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Review

Digitalisation in the Context of Industry 4.0 and Industry 5.0: A Bibliometric Literature Review and Visualisation

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Abstract

This study examines industrial digitalization, with a particular focus on the transformation from Industry 4.0 to Industry 5.0. The research is based on a database of 1441 Scopus-indexed articles, which forms the basis of a systematic literature review and bibliometric network analysis. The articles were ranked using Global Citation Score (GCS), followed by Co-Coupling Network (CCN) within VosViewer, the method to create arrays. The arrays were analyzed based on the connection strengths of the citations in them. Next, we performed Burst Detection using the CiteSpace app. Finally, the most relevant keywords, determined in the Burst Detection, were used for Co-Occurrence Network (CONK), with which we could create new arrays and analyze them. By connecting the various, fragmented scientific findings, our results highlight that digital twins, artificial intelligence, supply chain resilience and the Internet of Things are the focus of Industry 4.0, i.e., the technological side is dominant. In contrast, Industry 5.0 places employees at the center. It also emphasizes the analysis of human–machine interaction and the importance of green digital sustainability. The results provide a comprehensive picture of how decision-makers, researchers, and professionals can interpret a changing mindset and apply it as practical advice.

Keywords: digitalisation; Industry 4.0; Industry 5.0; digital twin; supply chain resilience

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1. Introduction

Industrial production and business processes have been transformed by successive Industrial Revolutions. The first, in 18th-century England, was driven by the steam engine; the second by electricity and mass production; and the third, often called the information systems revolution, by computers and automation [1]. The fourth industrial revolution is still ongoing, with the term first appearing at a trade fair in Hanover in 2011. The fourth industrial revolution, also known as Industry 4.0, primarily enhances the efficiency and flexibility of production systems through the deeper integration of digital technologies [2].

In this study, digitalization refers to the connection of physical and organizational elements of industrial processes and services with digital platforms. According to the Reference Architecture Model for Industry 4.0 (RAMI 4.0), digitalization can be implemented in several ways: (1) as a prerequisite for Industry 4.0, which provides a digital infrastructure for cyber-physical systems; (2) it can also mean the digitalization of manufacturing, a concept that overlaps with Industry 4.0; (3) it is a cornerstone of Industry 4.0, which enables the implementation of smart technologies, real-time data transmission, and automation [3].

In our research, we consider the concept of digitalization as a fundamental pillar of the transition from Industry 4.0 (which includes smart manufacturing and cyber-physical systems) to Industry 5.0, where the essence of Industry 5.0 is to improve the collaboration between people and machines, with a focus on sustainability.

One of the key objectives of Industry 4.0 is to connect previously disparate technological and organisational processes through various digital solutions, thereby accelerating decision-making and reducing the number of errors that can occur [4]. The key elements of Industry 4.0 are cyber-physical systems (CPS), the Internet of Things, the emergence of big data analytics in production systems, and, increasingly in recent years, artificial intelligence (AI) [5]. All of these technologies are based on the principle that production systems and devices can communicate with each other. That decision-making can occur in real-time, either in a centralized location or a decentralized manner (taking into account the rest of the system) [6]. The proper application of Industry 4.0 will enhance production efficiency, improve product quality, and make industrial processes more sustainable [7].

Digitalisation is one of the key pillars of Industry 4.0, creating a link between automated systems and the physical reality outside [8]. By digitalisation, we mean that companies are increasingly relying on data to make decisions, relying more and more on automation in production, and utilizing intelligent algorithms in their processes. Digitalization and Industry 4.0 are closely related concepts, but they are not entirely the same. Digitalization generally refers to the transformation of processes through the application of digital technologies in all economic sectors, while Industry 4.0 refers to a specific manufacturing paradigm that is primarily optimized for manufacturing. This research interprets digitalization as a broader technology, which is also a central pillar of Industry 4.0.

Digitalisation is also affecting logistics and customer relations [9]. Thus, with a high degree of digitalisation, companies are able to collect data in real-time, store and analyze it, and thus anticipate maintenance or production needs, which allows them to adapt more easily to market requirements [10].

One of the key elements of industrial digitalisation is the design and deployment of smart factories, where production tools communicate with each other and can optimise production processes autonomously. In order to react quickly, such systems use various sensors and embedded systems to collect data, which are processed by advanced computing units, thus enabling rapid decision-making [11].

Industry 4.0 and digitalisation bring many great benefits, but there are also challenges in using these technologies, such as the organizational and infrastructural readiness of firms in emerging economies [12]. These challenges include cybersecurity, as the more devices we connect to a network, the more vulnerable the system becomes. This makes it crucial for companies to build and continuously improve appropriate protection systems [13]. In addition, new technologies have a clear impact on the labour market, as new types of devices are significantly transforming the nature of human work. What can be said is that the spread of Industry 4.0 and digitalisation is displacing labor in some sectors, but it is also increasing the demand for highly skilled workers with digital skills and enhancing the productivity of the economy.

Overall, Industry 4.0 and digitalisation are fundamentally changing production systems by making it easier for companies to adapt to market challenges and increasing their flexibility in dealing with possible future technological innovations, thanks to intelligent systems and automated processes [14]. In addition to technological progress, however, attention should also be paid to human resource management and cybersecurity issues due to the vulnerability of large systems [15]. Industry 4.0 and industrial digitalisation are not only technological developments, but also a process capable of triggering broad economic and social transformations that could determine the future of industrial production in the long term [16].

The concept of Industry 5.0 is the next step in the evolution of the industry, an approach that goes beyond simple automation and digitalisation [17,18]. It aims to integrate human capabilities and sustainability considerations into industrial systems. Industry 4.0 focuses on the use of intelligent systems and machines, while Industry 5.0 emphasises the importance of human–machine interaction, i.e., putting technology back in the hands of humans [19]. Collaborative robots (cobots), as a technology, are already part of Industry 4.0, but one of the main goals of Industry 4.0 is to coordinate such systems with humans, thereby complementing the skills of workers and enabling personalized production. These devices complement rather than replace human work [20–22]. In addition, the modelling and integration of human decision-making into digital systems is made possible through human digital twins [23]. Research is increasingly showing that the human factor in a production process is not treated as a mere labour force, but is seen as an active and adaptive element of the systems. The concept of Industry 5.0 is also closely linked to the circular economy, digital green innovation, and artificial intelligence [24,25]. In sum, Industry 5.0 is not only a technological shift, but also a shift in approach and organisation that is rethinking industrial systems [26].

The large number of topics mentioned above demonstrates that synthesis studies play a significant role in integrating and making sense of the diverse range of research.

