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Main Trend Topics on Industry 4.0 in the Manufacturing Sector: A Bibliometric Review

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Abstract: The main objective of this research is to identify current trends in Industry 4.0 within the manufacturing sector through bibliometrics. A dataset of 1069 documents from 2020 to 2024 obtained from the Web of Science is processed. Using the R-Bibliometrix package, research trends, leading authors, and institutional contributions are identified. The accelerated growth rate of 30.77% in publications confirms research interest. Thematic exploration reveals the convergence of Industry 4.0 with sustainability, AI, the Internet of Things, smart manufacturing, and digitalization as dominant themes. The transition towards smarter and more efficient systems is evident, with an emphasis on integrating sustainability into Industry 4.0 practices. Challenges persist in management adjustment, technological integration, and strategy for digital transformation. The study identifies sustainability and machine learning as critical enabling factors for Industry 4.0, while security and collaboration have emerged as key focus areas in recent years. A wide geographic distribution of research contributions with substantial international cooperation is observed, highlighting India, Italy, and China. Major journals like Sustainability and Journal of Manufacturing Systems emerge as influential platforms for disseminating research on the topic. The analysis of citation networks, co-occurrence, and thematic evolution underscores the multidimensional impact of Industry 4.0 technologies on manufacturing.

Keywords: Industry 4.0; Web of Science; smart factories; digital manufacturing; bibliometric; Bibliometrix

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1. Introduction

The manufacturing industry is crucial for economic development, innovation, and social progress, providing well-paying jobs and significantly contributing to GDP [1]. With Industry 4.0 (I4.0 see Abbreviation section), also known as the Fourth Industrial Revolution, the sector is transforming through digital technologies, enhancing its impact. This transformation is driven by advancements such as cyber-physical systems, the Internet of Things (IoT), artificial intelligence, big data analytics, and digital twins, which collectively contribute to automated and interconnected manufacturing [2–5]. Technologies like IoT, Big Data, and cloud computing enhance productivity and flexibility in manufacturing [3,6,7]. According to [7], Industry 4.0 technologies are predominantly applied in smart manufacturing focusing on production programming and control, indicating a trend towards smarter production and more efficient systems.

Smart factories represent a significant shift from traditional manufacturing practices. They integrate physical and cyber technologies, using advanced sensors and IoT to improve performance, quality, control capability, management, and transparency of manufacturing processes [8]. They leverage digital technologies, AI, and automation to facilitate real-time communication between the factory and the market, supporting dynamic adaptation and maximizing efficiency [9]. Advanced manufacturing capabilities drive innovation, especially in high-wage regions [10]. Smart manufacturing systems require a shift from traditional manufacturing philosophies, incorporating intelligent system requirements to remain competitive in the future market [11]. This shift requires support and understanding from top management, and the performance of existing production systems influences perceived benefits and adoption intentions [12]. Benefits of smart factories include improved quality, safety, cost savings, increased productivity, and a competitive edge over traditional production systems [13].

The transition to Industry 4.0 presents challenges that require comprehensive understanding and systematic methodologies for effective implementation [3,6,14]. This complex process is fraught with challenges. According to [15,16], implementing Industry 4.0 technologies is hindered by management and organizational adjustment challenges, including the need for strategic planning and the development of new competencies. Companies face difficulties integrating cyber-physical systems, big data analytics, and other technologies into existing manufacturing processes [15,17]. Other challenges include infrastructure transformation and financial requirements [18]. The perception and impact of Industry 4.0 opportunities and challenges vary by company size, industrial sector, and whether the company is a provider or user of Industry 4.0 [16]. Additionally, refs. [19,20] add that such transformation poses multi-level technological challenges to local production systems, especially SMEs, which may require integrated place-based industrial policies to leverage opportunities and mitigate threats.

The current state of Industry 4.0 implementation varies across different industrial sectors, with significant advancements and strategic initiatives underway in countries like Germany and China [4]. SMEs are actively working to adopt Industry 4.0 principles, using frameworks and models to facilitate this transition [21]. In logistics, the potential for transformative change is recognized, although the concept has yet to be fully realized in practice [22]. Overall, Industry 4.0 is shaping the future of manufacturing and logistics, with ongoing efforts to overcome challenges and fully harness the benefits of this industrial evolution.

The Fourth Industrial Revolution represents a paradigm shift in manufacturing, driven by the integration of digital technologies such as cyber-physical systems, the Internet of Things, artificial intelligence, and big data analytics. Smart factories, as part of this transformation, offer significant improvements in quality, safety, efficiency, and competitiveness. Manufacturing remains vital for economic growth and employment in developing countries [1]. Figure 1 shows that the percentage of global merchandise exports has increased from 64.38% in 2013 to 70.87% in 2023, highlighting the growing importance of manufacturing in international trade. Despite these challenges, Industry 4.0 is progressing across various industrial sectors, with ongoing efforts to overcome obstacles and fully leverage the benefits of this evolution. The increasing pace of scientific research and innovation in Industry 4.0 and manufacturing underscores the urgent need for effective tools to monitor and analyze this progress. This forward momentum is reflected in the steady shortening of intervals between successive industrial revolutions, as illustrated in Figure 2. Consequently, the ability to manage and analyze large volumes of scientific data accurately and efficiently has become essential to further advancing research in these fields. In this context, bibliometrics emerges as a valuable and relevant tool for tracking and evaluating research activity, enabling the identification of trends, prominent authors, leading institutions, and key research areas.

Previous research has provided valuable theoretical and methodological foundations. Ref. [23] explored the integration of sustainability and innovation in Industry 4.0, using case studies to illustrate how companies apply these concepts in practice, highlighting both benefits and challenges [23]. This practical approach complements the broader theoretical and bibliometric analysis of our study. Other studies, such as [24], introduce innovative methodologies like co-word analysis to investigate gas turbine maintenance. This scientometric method can be applied to other fields, providing a basis for identifying key areas and trends in research. Similarly, the analysis of structural reinforcement techniques in civil engineering presented in the article on the reinforcement of masonry structures with composite materials and fiber-reinforced cementitious materials provides crucial experimental data that can be used to develop and refine theories about structural behavior under specific loads [25]. These methods, although specific in their application, offer useful perspectives that enrich our bibliometric approach.

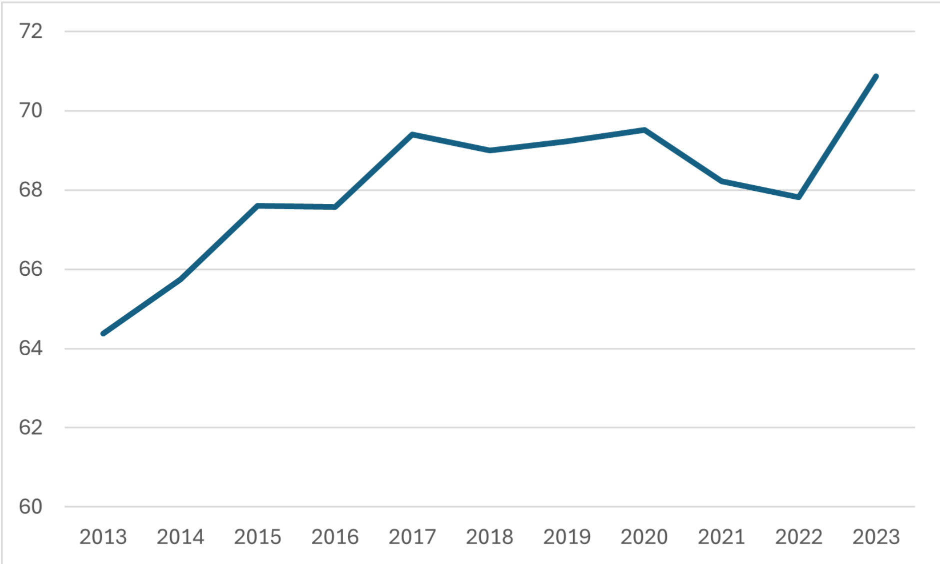


Figure 1. Manufactures exports (% of merchandise exports). By World Bank.

