologies in enhancing manufacturing processes through automation, data analytics, and machine learning. The evolution of research themes from foundational technologies to sophisticated applications like digital twins and edge computing reflects the industry’s ongoing drive towards innovation and efficiency. However, the study also highlights significant challenges such as integration complexities, security concerns, and the need for skills development, which must be addressed to harness the full potential of IoT in manufacturing. Moving forward, fostering global collaborations, standardizing IoT protocols, and focusing on sustainable practices will be crucial for overcoming these barriers and achieving a transformative impact on the manufacturing sector. This research not only enriches our understanding of the current state of IoT in manufacturing but also sets a clear direction for future studies to explore uncharted territories in this technologically evolving field.

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