The aim of this study is to provide an integrative bibliometric analysis of the Industry 4.0–Industry 5.0 transition by mapping the interconnections between human–machine interaction, AI and digital twins for sustainability, and blockchain for supply chain resilience. Industry 4.0 and Industry 5.0 have a significant body of literature, which is often fragmented in terms of its topics and conceptual frameworks, making it difficult for researchers and practitioners to gain a coherent picture of the field. This fragmentation underscores the need for a comprehensive, integrative analysis that maps the intellectual structure and emerging trends across these domains. In this regard, synthesis studies are essential to summarize and integrate diverse knowledge. Bibliometric literature analysis is an excellent way to do this, identifying key trends and correlations between scientific research. Our research focused on three research questions, which examine different but complementary aspects of the topic, the technological and operational foundations of the transition from Industry 4.0 to Industry 5.0, with particular emphasis on the role of advanced digital technologies (such as digitalisation, artificial intelligence, digital twins, and blockchain) and human–technology collaboration in building sustainable and resilient industrial systems: The first research question (RQ1) is how the transition from Industry 4.0 to Industry 5.0 is reshaping human–machine interaction, and what supporting role does digitalisation play in this process. The second research question (RQ2) is how digital twins and artificial intelligence impact the development of Industry 5.0 and contribute to the creation of a sustainable industry. The third research question (RQ3) is: How will the introduction of blockchain technology impact the digitization and resilience of supply chains?

The research questions focus on three critical areas that underpin the Industry 5.0 transition, collectively providing a multifaceted picture of how modern digital technologies and approaches, human-technology integrations, and sustainable industrial practices are evolving together. In addition to answering research questions, the aim of the research is to summarize practical knowledge that contributes to the development of industrial, economic, and political strategies with sustainability in mind, in such a way that employee well-being and operational efficiency are in harmony.

To support the understanding of our research questions, we first clarify three key concepts that underpin the analysis. Human digital twins are virtual representations of human operators or teams, generated by combining real-time sensor data, physiological monitoring, and behavioural modelling; these systems enable simulation, performance evaluation, and decision-making support in industrial contexts, such as improving ergonomics and safety in smart factories [27,28]. Collaborative robots (cobots) are special robots that can work safely alongside humans in shared workspaces. They are equipped with advanced sensors and are connected to artificial intelligence. Working alongside humans means that while the robot can perform monotonous tasks such as assembly work, the employee can concentrate on tasks that require judgment and precision [29,30]. Digital sustainability refers to the use of digital technologies that support environmental, social, and sustainability goals (e.g., reducing resource use, introducing circular economy practices, reducing emissions) [31,32].

To answer the research questions, the article employs a systematic literature review with various visual techniques. The methods and baseline data are presented in the second part of the publication. In the third part, visualisation methods are used to identify the most relevant articles and authors in the field, followed by keyword analysis to identify the most critical trends in the field. The articles were then clustered according to keywords, where the most cited articles were analysed according to the keywords with the highest occurrence. Finally, in the Section 4, we summarised the main conclusions, assessed the limitations of our research, and made suggestions for possible directions for further study.

2. Materials and Methods

The research methodology is based on a combination of a Systematic Literature Review (SLR) and a Bibliometric Network Analysis and Visualisation (BNAV) (Figure 1). The first step is to apply a Systematic Literature Review (SLR). In the first part of the research, a structured bibliographic search process is applied to the relevant literature. The literature search is based on the Scopus database, which provides a reliable indexing system and extensive coverage for the subsequent research steps [33]. We used Scopus because it offers broader and more comprehensive content coverage compared to other major databases [34]. The first step of the SLR is to define the research question(s). In this step, we need to identify relevant research questions that focus on relevant aspects of the area under study. In the next step, relevant articles are collected using keyword queries. The literature was collected by performing keyword searches in the Scopus database using predefined search terms and various Boolean operators to identify relevant publications. The resulting data were then cleaned of duplicates and possible irrelevant publications, excluding sources that did not meet the inclusion criteria.

The second major step is to conduct a Bibliometric Network Analysis and Visualisation using the scientific publications identified in the first step. The application of BNAV techniques has enabled us to conduct a detailed analysis of the evolution and networks of relations within the research area. In applying BNAV, we first determined the Global Citation Score (GCS). This means that we used citation indicators to identify the publications and authors considered most relevant and their impact in the research area [35]. We then performed a Co-Coupling Network Analysis on the collected articles. This analysis was used to identify the structural relationships between the publications considered most important, as determined by GCS [36]. Burst Detection was used to identify research topics that have been researched in outliers in the recent past, and thus to describe the dynamically changing research trends [37]. Finally, using the Co-Occurrence Network method, we examined co-occurring keywords that highlighted the most important themes and trends in the research area [38,39].

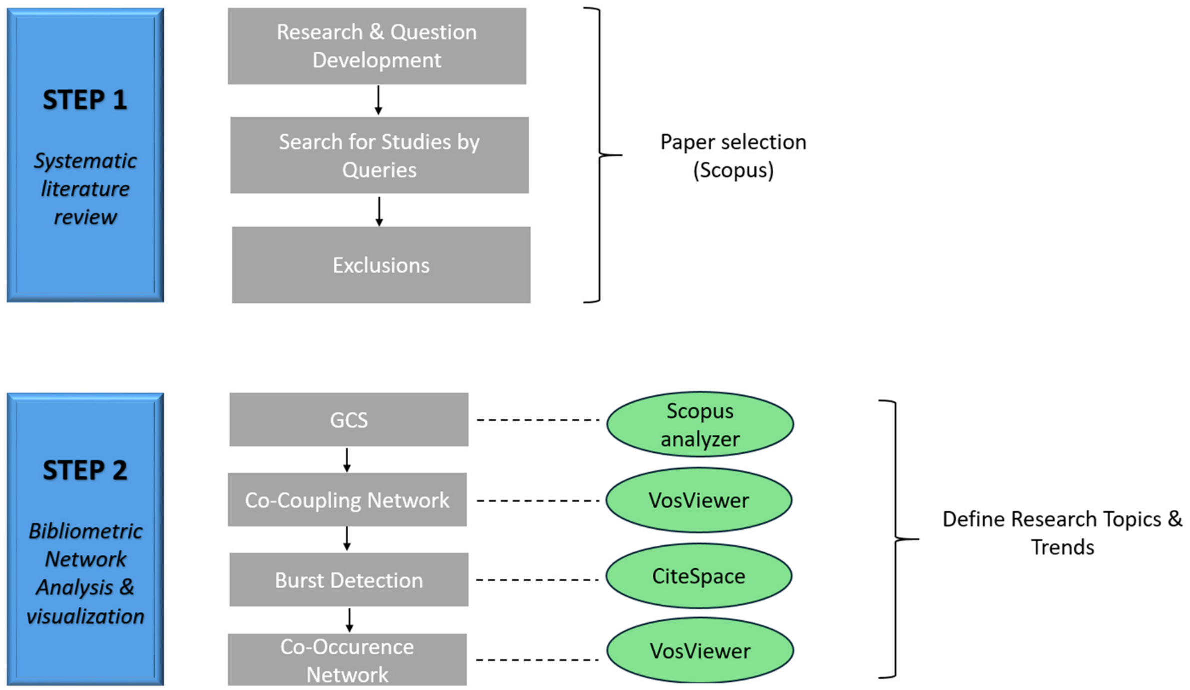

Figure 1. Overview of the Search and Filtering Process in the Bibliometric Literature Review.