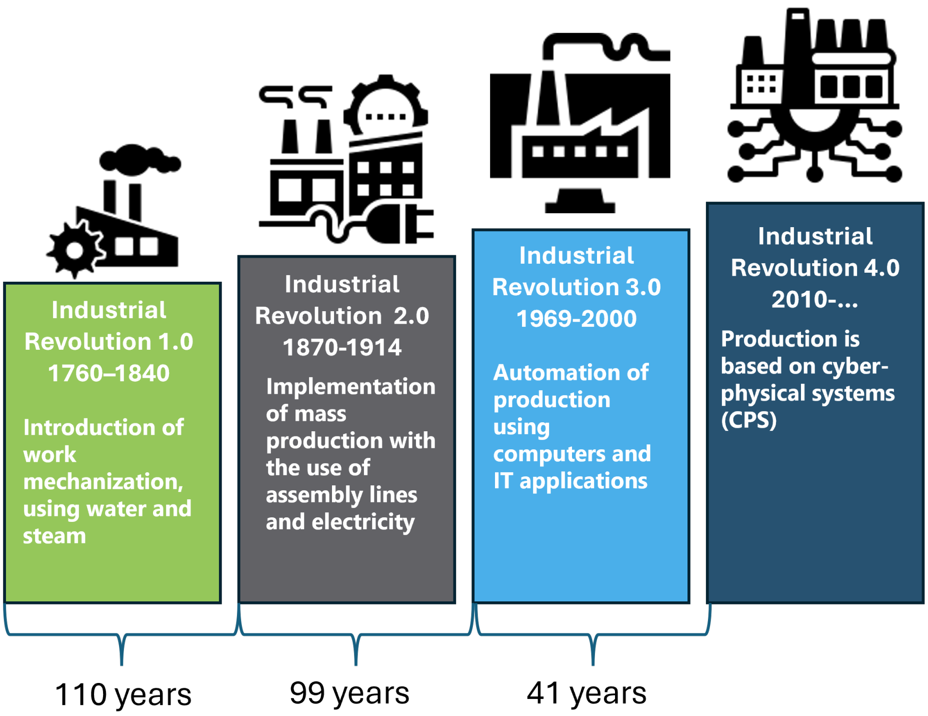


Figure 2. From Industry 1.0 to Industry 4.0—stages of evolution.

Compared to these previous studies, the present article stands out for its comprehensive and multidimensional approach to Industry 4.0. Through a detailed bibliometric analysis using the R-Bibliometrix package, it provides a robust quantitative and qualitative view of research trends and patterns. This approach allows for the identification of international collaborations and theorizing about the interaction of critical factors such as sustainability and digitalization, offering a unique holistic perspective. By identifying emerging themes and high-relevance areas, this study not only contributes to existing knowledge but also offers clear directions for future research and industrial applications in Industry 4.0. This study aims to use bibliometrics as a tool to identify and analyze relevant metrics related to research in Industry 4.0 and manufacturing. To achieve this goal, the Bibliometrix web platform will be employed to analyze a sample of data collected from the Web of Science, covering the period between 2020 and February 2024. This analysis will provide a detailed insight into the most influential authors, prominent research centers, impactful publications, and emerging trends in these constantly evolving fields.

2. Materials and Methods

Bibliometrics is a field that applies mathematical and statistical methods to analyze and quantify the proliferation of academic publications, their distribution, and their impact on the scientific community. Bibliometrics has roots in the last century with the pioneering contributions of Lotka and Bradford, later modernized by other authors [26]. The evolution has involved a variety of applications in different fields such as the evaluation of scientific production, cooperation among institutions, and the impact of funded research [27]. Bibliometric studies consist of citation analysis, co-citation, authorship and co-authorship, and keyword coupling, among other analyses [28]. This method is useful for increasing rigor and reducing bias in literature reviews complementing other methodologies such as meta-analysis and structured qualitative literature reviews [27,28]. The success of scientific research and academic performance is supported by the use of bibliometric parameters and indices with implications for the evolution and professional career of researchers [29,30]. These parameters are based on the development of indicators such as the H-index, the g-index, and the impact factor, each with different levels of complementarity [31]. To facilitate data acquisition, analysis, performance, and visualization, bibliometric 4.3.0 software has been developed [32]. Precisely, the Bibliometrix R package (version: 4.3.0), supported by the R language, is a useful technology for the development of quantitative bibliometric research, supporting bibliographic data obtained from major repositories [33]. Bibliometric processing involves data acquisition, data pre-processing, statistical calculation, visualization, and data analysis [33,34]. For this research, the data were obtained from the Web of Science (WoS) for the period between 2020 and 2024. The concepts supporting the initial notions are Digital manufacturing, Smart factories, Flexible manufacturing systems (FMS), computer-aided design, computer-aided manufacturing, and Industry 4.0, from which the following search phrase is constructed: "Digital manufacturing" OR "Smart factories" OR "Industry 4.0". On the other hand, a set of WoS categories related to research interests was discriminated:

- Manufacturing Engineering
- Industrial Engineering
- Management
- Green Sustainable Science Technology
- Electrical Electronic Engineering
- Research Management Science
- Multidisciplinary Engineering
- Computer Science Interdisciplinary Applications
- Computer Science Information Systems
- Business
- Automation Control Systems
- Mechanical Engineering
- Computer Science Artificial Intelligence
- Multidisciplinary Sciences
- Robotics
- Computer science software engineering
- Computer science hardware architecture

- Business Finance
- Industrial Relation Labour

Finally, the order of the documents was maintained under the criterion of "Relevance", and the dataset was exported in .BibTex format, compatible with various reference managers and the R Bibliometrix tool. Other criteria such as language were not modified. After the application of the criteria, a total of 1069 resources remain. In Figure 3, the methodology followed by the authors is outlined.

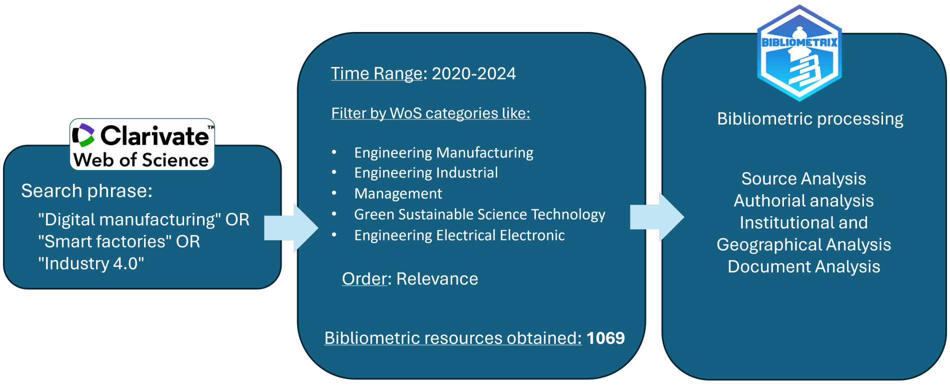


Figure 3. Bibliometric Review Methodology.

3. Results

The data processed provide a detailed overview of academic research on Industry 4.0 and digital manufacturing over a five-year period, from 2020 to 2024 (See Table 1). During this time, a total of 1069 documents from 286 different sources were compiled, suggesting a steady flow of research in this field (see Figure 4). The annual growth for the range from 2020 to 2023 experienced a positive rate of 30.77%, which may indicate an acceleration in interest or the publication of new works on this topic; it would be a mistake to reference the range from 2020 to 2024 because at the time these results are conceived, the year 2024 has not concluded yet.

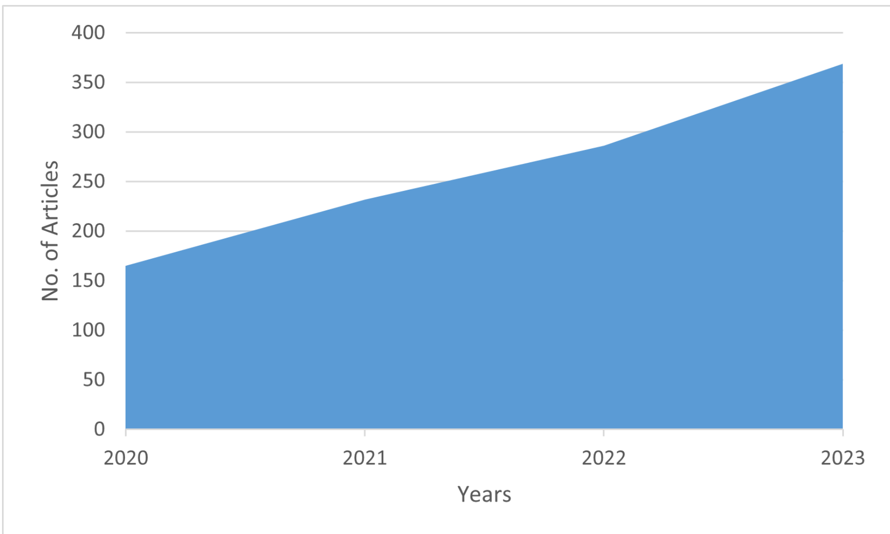


Figure 4. Annual Scientific Production.