The following steps were followed to define the query. First, we defined the research questions in the Section 1. Based on the research questions, we identified the most important keywords and their synonyms. These keywords included Industry 4.0, the increasingly prevalent Industry 5.0, digitalisation, and the Internet of Things, along with their variants. The keywords were then linked using Boolean operators (AND, OR), and the search was run. Included were peer-reviewed English-language journal articles and review papers published between 2005 and 2025 that are directly relevant to the Industry 4.0–Industry 5.0 transition. The following were excluded:

1. Non-English language publications;
2. Non-peer-reviewed materials (e.g., white papers, theses, editorials);
3. Duplicate records.

The result of the first search was 1625 hits for the period 2005–2025, and then only English language hits were selected. Out of the 1536 English language results obtained, 623 were scientific articles, 550 conference papers, 192 book chapters, and the remaining 171 were other categories (review, book, editorial, etc.). The resulting data were cleaned (removing duplicate titles, filtering out potentially outdated articles with time-order), resulting in a total of 1441 articles:

TITLE ((indust* AND 4* OR 5*) AND digital* OR (internet AND of AND things OR iot)) AND PUBYEAR > 2004 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, “re”) OR LIMIT-TO (DOCTYPE, “ch”) OR LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (LANGUAGE, “English”))

During the research, several software tools were used in the Bibliometric Network Analysis and Visualisation steps. For the GCS, we used the Scopus analyzer. For the Co-Coupling Network and the Co-Occurrence Network, we used VOSviewer (version 1.6.18). For the Burst detection step, we used the CiteSpace (6.3.R1) app [40].

To improve the clarity of how each bibliometric technique contributes to answering the research questions, Table 1 explicitly links the applied methods to RQ1–RQ3. This mapping shows which analytical approaches were used for each question and outlines their specific purpose within the study.

Table 1. Linking bibliometric techniques to research questions and their purpose.

Research Question	Bibliometric Technique(s)	Purpose
RQ1—How is the transition from Industry 4.0 to Industry 5.0 reshaping human–machine interaction, and what supporting role does digitalisation play in this process?	Keyword co-occurrence analysis; temporal trend analysis	Identify key terms, their relationships, and how the thematic focus on human–machine collaboration has shifted towards human-centric objectives.
RQ2—How do digital twins and artificial intelligence impact the development of Industry 5.0 and contribute to the creation of a sustainable industry?	Co-citation network analysis; thematic clustering	Map the intellectual structure of AI and digital twin research and reveal how these technologies are linked to sustainability-related themes.
RQ3—How will the introduction of blockchain technology impact the digitization and resiliency of supply chains?	Bibliographic coupling; cluster analysis	Identify recent research on blockchain in supply chains and examine its connections to flexibility and decentralised coordination.

3. Results—Bibliometric Network Analyses and Visualisation

3.1. Time-Weighted Global Citation Score

The Global Citation Score (GCS) shows the total number of citations a scientific article has received in the Scopus database. This indicator measures the impact of an article on the discipline through the number of other articles citing it. However, looking only at the total number of citations received for an article would give an inadequate result because older articles have had more time to collect citations. In comparison, newer articles have had less time [41]. To avoid this bias, we used the Time-weighted GCS method, which means that the original GCS value was corrected for the time since the publication, i.e., the total number of citations divided by the number of years since publication.

This weighting can provide several advantages: on the one hand, it smooths out the temporal imbalance between old and new publications, so that an article with a rapidly growing impact appears early in the analysis, and on the other hand, it makes it easier to identify the latest trends and directions in research. Based on our calculations, the 10 articles with the highest Time-weighted GCS are shown in Table 2.

Table 2. Leading Publications by Time-weighted GCS.

	Title	Year	Cited by	References	Time-Weighted GCS
1.	The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics	2019	1197	[42]	200
2.	A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0	2021	743	[43]	186
3.	The future of industrial communication: Automation networks in the era of the internet of things and Industry 4.0	2017	1404	[44]	176
4.	Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison	2018	1204	[45]	172

Table 2. *Cont.*

	Title	Year	Cited by	References	Time-Weighted GCS
5.	Human Digital Twin in the context of Industry 5.0	2024	149	[46]	149
6.	Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison	2019	890	[47]	148
7.	Applications of Wireless Sensor Networks and Internet of Things Frameworks in the Industry Revolution 4.0: A Systematic Literature Review	2022	403	[48]	134
8.	A review of Internet of Things (IoT) embedded sustainable supply chain for Industry 4.0 requirements	2019	775	[49]	129
9.	Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective	2019	725	[50]	121
10.	Digital twins-based smart manufacturing system design in Industry 4.0: A review	2021	458	[27]	115

The top 10 articles primarily explore the relationship between Industry 4.0, Industry 5.0, and digitalisation, but from different perspectives. The main topics covered by the articles include the link between digitalisation and smart manufacturing [27,44,45,47], supply chain digitalisation, which is the focus of several articles [42,43,49], service-oriented business models [50], risks and challenges associated with Industry 4.0 [42,43], and prospects [46,49].

The articles show that Industry 4.0, Industry 5.0, and digitalisation are closely linked. Their application in industry will transform industrial production processes, supply chains, and business models.

For companies adopting Industry 4.0 and, to some extent, Industry 5.0, maintaining supply chain security and resilience is a key priority, as the widespread adoption of digital technologies can have a significant impact on system stability. Research shows that intelligent data analytics and high levels of automation of process steps can help reduce supply chain disruptions [42,43]. Digital models of the supply chain are increasingly important for managing disruptions and building resilience into systems. Companies can optimise their operations by using digital models that enable professionals to run real-time analyses and simulations to predict problems. Such supply chains contribute not only to cost-effective operations but also to sustainability [50]. Digital twins can also be used to enhance industrial processes, in addition to improving the supply chain. They can also be used to identify production problems through big data analysis and real-time simulations [27]. Using these methods, production problems and possible downtime can be predicted, and product quality can be improved. Today's high levels of artificial intelligence and automation enable a high level of process visibility, making digital twins of great importance for smart manufacturing [47].

A key element of the Industry 5.0 concept is the human digital twin. This technology is designed to enable different levels of communication between workers and digital or automated systems. The use of a human digital twin can help companies achieve higher productivity and optimize workflows for collaboration with human resources [49].