The average age of the documents is relatively low, with a value of 2.15 years, indicating that most of the research is recent and reflects current advancements in the field. Additionally, the average number of citations per document is significantly high, with an average of 27.28 citations per document, suggesting that research in this field is widely recognized and cited by other scholars.

Table 1. Summarizes an approximation of the characteristics of the sample obtained.

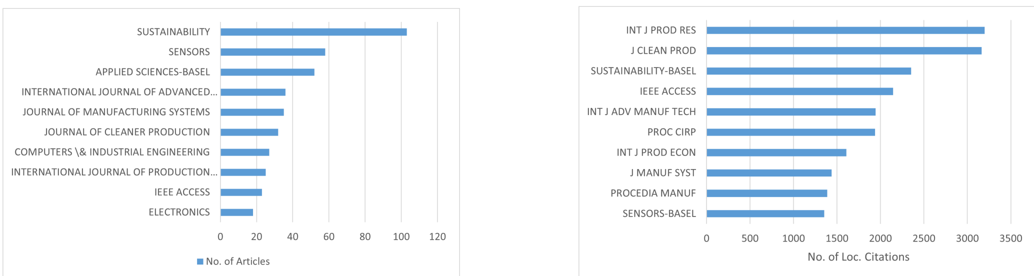
Description	Results
Main Information about Data	
Timespan	2020:2024
Sources (Journals, Books, etc.)	286
Documents	1069
Annual Growth Rate %	30.77
Document Average Age	2.15
Average citations per doc	27.28
References	94,694
Document Contents	
Keywords Plus (ID)	2247
Author's Keywords (DE)	2813
Authors	
Total Authors	3433
Authors of single-authored docs	45
Authors Collaboration	
Single-authored docs	50
Co-Authors per Doc	3.81
International co-authorships %	36.11
Document Types	
Review	592
review; book chapter	1
review; early access	476

Regarding collaboration among authors, it is observed that there is a significant proportion of documents written collaboratively, with an average of 3.81 co-authors per document. Moreover, approximately 36.11% of these collaborations are international, indicating strong global cooperation in research on Industry 4.0 and digital manufacturing.

In terms of document types, the majority of works are reviews, representing 592 documents. Additionally, there is a small number of documents that are reviews combined with book chapters or early access articles.

3.1. Source Analysis

Figure 5a displays the ranking of journals based on the quantity of published articles, while Figure 5b illustrates the scientific journals with the highest level of discussion and citation within the sample obtained.



(**a**) (**b**)

Figure 5. Journal Metrics: Quantity and Quality. (**a**) Most Relevant Sources (2020–2024); (**b**) Most Local Cited Sources (2020–2024).

Although both indicators are fundamental, there are others that weigh factors such as the number of citations, the quantity of cited articles, and the relationship between them (see Table 2 and Figure 6).

Table 2. Sources' Local Impact.

Element	h_Index	g_Index	m_Index	TC	NP	PY_Start
SUSTAINABILITY	27	47	5.4	2487	103	2020
JOURNAL OF MANUFACTURING SYSTEMS	19	35	3.8	1588	35	2020
SENSORS	19	35	3.8	1356	58	2020
APPLIED SCIENCES-BASEL	17	28	3.4	889	52	2020
JOURNAL OF CLEANER PRODUCTION	17	32	3.4	1897	32	2020
COMPUTERS & INDUSTRIAL ENGINEERING	16	27	3.2	1320	27	2020
INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH	16	25	3.2	1433	25	2020
INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY	14	27	2.8	738	36	2020
COMPUTERS IN INDUSTRY	13	16	2.6	1106	16	2020
ELECTRONICS	10	16	2	260	18	2020

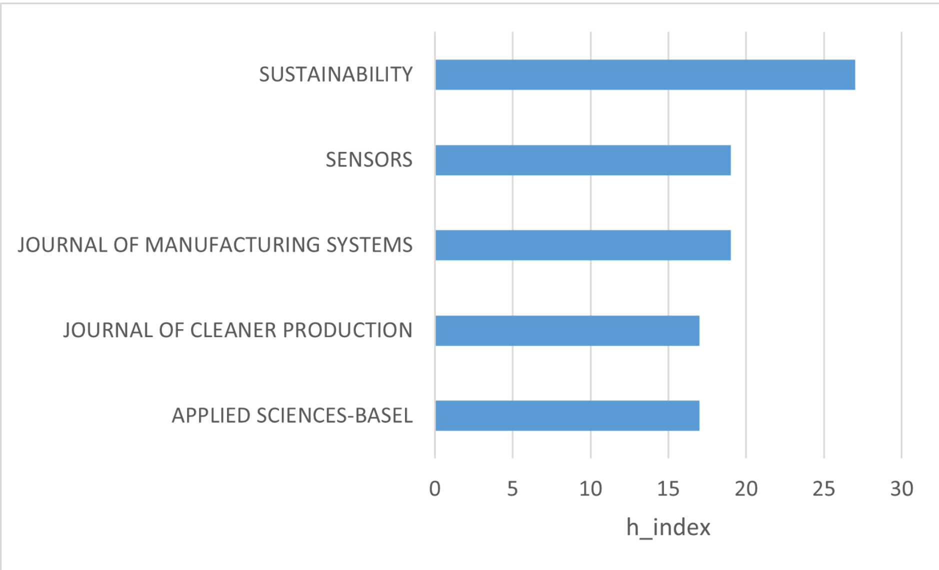


Figure 6. H Index.

For example, the H-index is a widely used metric to assess the impact of a researcher based on their publications and citations [35,36], which many authors complement with the G-index, a measure that provides a distinctive ranking of authors based on accumulated values of the square root, enabling a unique evaluation of productivity and impact [37,38].

From this analysis, the top 5 scientific journals in the research domain in question are identified:

1. Sustainability: This journal has the highest h-index (27) among those analyzed and a high g-index (47), indicating significant influence and a considerable number of

cited documents. Additionally, it has a high total number of citations (2487) and a significant quantity of published documents (103).

2. Journal of Manufacturing Systems: With an h-index of 19 and a g-index of 35, this journal also demonstrates strong influence in the field. It presents a considerable number of citations (1588) and a moderate quantity of published documents (35).
3. Sensors: This journal has h-index and g-index values similar to those of the Journal of Manufacturing Systems (19 and 35 respectively), indicating significant influence in the field. However, it has a slightly higher number of published documents (58).
4. Journal of Cleaner Production: With an h-index of 17 and a g-index of 32, this journal also exhibits substantial influence. It has a high total number of citations (1897) and a moderate quantity of published documents (32).
5. Applied Sciences-Basel: Although it has a slightly lower h-index (17), this journal has a similar g-index (28), suggesting considerable influence in the field. Additionally, it has a moderate number of citations (889) and a significant quantity of published documents (52).

Another pertinent analysis is related to co-citation networks. According to [33], journals at the extreme edges of each group in the network indicate a lower relationship with the other group, the size of the node indicates the level of interaction, and the thickness of the line indicates the level of interconnection with adjacent journals. In Figure 7, two clear clusters can be identified. For the red cluster, it is observed that the general themes addressed by the journals within it are advanced manufacturing technologies, manufacturing systems, industrial sensors, computer engineering applied to industry, and access to technological information. Meanwhile, in the case of the blue cluster, the main themes are production research, sustainable production, production economics, technological forecasting, and social changes related to technology in the industry. Additionally, the journals Computers & Industrial Engineering, Applied Sciences-Basel, and Procedia Manufacturing show the highest level of internal co-citation within the red cluster, while the International Journal of Production Research, Journal of Cleaner Production, and Sustainability exhibit the highest level of internal co-citation within the blue cluster.