The use of IoT devices and wireless sensors is essential for industrial digitalisation. Continuous data collection, transmission, storage, and analysis rely on these devices. Thanks to intelligent sensor networks, companies can optimise energy use, increase the detection or even prediction of faults, and allocate human resources more efficiently [48]. Today, IoT-enabled systems can also be utilized to achieve the increasingly important goal of waste reduction [49]. Furthermore, the abundance of data and the conclusions that can be drawn from it can lead to the introduction of new technologies and methods that can increase the market competitiveness and value creation capabilities of companies through customer-centric solutions [50].

3.2. Co-Coupling Network (CCN) Analysis

The VOSviewer software (in our research, we used VOSviewer version 1.6.18) is used to map links between scientific publications. One of the software's capabilities is Coupling Network (CCN) Analysis, which examines the common links between different publications [51].

The VOSviewer sorted the selected articles into 8 clusters (Figure 2). Within these clusters, we retained the articles with the top 3 citations; the others were removed at this step (see Table 3).

This method is beneficial for identifying new research trends and the most prominent authors and articles in a specific subject area. Articles are displayed as nodes in the program, with links between them, thicker for stronger links. The program automatically sorts related articles into clusters, which are indicated by different colours. VOSviewer generates clusters based on the similarity of content or links. Furthermore, the relationships between the displayed clusters can help to highlight the connections between different subject areas [52].

The articles in the *first cluster* demonstrate that the connection between Industry 4.0 and digitalisation is fundamentally reshaping supply chains. Digitalisation, combined with other Industry 4.0 methods (such as AI and big data), will make logistics networks significantly more flexible and agile [53,54].

Queiroz et al. have developed a framework to define the capabilities of digital supply chains, which is translated as DSCCs (Digital Supply Chain Capabilities). The application of this methodology allows for the identification of key technological and organizational factors to measure digital transformation. In contrast, the Digital Supply Chain (DSC) Model, besides highlighting the benefits of digital integration and automated decision making, presents potential drawbacks such as data security or the transformation of corporate culture [53].

Table 3. Clusters with the TOP 3 most cited publications by CCN.

Clusters	Authors	References	Citations	Publish Year
1	Queiroz M.M.; Pereira S.C.F.; Telles R.; Machado M.C.	[53]	236	2019
	Garay-Rondero C.L.; Martinez-Flores J.L.; Smith N.R.; Caballero Morales S.O.; Aldrette-Malacara A.	[54]	236	2019
	Ghobakhloo M.; Iranmanesh M.	[55]	200	2021
2	Frank A.G.; Mendes G.H.S.; Ayala N.F.; Ghezzi A.	[50]	725	2019
	Aceto G.; Persico V.; Pescapé A.	[56]	672	2020
	Li Y.; Dai J.; Cui L.	[57]	566	2020

Table 3. *Cont.*

Clusters	Authors	References	Citations	Publish Year
3	Wollschlaeger M.; Sauter T.; Jasperneite J.	[44]	1404	2017
	Manavalan E.; Jayakrishna K.	[49]	775	2019
	Özdemir V.; Hekim N.	[58]	410	2018
4	Tao F.; Qi Q.; Wang L.; Nee A.Y.C.	[47]	890	2019
	Shrouf F.; Ordieres J.; Miragliotta G.	[59]	766	2014
	Leng J.; wang d.; Shen W.; Li X.; Liu Q.; Chen X.	[27]	458	2021
5	Aazam M.; Zeadally S.; Harras K.A.	[60]	482	2018
	Nagy J.; Oláh J.; Erdei E.; Máté D.; Popp J.	[61]	468	2018
	Wang M.; Wang C.C.; Sepasgozar S.; Zlatanova S.	[62]	228	2020
6	Ivanov D.; Dolgui A.; Sokolov B.	[42]	1197	2019
	Ivanov D.; Dolgui A.	[43]	744	2021
	Ardito L.; Petruzzelli A.M.; Panniello U.; Garavelli A.C.	[63]	411	2019
7	Qi Q.; Tao F.	[45]	1204	2018
	Dutta G.; Kumar R.; Sindhwani R.; Singh R.K.	[64]	177	2020
	Lee J.; Cameron I.; Hassall M.	[65]	147	2019
8	Yin S.; Yu Y.	[66]	227	2022
	Wang B.; Zhou H.; Li X.; Yang G.; Zheng P.; Song C.; Yuan Y.; Wuest T.; Yang H.; Wang L.	[46]	149	2024
	Javaid M.; Haleem A.; Suman R.	[67]	127	2023

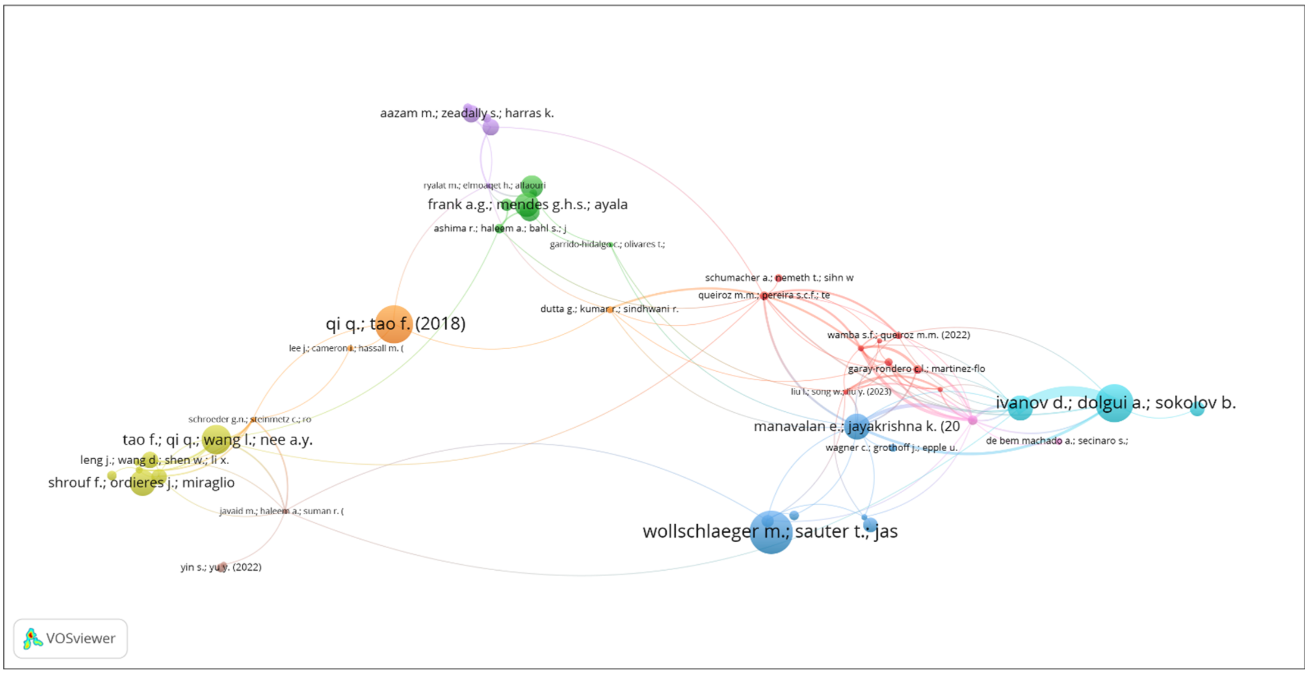

Figure 2. Co-Coupling Network (CCN) Analysis—Cluster Visualisation of Key Publications.