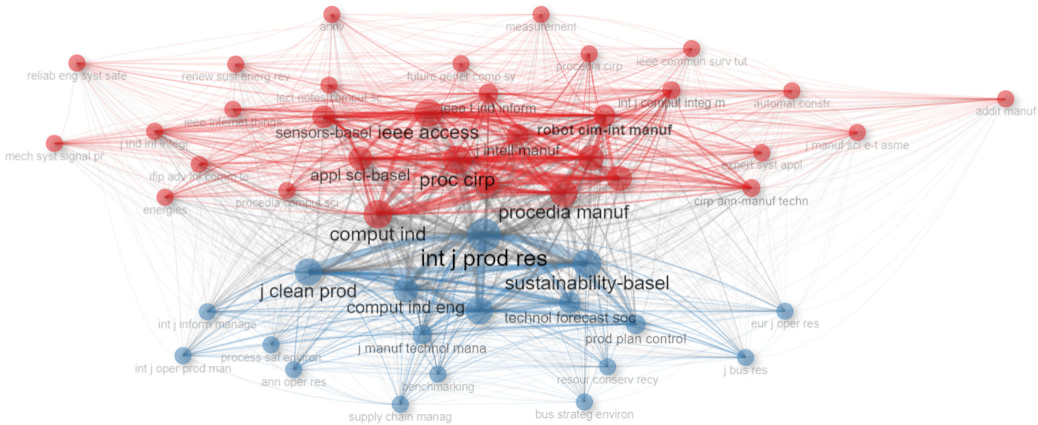
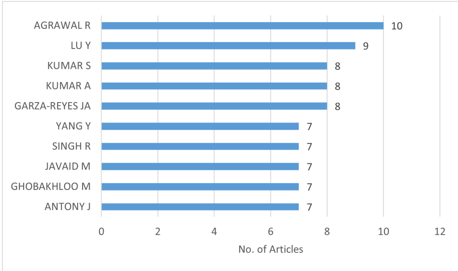


Figure 7. Co-citation network among scientific journals.

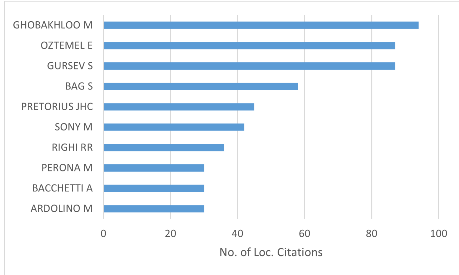
3.2. *Authorial Analysis*

In Figure 8, the top 10 authors in the investigated topic can be observed in terms of the number of published articles.

The authors with the highest number of articles are Agrawal R (10), Lu Y (9), Garza-Reyes JA (8), Kumar A (8), and Kumar S (8). Meanwhile, the authors with the best fractional article indicator are Pearce JM (2.00), Psomas E (2.00), Bag S (3.20), Akbari M (2.50), and Yang Y (2.77). These authors have a fractional article indicator greater than 1, indicating that they have significantly contributed to a considerable number of articles in which they participated as co-authors. On the other hand, the most cited authors are shown in Figure 8b, with GURSEV S (87), OZTEMEL E (87), and GHOBAKHLOO M (97) standing out.



(**a**)



(**b**)

Figure 8. Authors Metrics: Quantity and Quality. (**a**) Most Relevant Authors (2020–2024); (**b**) Most Local Cited Authors (2020–2024).

Considering the H-index (Table 3), the main authors are AGRAWAL R, GHOBAKHLOO M, LU Y, AHMED S, JAVAID M, CHEN Y, GARZA-REYES JA, GEHLOT A, GUPTA MK, and KUMAR A. Based on a limited analysis of the article titles, the main topics addressed by these authors are as follows:

- **AGRAWAL R:** Digital technologies in supply chain and quality management. Sustainability in manufacturing and integration of Industry 4.0 in the circular economy.
- **GHOBAKHLOO M:** Application of emerging technologies such as blockchain. Integration of Industry 4.0 in sustainable manufacturing.
- **LU Y:** Applications of digital technology in various fields, such as digital twins, blockchain, and 3D printing. Integration of digital technology in optimization and management of manufacturing processes.
- **AHMED S:** Development and application of artificial intelligence-based tools and strategies in supply chain management. Integration of digital technologies to enhance supply chain resilience.
- **JAVAID M:** Applications of digital technology in the medical and healthcare fields, such as wireless medical sensors and blockchain technology. Development of cybersecurity strategies for the Industry 4.0 era.
- **CHEN Y:** Applications of digital technologies in supply chain management and optimization. Integration of emerging technologies such as artificial intelligence and machine learning in supply chain management.
- **GARZA-REYES JA:** Adoption of digital technologies in different sectors and their impact on the supply chain. Integration of continuous improvement methodologies such as Lean Six Sigma with Industry 4.0.
- **GEHLOT A:** Development of strategies to improve efficiency and sustainability in supply chain management. Applications of digital technologies in logistics and transportation.
- **GUPTA MK:** Applications of digital technology in manufacturing process management and optimization. Development of strategies to improve efficiency and productivity in manufacturing.
- **KUMAR A:** Sustainability in manufacturing and integration of Industry 4.0 in the circular economy. Applications of digital technologies in supply chain and quality management.

These authors primarily analyze the application of digital technologies, such as artificial intelligence, blockchain, digital twins, and 3D printing, in supply chain management, manufacturing, and sustainability. They also focus on integrating continuous improvement methodologies, such as Lean Six Sigma, with Industry 4.0 to enhance efficiency and quality in industrial processes. Additionally, they address topics related to cybersecurity, supply chain resilience, and optimization of logistics and transportation.

Table 3. Authors' Local Impact. H Index.

Authors	h_Index
AGRAWAL R	7
GHOBAKHLOO M	7
LU Y	7
AHMED S	6
JAVAID M	6
CHEN Y	5
GARZA-REYES JA	5
GEHLOT A	5
GUPTA MK	5
KUMAR A	5

3.3. Institutional and Geographical Analysis

In what concerns institutions and research centers, Table 4 contains the main ones in terms of thematic production. The University of Minho (Portugal) leads thematic production with 42 articles, indicating a strong contribution from this institution in the specific analyzed field. It is followed by the University of Johannesburg (South Africa), which ranks second with 31 articles, and the Federal University of Sao Carlos (Brazil) with 25 articles, in third place.

Table 4. Most Relevant Affiliations.

Order	Affiliation	Articles	Countries
1	Minho Univ	42	Portugal
2	Johannesburg Univ	31	South Africa
3	Fed Sao Carlos Univ	25	Brazil
4	Teknol Malaysia Univ	21	Malaysia
5	West Scotland Univ	21	United Kingdom
6	Fed Santa Catarina Univ	18	Brazil
7	Naples Federico Ii Univ	18	Italy
8	Kaunas Technol Univ	16	Lithuania
9	Derby Univ	16	United Kingdom
10	Kebangsaan Malaysia Univ	16	Malaysia

When interpreting the data on thematic production by countries (see Figure 9), it stands out that the most scientifically productive countries are India, Italy, and China, which account for 11.5%, 9.5%, and 6.7% respectively of the total articles in the sample, followed by countries such as Brazil, the United Kingdom, and the United States, among others. It is noteworthy that the top 10 countries in the ranking generate 58.2% of the total publications. Another notable aspect is the ratio of Single Country Publications (SCP) to Multi-Country Publications (MCP). As seen in the graphic, national production and collaboration prevail; however, countries such as the USA, China, and Australia stand out with more than 40% of their total publications being in collaboration with international authors.

In terms of international collaboration, as can be observed in Figure 10, there is abundant collaboration among several countries, primarily those mentioned earlier.

Some observations and patterns that can be noted: there are strong connections between some countries, for example, China has strong collaboration with the United States, the United Kingdom, Australia, and Canada. Similarly, India has many collaborations with the United States, the United Kingdom, and Canada. On the other hand, there is a trend towards regional collaboration; several countries in Latin America, such as Brazil, Colombia, and Mexico, have significant collaborations among themselves. The same occurs with several countries in Europe, such as Germany, France, and Italy. Some countries act as "hubs" of global collaboration; the United States and the United Kingdom have significant connections with a wide range of countries in different regions. Identifying these relationships helps identify trends and opportunities for future collaboration.

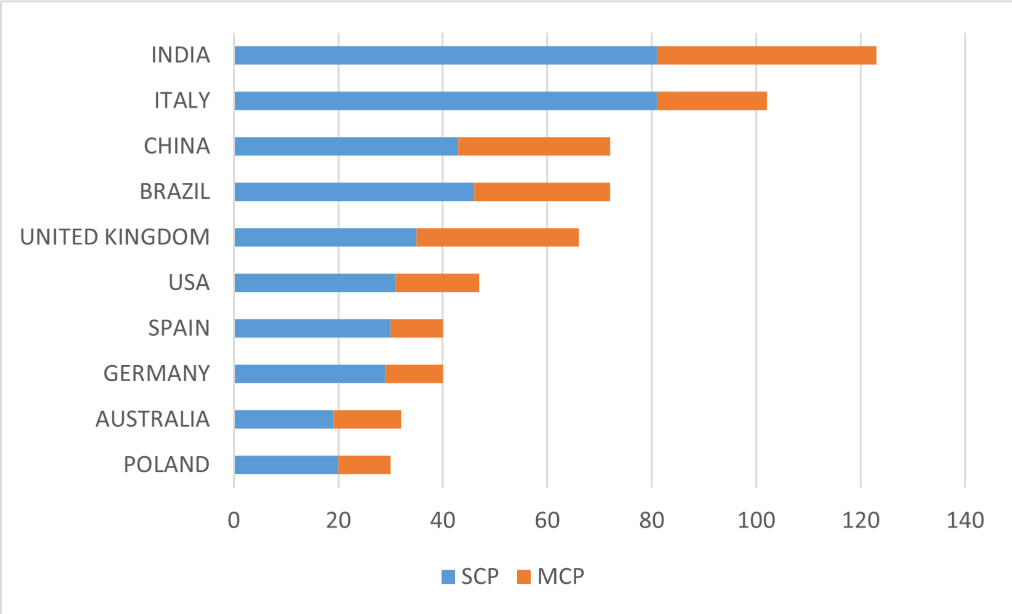


Figure 9. Countries' Scientific Production.

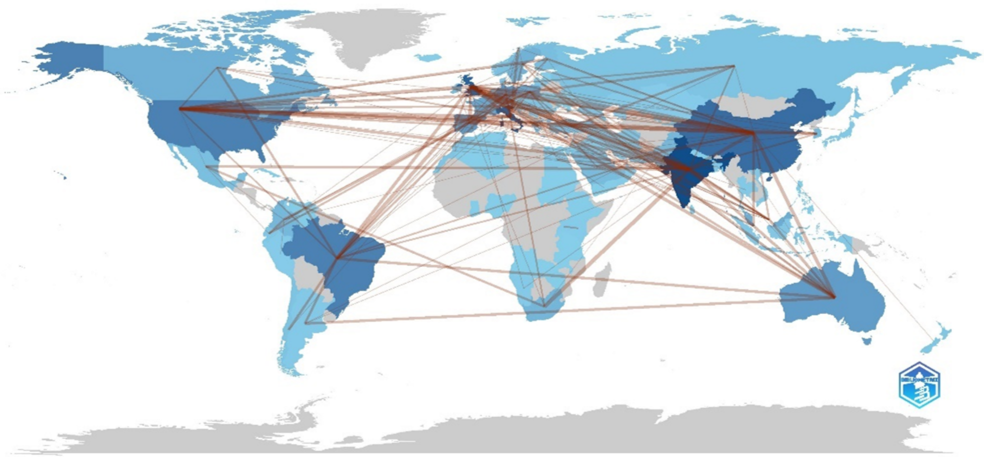


Figure 10. Countries' Collaboration World Map.

Using a collaboration network as the analysis source (Figure 11) and its associated data, it can be observed that India, the United Kingdom, and China are the nodes with the highest intermediary values, suggesting that they act as important bridges between other countries in the collaboration network. In terms of closeness, Norway, Canada, and Croatia have relatively high values, indicating that they are well connected with other nodes in the network. In PageRank terms, India, the United Kingdom, and China also have the highest values, indicating that they are prominent countries in the collaboration network. PageRank is an algorithm used to measure the relative importance of a node in a network, taking into account both the quantity and quality of its connections [39,40]. Higher values indicate a greater relative importance of the node in the network.

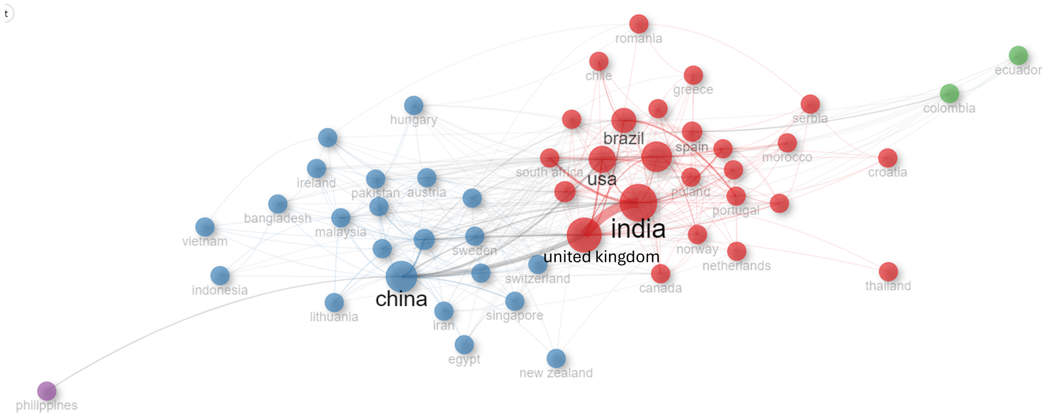


Figure 11. Countries Collaboration Network.

3.4. Document Analysis

For the analysis of documents, indicators related to citations will be primarily considered. Table 5 shows the top 25 articles with the highest number of citations from the sample analyzed. The most cited article with 807 citations at the time of this study is presented by [3], which addresses the impact of the manufacturing industry on economic and social progress, focusing on the Industry 4.0 initiative. It explores how this concept, although not new, has gained attention in both academia and industrial society, highlighting the need to understand its characteristics for a successful transition to digital manufacturing. It also discusses the importance of developing technological infrastructures and management models to facilitate this transformation, while highlighting the lack of evaluation methodologies in the current literature. It is proposed that a comprehensive literature review can help clearly define the design principles of Industry 4.0 and develop implementable scenarios to drive research and practice in this rapidly developing field. Following in the ranking is the document presented by [41] with 612 citations, on how Industry 4.0 is transforming sustainability. It identifies sustainability functions, highlighting that economic ones are immediate outcomes and pave the way for socio-environmental functions. Its aim is to help stakeholders better understand the opportunities offered by the digital revolution for sustainability and to work together to ensure its effectiveness and fairness. The article by [42], ranked third in the ranking, addresses the development of Digital Twin technologies in manufacturing, analyzing their connotation, applications, and challenges in Industry 4.0. It summarizes the definition and current state of Digital Twins, reviewing existing technologies and representative applications. Pending research issues in the development of Digital Twins for smart manufacturing are identified. The article by [43] analyzes how the integration of Industry 4.0 technologies is transforming the healthcare sector towards Health 4.0, describing key technologies, application scenarios, interdisciplinary benefits, and challenges. Meanwhile, ref. [44] presents a literature review on the evolution of Agriculture 4.0, highlighting the challenge of efficiently organizing complex networks to meet the dynamic needs of the agricultural supply chain. In the article by [45] the focus is on integrating Industry 4.0 technologies into predictive maintenance in the context of manufacturing, discussing methods, standards, and applications, and highlighting the growing importance of computing in a field traditionally dominated by engineering. In [7] it examines how Industry 4.0 technologies are applied in the business processes of manufacturing companies, focusing on production scheduling, servitization, circular supply chain management, as well as the increasing combination of IoT, Big Data Analytics, and Cloud. At the same time, it addresses the use of blockchain technology in various Industry 4.0 applications, highlighting the importance of this technology in addressing security and privacy concerns in applications such as smart agriculture and energy management. In the review conducted by [46] the use of machine learning techniques in additive manufacturing is examined, identifying potential applications in various areas, discussing challenges, and emphasizing the importance of data sharing for the effective adoption of machine learning. Closing the top 10 articles is the one developed by [47] in which the relationship between Circular Economy and Industry 4.0 is analyzed, highlighting how this combination can directly contribute to various Sustainable Development Goals (SDGs), such as affordable and clean energy, decent work and economic growth, and industry, innovation, and infrastructure.