The elements of the *second cluster* indicate that digitalisation is a key driver for the development of various systems and sustainability. Research suggests that the adoption of multiple methods not only enhances the competitiveness of companies but also fosters a more sustainable and customer-centric approach [50,56,57]. Frank et al. investigated in their research how Industry 4.0 and servitization are linked. Servitisation means that companies are shifting their focus from selling products to providing services. The research has identified three levels of servitisation (smoothing, adapting, substituting) and three levels of digitalisation, which can be combined to create nine different combinations. The results show that a more service-centric model can improve the efficiency of companies [50]. The second most cited article in the cluster [56] also focuses on services through the use of digitalisation in healthcare. According to the article, the creation of Healthcare 4.0 has a significant impact on cost reduction, telemedicine, and predictive diagnosis within the healthcare system. IoT solutions can be used to improve personalized patient care and intelligent condition tracking significantly.

Increasing sustainability through cutting-edge technologies remains an important research issue. The results indicate that the digital supply chain serves as a mediating factor between digital technologies and sustainability [57].

According to the research of the *third cluster*, Industry 4.0 and Industry 5.0 share a common goal of improving industrial automation and digitalisation. The research highlights that the next stage of industrial development is digitalisation and related modern technologies such as IoT-based systems. The concept of Industry 5.0 focuses on enhancing the value of the human workforce by leveraging AI, whereas the primary goal of Industry 4.0 remains to increase automation and efficiency [49,58].

As IoT-based industrial communication is one of the key pillars for the expansion of Industry 4.0, it is essential to unify these systems. Industrial automation is increasingly relying on the deployment of highly reliable networks that provide fast data transmission [44]. In addition to communication, the digital supply chains mentioned in the first cluster also rely heavily on IoT-based systems. Closed-loop supply chains (CLSCs) and sustainable supply chains (SSCs) play an important role in industrial digitalisation. Manavalan et al. have developed a framework that identifies five key aspects for measuring the digital transformation of supply chains: management, technology, sustainability, business strategy, and collaboration [49]. Industry 4.0 plays a crucial role in the advancement of digitalisation, but one of the primary goals of Industry 5.0 is to support human-centered innovation, complemented by AI. The ultimate goal is to create more ethical and sustainable business processes [58].

The articles in the *fourth cluster* provide a comprehensive overview of the relationship between IoT-based energy efficiency and digital twins, highlighting that cyber-physical systems and digital twins are essential for the digitalisation of manufacturing [27,47]. The most cited article in the cluster highlights that digital twins (DT) and cyber-physical systems (CPS) integrate the physical and digital worlds in distinct ways. Although they serve similar purposes, they are designed for different principles and applications. The study concludes that while digital twins can model manufacturing processes with higher accuracy, CPS are optimised for real-time control [47].

Furthermore, DT technology provides real-time simulations and predictions for smart manufacturing systems. The study also proposes a new model (FSBCIP) that defines the main design aspects of digital twins from the perspective of manufacturing requirements [27].

The elements of the *fifth cluster*, like the previous ones, emphasize optimized energy consumption, data security, and the expected benefits for companies using modern technologies. However, in this cluster, they build on Porter's value chain model [60,61]. The application of Fog computing further enhances the reliability of real-time decision-making, accelerates processes, and enables local data processing [48]. The application of digitalisation and Industry 4.0 in the construction industry is also driving significant progress, but it comes with several technological and organizational challenges [46].

A *sixth cluster* of publications argues that digital twins, IoT, and risk management models play a critical role in increasing supply chain flexibility, demonstrating the impact of digital technologies on business strategies through which the integration of industrial processes and marketing is increasingly being achieved [42,43,63]. A model has been developed to address potential disruptions in digital supply chains, linking the impact of digital technologies to risk management, called the Ripple Effect Control Framework. The Ripple Effect refers to disruptions that do not remain localized problems but spread throughout the entire supply chain, affecting its overall performance. Research suggests that digital techniques may be able to mitigate these types of disruptions, but may also exacerbate these adverse effects [42]. Another model for managing supply chain disruptions is the so-called Digital Supply Chain Twin (DSC-T) model. The results show that the application of the DSC-T model can help implement appropriate preventive measures, increase supply chain visibility, and expedite possible recovery [43].

Research in the *seventh cluster* will focus on the impact of digital twins. The conclusions show that digitalisation can be successfully applied not only in large enterprises, but also in small and medium-sized enterprises (SMEs), which need to adopt digitalisation techniques to improve their performance [45]. The pace of digitalisation has also necessitated the creation of various specific standards, such as ISO 15926, which covers communication solutions, thereby enabling the integration of digital systems [65].

The main research themes of the *eighth cluster* are the links between Industry 4.0 and Industry 5.0 and human-centred digitalisation and the application of green innovation models [46,66]. The fuzzy-set Qualitative Comparative Analysis (fsQCA) method was employed to assess digital green innovation performance (DGIP), which is well-suited for examining potential combinations of external factors and addressing causal asymmetries. The moderating effects of risk perception and complexity perception were also considered in the performance measurement [66].

3.3. Results of Burt Detection Analysis (BDA)

The CiteSpace app is a bibliometric and scientific network analysis software designed to track scientific trends, research areas, and collaborations among researchers. One of the features of the software is Burst Detection Analysis (BDA), a method for identifying topics of high interest at specific times. The method consists of creating a database of the most relevant data and loading it into the program's settings. The algorithm can work in several ways; for example, it can indicate a sudden increase in the number of citations [68]. Our research is based on keywords that can be used to determine the direction in which research into the relationship between Industry 4.0, Industry 5.0, and digitalisation is heading. For data collection, we used the same Scopus database as in the previous steps. The period chosen for the study is 2005–2025. A citation threshold (G-index) was defined within the program, below which no publications were examined. By clustering, the software identified the most important topics within the relevant discipline. Burst Detection Analysis analysed the frequency of occurrence of keywords and ranked them according to frequency. Modularity and density measures determine the internal coherence of article groups within keyword articles and the strength of these coherences [37]. Figure 3 shows the most important keywords related to Industry 4.0, Industry 5.0, and digitalisation.