Table 5. Most Global Cited Documents.

Ranking	Paper	DOI	TC	TC per Year	Normalized TC
1	OZTEMEL E, 2020, J INTELL MANUF [3]	10.1007/s10845-018-1433-8	807	161.40	10.35
2	GHOBAKHLOO M, 2020, J CLEAN PROD [41]	10.1016/j.jclepro.2019.119869	612	122.40	7.85
3	LU Y, 2020, ROBOT COMPUT-INTEGR MANUF [42]	10.1016/j.rcim.2019.101837	550	110.00	7.06
4	ACETO G, 2020, J IND INF INTEGR [43]	10.1016/j.jii.2020.100129	345	69.00	4.43
5	LEZOCHE M, 2020, COMPUT IND [44]	10.1016/j.compind.2020.103187	297	59.40	3.81
6	ZONTA T, 2020, COMPUT IND ENG [45]	10.1016/j.cie.2020.106889	267	53.40	3.43
7	ZHENG T, 2021, INT J PROD RES [7]	10.1080/00207543.2020.1824085	254	63.50	5.86
8	BODKHE U, 2020, IEEE ACCESS [48]	10.1109/ACCESS.2020.2988579	250	50.00	3.21
9	GOH GD, 2021, ARTIF INTELL REV [46]	10.1007/s10462-020-09876-9	239	59.75	5.51
10	DANTAS TET, 2021, SUSTAIN PROD CONSUMP [47]	10.1016/j.spc.2020.10.005	227	56.75	5.24
11	DOLGUI A, 2020, INT J PROD RES [49]	10.1080/00207543.2020.1774679	218	43.60	2.80
12	IVANOV D, 2021, INT J PROD RES [50]	10.1080/00207543.2020.1798035	214	53.50	4.94
13	PERERA S, 2020, J IND INF INTEGR [51]	10.1016/j.jii.2020.100125	210	42.00	2.69
14	PASCHOU T, 2020, IND MARK MANAGE [52]	10.1016/j.indmarman.2020.02.012	205	41.00	2.63
15	OSTERRIEDER P, 2020, INT J PROD ECON [53]	10.1016/j.ijpe.2019.08.011	203	40.60	2.60
16	LENG J, 2021, J MANUF SYST [54]	10.1016/j.jmsy.2021.05.011	200	50.00	4.61
17	AWAN U, 2021, BUS STRATEG ENVIRON [55]	10.1002/bse.2731	196	49.00	4.52
18	SIMA V, 2020, SUSTAINABILITY [56]	10.3390/su12104035	186	37.20	2.39
19	LU Y, 2020, J MANUF SYST [57]	10.1016/j.jmsy.2020.06.010	183	36.60	2.35
20	SEMERARO C, 2021, COMPUT IND [58]	10.1016/j.compind.2021.103469	179	44.75	4.13
21	ZHANG C, 2020, J IND INTEGR MANAG [59]	10.1142/S2424862219500192	178	35.60	2.28
22	BAG S, 2022, INT J ORGAN ANAL [60]	10.1108/IJOA-04-2020-2120	178	59.33	11.14
23	CINAR ZM, 2020, SUSTAINABILITY [61]	10.3390/su12198211	178	35.60	2.28
24	BEIER G, 2020, J CLEAN PROD [62]	10.1016/j.jclepro.2020.120856	175	35.00	2.25
25	SONY M, 2020, BENCHMARKING [63]	10.1108/BIJ-09-2018-0284	173	34.60	2.22

Delving into a content analysis based on available metadata such as keywords and plus keywords yields valuable insights, especially when analyzing their behaviour over temporal periods or subjecting them to certain bibliometric processes.

In the word cloud (Figure 12), the most frequent keywords from the sample are displayed. Given the terms used to obtain the article sample, the appearance of terms like "Industria 4.0" is not relevant; however, it is pertinent to analyze related topics such as sustainability, artificial intelligence, the Internet of Things, and smart manufacturing. Some of the standout terms include "sustainability", "artificial intelligence", "internet of things", "manufacturing", and "smart manufacturing". Terms like "machine learning", "digital twin", "circular economy", "additive manufacturing", and "blockchain" are also prominent, indicating a focus on advanced technologies and concepts in the context of Industry 4.0. Other relevant terms include "predictive maintenance", "big data", "cyber-physical systems", "supply chain", "digital transformation", and "healthcare", suggesting particular attention to areas such as predictive maintenance, supply chain management, and digital transformation across different sectors, including healthcare. Therefore, it can be affirmed that this analysis reveals a broad and diverse landscape of topics and technologies being researched and discussed in the context of Industry 4.0, ranging from smart manufacturing to sustainability and the application of emerging technologies such as artificial intelligence and the Internet of Things.

Figure 12. WordCloud. Most Frequent Key Words.

Upon analyzing the behavior of the main terms over the 5 years taken as reference, with emphasis on the top 4 terms, we obtained the "Trend topics" graph (Figure 13), from which the following analysis emerges: "Industry 5.0" appears in 2023, indicating a growing interest in the next phase of industrial development, while "Learning" and "Sustainability" appear in 2022 and 2023, suggesting a shift towards a focus on continuous improvement and sustainability within Industry 4.0. On the other hand, concepts such as "Cyber-Physical Systems" and "Smart Factory" mature, as they are present throughout the period, indicating that they are established areas within Industry 4.0.

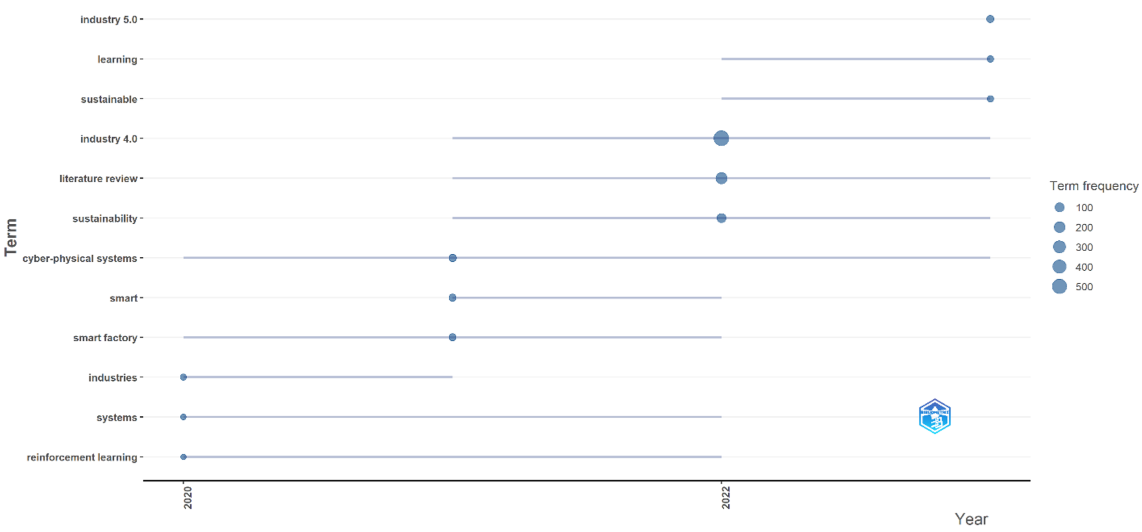


Figure 13. Trend Topics.

From the analysis of the co-occurrence network (Figure 14) and its accompanying data, emerging trends, mature concepts, and relationships between keywords can be identified. The network is comprised of three main clusters.

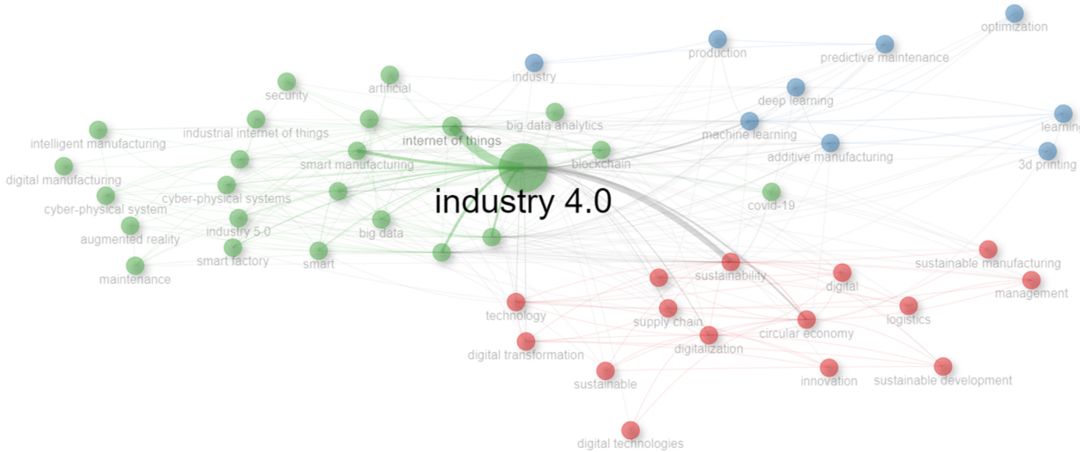


Figure 14. Co-occurrence Network: Keywords.

Cluster 1 (red): Sustainability is formed by keywords related to sustainability in general, including the term itself, sustainable development, circular economy, sustainable supply chain, and supply chain management. The terms in this cluster have a high betweenness centrality and closeness, indicating their importance in connecting different areas of sustainability research. The terms in this cluster suggest a growing integration of these concepts in Industry 4.0 and their significance for the evolution of manufacturing industries toward Industry 5.0.

Cluster 2 (green): Industry 4.0 is composed of keywords related to Industry 4.0 technologies, including the term itself, Internet of Things (IoT), artificial intelligence (AI), smart manufacturing, and digital twin. A strong connection is observed among the terms in this cluster. These keywords have a high PageRank, indicating their importance within the analyzed articles. Industry 4.0 emerges as a significant term in research on sustainability and digital transformation. The presence of "Covid-19" in this cluster suggests a possible analysis of the pandemic's impact on smart manufacturing and the need for resilient environments to such phenomena.

Cluster 3 (blue): Machine Learning and Optimization consists of keywords related to machine learning and optimization techniques, including machine learning, additive manufacturing, predictive maintenance, deep learning, and optimization. These keywords have a moderate betweenness centrality, indicating their role in connecting Industry 4.0 with other research areas. Machine learning and optimization appear to be important tools for implementing sustainable Industry 4.0 technologies.

Furthermore, from the analysis of the data associated with the network, it can be identified that Industry 4.0 technologies, especially the Internet of Things and artificial intelligence, are gaining importance in sustainability research. Additionally, there is an emphasis on using machine learning and optimization techniques to implement sustainable technologies in the Industry 4.0 environment.

Continuing with the co-occurrence analysis, significant relationships between keywords from the clusters are identified. As expected, sustainability is related to circular economy, sustainable supply chain, and supply chain management. Industry 4.0 is associated with the Internet of Things, artificial intelligence, smart manufacturing, and digital twin. Machine learning and optimization are linked to additive manufacturing, predictive maintenance, and deep learning.

The previous analysis can be complemented with an assessment of thematic evolution based on keywords. In Figure 15, keywords such as "security" and "collaboration" show high values in the Weighted Inclusion Index and the Inclusion Index for the period 2022–2024, suggesting a growing emphasis on these aspects of Industry 4.0 implementations. Likewise, the same high values are observed for "manufacturing systems" within the "sustainability" theme in 2022–2024, indicating a growing interest in integrating sustainable practices into manufacturing processes.

As expected, given the keywords used to obtain the reference sample, terms around Industry 4.0 consistently have high values, while the Internet of Things stands out, reaffirming its maturity within the research field.

Other notable relationships are established among keywords such as "artificial intelligence", "machine learning", "big data", and "smart," which frequently appear alongside "Industry 4.0", reaffirming their role as enabling technologies. Meanwhile, "sustainability" appears alongside keywords such as "circular economy", "digitalization", and "supply chain management", suggesting a focus on holistic sustainability practices within Industry 4.0. The data also suggests a growing interest in applying machine learning for various purposes within Industry 4.0, including topics like "predictive maintenance" and "deep learning". While security remains a concern, as keywords such as "security" and "human-robot collaboration" consistently appear.

The concept of "Industry 5.0" emerges in the data, possibly indicating a new paradigm shift toward the future industrial revolution.

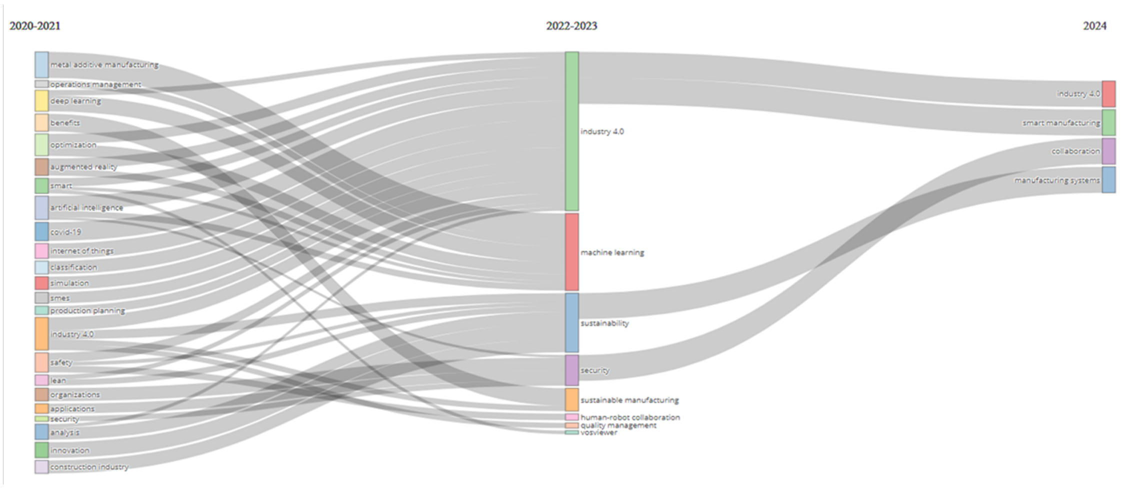


Figure 15. Thematic Evolution: Key words.

Figure 16 shows the thematic map based on the keywords defined by the authors. Thanks to this map and the analysis of the degree of theme development defined by the density variable and the degree of relevance defined by the centrality variable, driving themes can be identified, which are developed and fundamental for the research field. Niche or delimited topics have higher density but with a lower degree of centrality, so it can be interpreted that they are topics of lesser influence in the research domain despite their high development. Emerging or declining topics are those that present low centrality and density, so their degree of development and relevance is low. This can be analyzed from the temporal variable, meaning that at the time of the research, these are topics that are disappearing or emerging, so they do not have high levels in the analyzed variables. Basic topics, corresponding to the IV quadrant, are those that have not yet been fully developed but are relevant to research.

From the sample obtained and as can be seen in Figure 16, there are five thematic clusters. The topics of the Internet of Things and artificial intelligence associated with manufacturing (red cluster) are the most relevant and developed. At the same time, topics associated with circular economy and sustainability (blue cluster) have achieved considerable relevance above the average and possess a degree of development around the average, indicating that these themes associated with manufacturing processes have been gaining relevance in the last 5 years. Topics associated with measurements and uncertainty in manufacturing processes have experienced notable development but are well-divided or isolated with little impact on the analyzed research domain. Topics associated with security, human factors, and human–robot collaboration, although they have relevance around the average, do not reach development close to the average, so it can be interpreted that not all research opportunities have been exhausted in this regard. Finally, two thematic groups associated with applications and metal additive manufacturing are identified, which have both low relevance and low development degrees.