The most important keyword is 'digital twins'. It has experienced explosive growth in recent years, particularly since 2020. The term 'digital twins' is strongly linked to IoT technologies and smart manufacturing solutions for Industry 4.0 [27]. The second keyword is 'digital transformation', which has also shown strong growth in recent years, but is less linked to the other themes. For this keyword, it is assumed that it is closely related to various business processes beyond manufacturing; however, this topic requires further research [69]. 'Digital technologies' can be related to the 'digital twin' concept, as shown in Figure 3, which shows an increase in research at similar times [70]. The 'internet of things' was really in the spotlight between 2010 and 2015, and can be said to have played and continues to play a key role in the take-up of Industry 4.0 [71]. Industry 5.0 is a relatively new concept, as illustrated in Figure 3, and has begun to appear more frequently in research topics since 2020. The concept of Industry 5.0 is that, in addition to digitalisation, it also places a strong emphasis on human capital [72]. The keyword 'eis' refers to Executive Information Systems, early managerial dashboard solutions that anticipated today's analytics and decision-support layers in Industry 4.0 and 5.0. The emergence of the keywords 'supply chain design' and 'blockchain technology' may be an indicator that data security and traceability are gradually gaining prominence. Overall, it can be said that digital twins have been at the centre of research, and Industry 5.0 is becoming increasingly dominant [73]. However, Industry 4.0 remains at the forefront, and previous research on IoT and digital techniques has laid the groundwork for the development of a new generation of industrial technologies [74]. This suggests a transition from Industry 4.0 to Industry 5.0, where digital twins and human-centric digitization are becoming increasingly central [75].

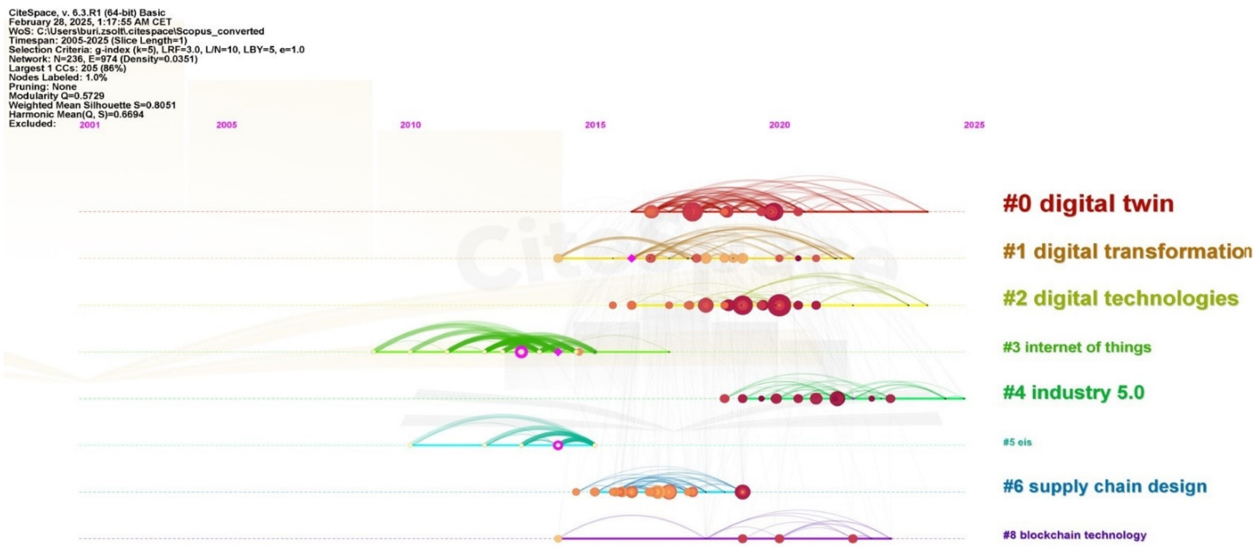

Figure 3. Keyword Burst Detection—Temporal Trends in Industry 4.0 and 5.0 Research.

3.4. Co-Occurrence Network of Keywords (CONK) Analysis

Figure 4 presents the Co-Occurrence Network of Keywords, illustrating the clustered thematic relationships among key concepts in the literature on Industry 4.0, Industry 5.0, and digitalisation.

The first cluster analyses digital twins as a technology that is an important element of the transition between Industry 4.0 and Industry 5.0. The articles in the cluster analyse data-driven methods to optimise industrial processes, increase productivity, and reduce potential disruptions. The data used are most often related to supply chains, physical parameters measured by sensors, and historical data that can be later processed using machine learning. Discrete Event Simulation (DES) and Agent-Based Modeling (ABM) enable the testing of alternative strategies before implementing a specific strategy. Industry 5.0 adopts a new approach, where machine-human collaboration plays a crucial role alongside artificial intelligence and automation. Integrating human decision-making with artificial intelligence and robotisation will result in hybrid systems that increase the flexibility and adaptability of industrial processes and cognitive computing and self-regulating algorithms ensure the continuous and autonomous evolution of industrial systems with predictive maintenance models such as Digital Predictive Maintenance (DPM) providing practical examples even in healthcare contexts [76,77]. In addition, sustainability is increasingly driving the role of various Life Cycle Assessment (LCA) methods.

The publications of the second cluster highlight that digitalisation not only supports automation but also the development of new business models and sustainable manufacturing processes. Özdemir and Hekim [58] interpret the concept of Industry 5.0 as a response to the challenges of extreme automation and Big Data, based on the integration of the Internet of Things (IoT), Artificial Intelligence (AI), and collaborative robots (cobots) into industrial processes. Aheleroff et al. investigated the simulation and optimization of manufacturing processes in a Digital Twin as a Service (DTaaS) model, which enables real-time monitoring and automated maintenance. Here again, the inputs to such systems are mainly from big data analytics, RFID technology, or cloud-based systems [78].

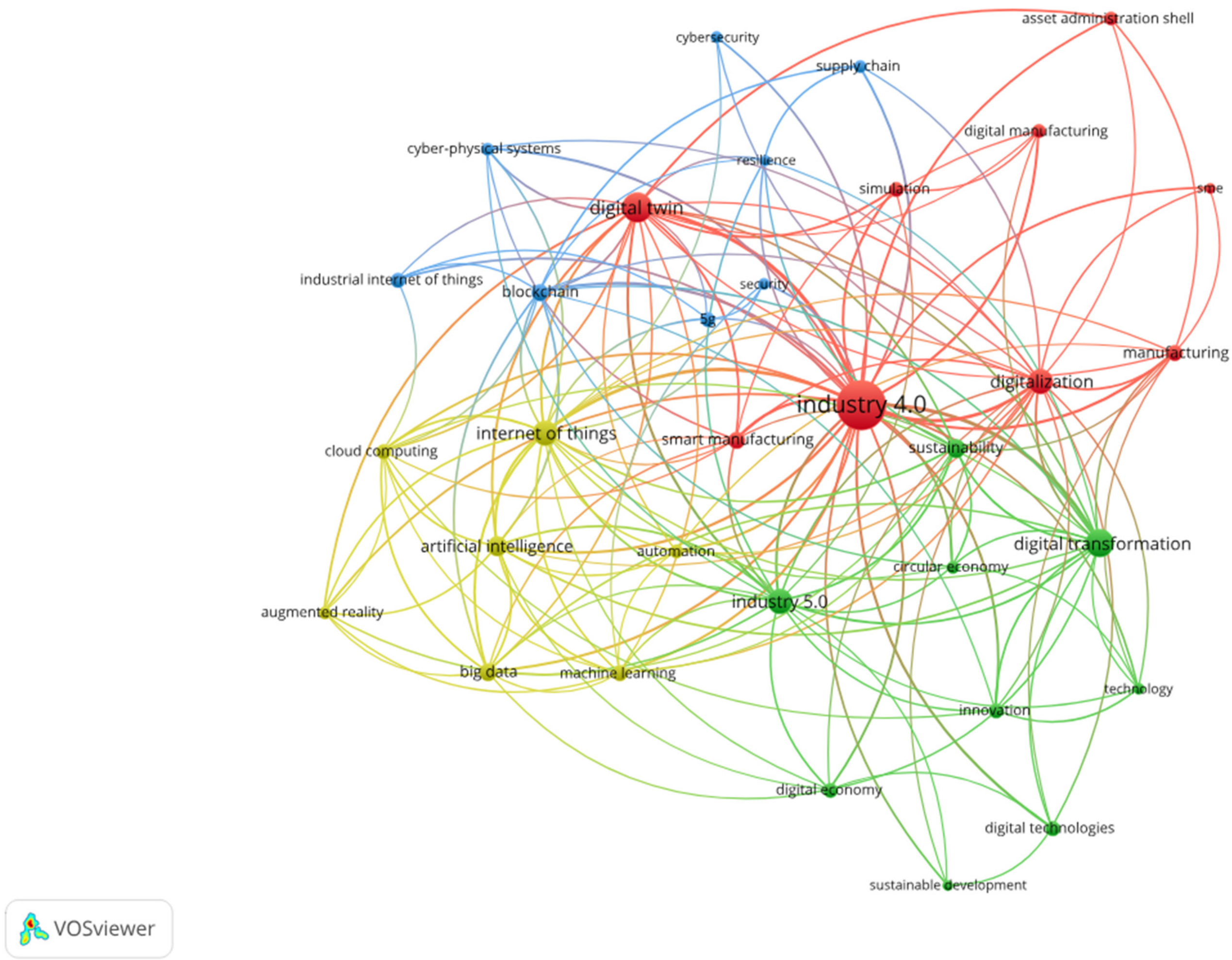

Figure 4. Co-Occurrence Network of Keywords—Clustered Themes in Industry 4.0 and 5.0.

Research in the third cluster examines the transition from Industry 4.0 to Industry 5.0 from the perspective of industrial digitalisation. Wamba and Queiroz have developed a multiphase model based on the diffusion theory of dynamic capabilities and innovation from a resource-based perspective, which can analyse the stages of blockchain integration in the supply chain. In the study, several countries are compared, and it is concluded that the motivations for integrating technology may differ [78]. An important element of digitalisation is edge computing and 5G within IoT systems. These methods are increasingly critical in providing flexible resource allocation in industrial environments. In this paper, the optimization is solved by applying a cross-domain sharing-enabled edge resource scheduling scheme and credit-differentiated transaction [79]. The Industrial Internet of Things is also a key focus of cluster research. The publication emphasizes the significance of artificial intelligence, sensor networks, and robotics in various industrial sectors, including agriculture, energy management, and healthcare. The primary outcome of the research is a layered architecture that provides scalability in the context of Industry 4.0 [80]. Aazam et al. investigated the relationship between 5G fog computing and the Internet of Things (IoT) for the Tactile Internet. They investigate the combination of ultra-reliable low-latency communication and Quality of Experience (QoE) models across various industrial sectors. The publication results in the construction of a QoE Ratio (QoER) model that incorporates customer feedback and latency requirements into the original QoE model, thereby achieving higher levels of optimization [60].

The fourth cluster will focus on Industry 4.0 and the evolution of industrial digitalisation. The Software-Defined Industrial IoT (SD-IIoT) analyses the combination of software-defined networking and industrial IoT. The research proposes to decompose architectures into three layers: a physical layer, a control layer, and an application layer. The paper also presents a testbed for evaluating SD-IIoT, which is suitable for validation [81]. In their paper, Wollschlaeger et al. highlight the role of 5G, time-sensitive networks (TSN), and industrial Ethernet in smart manufacturing environments. One of the main findings of their research is that the integration of automated data management and machine learning is of paramount importance for industrial systems [44].

4. Discussion and Conclusions

We used a Systematic Literature Review (SLR) and visualisation techniques to find answers to our research questions. By applying these methods, the study provides a broader overview of the technological and operational foundations of the transition from Industry 4.0 to Industry 5.0, supplementing and expanding on previous research on this topic. While most of the studies published to date have been based on a single technology or conceptual framework [references] [82–86], our current results integrate multiple perspectives into a unified analytical framework (human–machine interactions, artificial intelligence, digital twins, and the development of blockchains for supply chain flexibility). This integrated analytical framework provides a broader, system-level view of how modern technologies contribute to the transformation of industrial and service processes.

The results related to human–machine interaction confirm previous observations that the relevant technologies were already present, but Industry 5.0 seeks to place them at the center of processes [16,74]. The significant presence of the terms AI and digital twins in our keyword and co-citation networks is consistent with previous research findings [87–89], but our analysis shows that these keywords have recently become increasingly associated with sustainability issues. Previous research on blockchains has largely emphasized their potential in supply and distribution chains [90,91], while our results emphasize the role of blockchains in flexibility and decentralized coordination.

The first research question (RQ1) investigated how the role of digitalisation is changing and how human–machine relationships are being transformed in the transition from Industry 4.0 to Industry 5.0. The publications reviewed highlight that while Industry 4.0 focuses on the development of smart manufacturing through IoT tools and the full implementation of digital twins, Industry 5.0 aims to put the human back at the center of manufacturing [92]. This human-centric approach can be achieved by utilizing technologies such as collaborative robots, AI-assisted human decision-making, and sustainability [93]. Digitalisation is a priority in both industrial revolutions, but while the primary goal of Industry 4.0 is to reduce costs and increase efficiency, Industry 5.0 focuses on human decisions and influence as its core objective [31,47,72,94]. Thus, in Industry 5.0, digitisation does not only focus on technology but also tries to use the human factor as a key indicator.