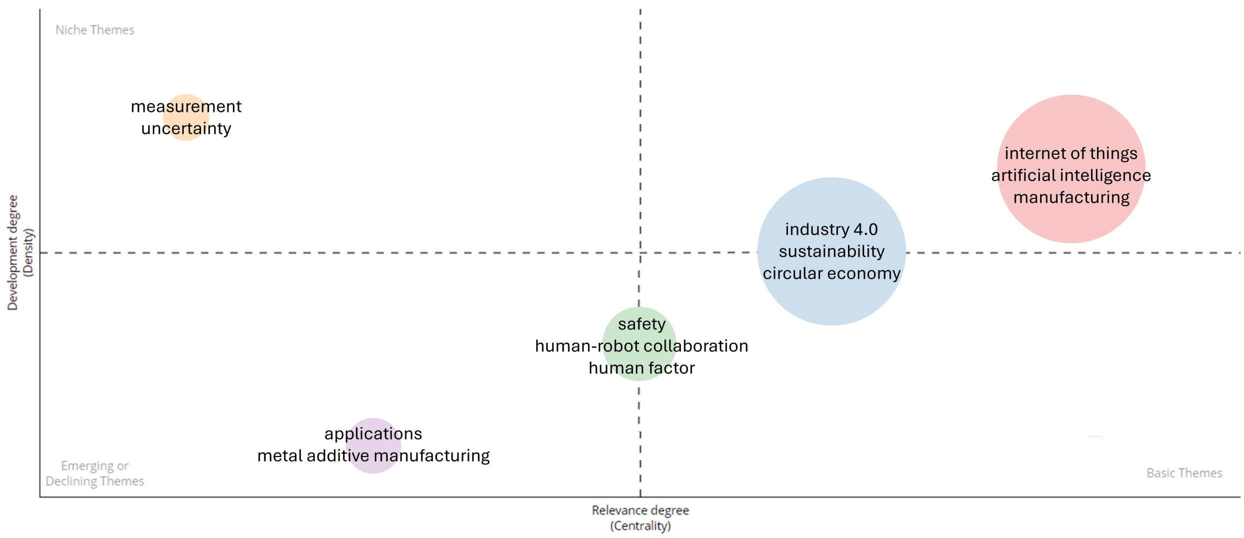


Figure 16. Thematic Map.

A Multiple Correspondence Analysis (MCA) is a multivariate statistical technique used to analyze relationships between categorical variables. In bibliometrics, this technique can be used to analyze relationships between keywords, identifying groups of related keywords that are frequently used together. Additionally, it helps identify relationships between keywords, such as synonyms, antonyms, or other related terms. MCA can help identify keywords that discriminate between different groups of articles.

The most significant cluster for this analysis according to Figure 17 is the red cluster, which groups terms related to research fields such as "sustainable development", "sustainability", "supply chain management", "manufacturing", "management", "digitalization", "digital twin", and "digital transformation". This cluster addresses topics related to sustainability, supply chain management, manufacturing, digital business management, and digital transformation, all of which are relevant aspects in manufacturing processes and Industry 4.0. Cluster 2 focuses on aspects related to security, connectivity, data protection, and information technology in the context of advanced manufacturing and Industry 4.0. These topics are critical for ensuring the integrity and efficiency of industrial processes in an increasingly digitized and connected environment. Cluster 3 is related to artificial intelligence, machine learning, optimization, and predictive maintenance in the industry. These terms suggest a focus on advanced technologies to improve efficiency, productivity, and quality in industrial processes, which is consistent with the trend toward Industry 4.0 and the adoption of digital technologies in manufacturing.

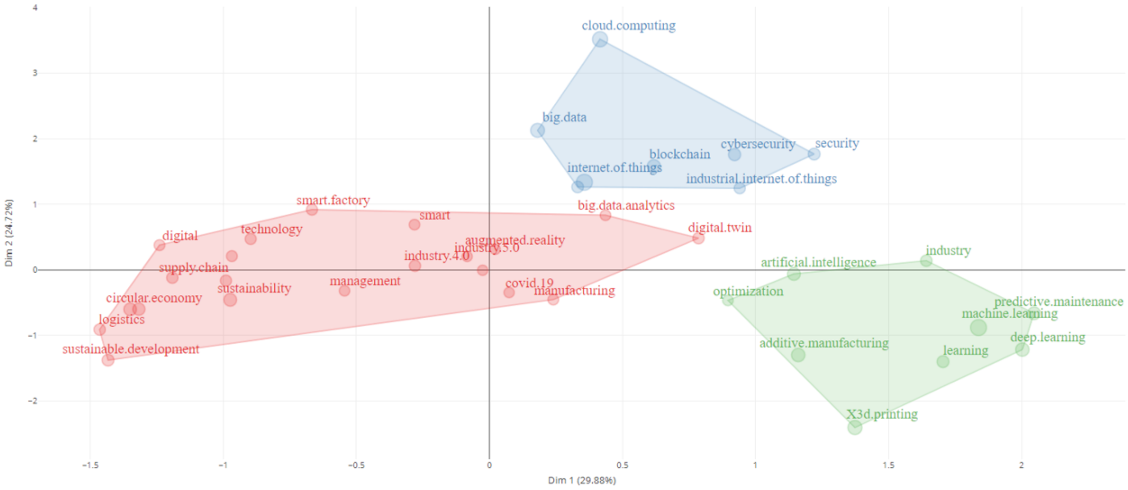


Figure 17. Factorial Analysis.

4. Future Research Directions

Future research should delve into the potential applications and implications of emerging technologies such as quantum computing, blockchain, and advanced robotics within the I4.0 framework. Additionally, integrating sustainable practices and green technologies is crucial to minimize the environmental impact of manufacturing processes. Addressing human factors, including workforce development, necessary skills, and human-machine collaboration, is also essential to ensure the smooth transition to and adoption of I4.0.

Furthermore, studies should explore strategies to enhance the resilience of manufacturing systems against various disruptions, such as cyber-attacks and supply chain issues. Long-term studies are needed to evaluate the impacts and benefits of I4.0 implementations over time, providing valuable insights into their sustainability and scalability. Employing content analysis techniques can help systematically analyze trends, identify gaps, and generate insights from extensive literature, thus enriching the depth of I4.0 research.

5. Conclusions

The study has successfully identified current trends in Industry 4.0 within the manufacturing sector through an exhaustive bibliometric analysis. The main trends revealed include advanced technological integration, the rise of smart manufacturing, a growing focus on sustainability and energy efficiency, human-machine collaboration, the critical importance of cybersecurity, and the global integration of supply chains. These findings highlight how I4.0 technologies are transforming manufacturing practices, driving efficiency, adaptability, and sustainability, and setting the stage for future innovations in the industry. The convergence of various advanced technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), machine learning, and big data analytics, is a defining characteristic of I4.0. These technologies are being increasingly integrated to enhance production efficiency, flexibility, and customization in manufacturing processes. The concept of smart manufacturing, which emphasizes the use of real-time data and autonomous systems, is gaining significant traction. This trend is driven by the need for more responsive and adaptive manufacturing systems that can quickly adjust to changing market demands and conditions. There is a growing emphasis on sustainability and energy efficiency within the manufacturing sector. Companies are adopting I4.0 technologies to reduce waste, optimize energy consumption, and lower their environmental footprint, reflecting a broader commitment to sustainable industrial practices. The role of human workers in the manufacturing process is evolving with the advent of I4.0. There is an increasing focus on collaborative robots (cobots) and augmented reality (AR) tools that enhance human capabilities and improve safety and productivity on the factory floor. As manufacturing systems become more interconnected, the importance of cybersecurity has become paramount. The research highlights a trend towards developing robust cybersecurity measures to protect sensitive data and ensure the integrity of manufacturing operations. I4.0 technologies are facilitating more integrated and transparent global supply chains. This trend is enabling better coordination and collaboration among different stakeholders, resulting in improved supply chain resilience and efficiency.

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Abbreviations

Abbreviation	Meaning
I4.0	Industry 4.0
WoS	Web of Science
FMS	Flexible Manufacturing Systems
H-index	Hirsch Index
g-index	Egghe's Index
DOI	Digital Object Identifier
IoT	Internet of Things
AI	Artificial Intelligence
SMEs	Small and Medium-sized Enterprises

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