The second research question (RQ2) concerned how artificial intelligence is shaping digital twins and how this contributes to Industry 5.0 in terms of sustainability. The research suggests that AI will help integrate digital systems into manufacturing within the framework of Industry 4.0, enabling faster and more accurate data-driven decisions. However, Industry 5.0 will take human expertise into account in decision-making and combine it with digital technologies to support sustainable development [45,47,95]. The use of artificial intelligence can improve supply chain management, further optimise industrial processes, and reduce energy consumption [79,96]. Based on the AI implication of digital twins, circular management, real-time monitoring, and predictive maintenance will become feasible, supported by risk-based approaches such as fuzzy-logic maintenance assessment [97,98]. Overall, AI and digital twins are among the most important technologies of Industry 5.0 that will enable production systems to reach the next level.

The third research question (RQ3) is the impact of digitalisation on supply chains and how the introduction of blockchain technology is shaping the resilience of supply chains. The data analysed shows that the introduction of blockchain technology plays a key role in improving the transparency and efficiency of supply chains. Its introduction increases the traceability of the process and reduces the risk of disruption thanks to decentralised decision points. According to the literature, the implementation of blockchain is always a multi-stage model in which the variables can vary widely from one industry to another (health, agriculture, industrial production, etc.) [43,50,56].

To enhance clarity, Table 4 explicitly links each research question (RQ1–RQ3) to the key results obtained in this study and specifies the bibliometric analyses from which these results were derived.

The three research questions focus on different technologies, but they converge on one common point today: the development of sustainable industrial and service systems. Our bibliometric data show that these areas are linked by common concepts (e.g., digitization, cyber-physical integration), which supports the joint examination of these areas. This is in line with the integrated bibliometric approach proposed by Rejeb et al. [99].

The wider implications include that, from an industrial perspective, the emergence of human-centred design principles and modern digital technologies means that balanced strategies are needed that consider employee wellbeing as well as an efficient operating environment. For technical, economic, and policy makers, the combined emergence of AI, digital twins, and blockchain offers opportunities to align innovation, environmental concerns, and social policy goals.

This study contributes novelty by mapping the intellectual structure of Industry 4.0–Industry 5.0 transition research across multiple enabling technologies, revealing previously underexplored interconnections between human–machine interaction, sustainability-oriented AI applications, and blockchain-based supply chain resilience. Bringing these domains together within one bibliometric framework helps overcome the existing fragmentation in the literature and offers a more comprehensive view of the transition. In summary, the transition from Industry 4.0 to Industry 5.0 will be a pivotal shift for all industrial sectors, with companies, professionals, and researchers all seeking to adopt new technologies through well-planned implementations [55,69].

The great advantage of the bibliometric research conducted in this study is that it brings together articles from different areas of the literature in a structured form, thereby reducing subjectivity in drawing key conclusions.

However, the interpretation and naming of clusters in bibliometric network analysis also involve a subjective element. Although our labeling was informed by keyword frequency, citation patterns, and representative documents, alternative yet equally valid interpretations may exist. This interpretive nature should therefore be considered as an inherent limitation of the method. In addition, systematic bibliometric research also has its limitations. First, the analysis was limited to Scopus database, peer-reviewed, English-language publications indexed in Scopus, which may exclude relevant studies published in other languages or indexed in other databases, potentially introducing a language or database bias. Second, bibliometric analyses are inherently influenced by citation patterns, which may bias results towards highly cited works and underrepresent recent but less-cited publications. Finally, the topic itself is subject to continuous reinterpretation, mainly due to the rapid development of artificial intelligence, and Industry 5.0 is an emerging paradigm that may incorporate or transform other pillars beyond the three main ones currently identified (industrial process improvement, human-focused perspective, and sustainability) in the coming years.

Table 4. Linking research questions to key results and the bibliometric analyses from which they are derived.

Research Question	Key Results	Source and Method
RQ1—How is the transition from Industry 4.0 to Industry 5.0 reshaping human–machine interaction, and what supporting role does digitalisation play in this process?	Human–machine interaction and collaborative robotics have been present since Industry 4.0, but are increasingly reoriented towards human-centric objectives in Industry 5.0.	Derived from keyword co-occurrence analysis and temporal trend analysis in the Section 3, showing a shift in term associations over time.
RQ2—How do digital twins and artificial intelligence impact the development of Industry 5.0 and contribute to the creation of a sustainable industry?	Strong linkages between AI, digital twins, and sustainability-related concepts indicate a recent shift in research focus towards environmental and social objectives.	Identified through co-citation network analysis and thematic clustering, where sustainability terms co-occurred with AI/digital twin clusters.
RQ3—How will the introduction of blockchain technology impact the digitization and resiliency of supply chains?	Blockchain's role has evolved from improving transparency to enabling flexibility and decentralised coordination in supply chains.	Based on bibliographic coupling and cluster analysis, revealing emerging research clusters on supply chain resilience and decentralised systems.

Future research should aim to gain deeper insights into how basic technologies and human-technology collaboration can jointly advance the goals of Industry 5.0. The most important options are as follows:

1. Sector-specific case studies examining the application of blockchain to improve supply chain resilience in the context of Industry 5.0.
2. Empirical evaluation of human–digital twin collaboration in a real manufacturing environment in terms of efficiency, adaptability, and operator well-being.
3. Longitudinal analyses tracking the adoption curve of collaborative robotics in sustainable production systems, identifying enabling factors or barriers related to technology, economics, and labor.
4. Interdisciplinary frameworks integrating politics, ethics, and technology that provide actionable guidelines for planning and managing Industry 5.0.
5. Addressing the ethical and social implications of human–digital twins and AI-driven collaboration. Key issues include privacy, autonomy, accountability, bias, and the evolving role of humans in industrial environments, which represent one of the core tensions in the Industry 5.0 paradigm.

By explicitly linking technological innovation with human-centered values and sustainability goals, future research can support the development of an Industry 5.0 paradigm that is not only technologically advanced but also socially responsible and environmentally friendly.

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Abbreviations

The following abbreviations are used in this manuscript:

ABM	Agent-Based Modeling
AI	Artificial Intelligence
BDA	Burst Detection Analysis
BNAV	Bibliometric Network Analysis and Visualisation
CCN	Co-Coupling Network (Analysis)
CLSCs	Closed-Loop Supply Chains
CONK	Co-Occurrence Network of Keywords
CPS	Cyber-Physical Systems
DES	Discrete Event Simulation
DGIP	Digital Green Innovation Performance
DSC	Digital Supply Chain
DSC-T	Digital Supply Chain Twin
DSCCs	Digital Supply Chain Capabilities
DT	Digital Twin
DTaaS	Digital Twin as a Service
GCS	Global Citation Score
IIoT	Industrial Internet of Things
IoT	Internet of Things
LCA	Life Cycle Assessment
QoE	Quality of Experience
QoER	Quality of Experience Ratio
SD-IIoT	Software-Defined Industrial Internet of Things
SLR	Systematic Literature Review
SSC	Sustainable Supply Chain
TSN	Time-Sensitive Network
fsQCA	Fuzzy-Set Qualitative Comparative Analysis

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