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The research landscape of industry 5.0: a scientific mapping based on bibliometric and topic modeling techniques

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Abstract
Industry 5.0 (I5.0) marks a transformative shift toward integrating advanced technologies with human-centric design to foster innovation, resilient manufacturing, and sustainability. This study aims to examine the evolution and collaborative dynamics of I5.0 research through a bibliometric analysis of 942 journal articles from the Scopus database. Our findings reveal a significant increase in I5.0 research, particularly post-2020, yet highlight fragmented collaboration networks and a noticeable gap between institutions in developed and developing countries. Key thematic areas identified include human-robot collaboration, data management and security, AI-driven innovation, and sustainable practices. These insights suggest that a more integrated approach is essential for advancing I5.0, calling for strengthened global collaborations and a balanced emphasis on both technological and human-centric elements to fully realize its potential in driving resilient and sustainable industrial practices. This study provides the first comprehensive bibliometric analysis of I5.0, offering valuable insights for both researchers and practitioners.

Keywords Industry 5.0 · Artificial intelligence · Human-Robot collaboration · Sustainability · Bibliometrics

1 Introduction

1.1 General background

The evolution of industrial revolutions has been marked by significant milestones, beginning with Industry 1.0's introduction of mechanical production facilities powered by water and steam, notably marked by Edmund Cartwright's power loom in 1784 (Adel 2023; Aydin et al. 2023). This mechanization significantly altered the

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textile industry and set a foundation for further technological advancements. Progressing into Industry 2.0, the advent of electricity facilitated mass production, which revolutionized the automotive industry by drastically reducing the time required to produce a single vehicle (Ahmad et al. 2023; Ben Youssef and Mejri 2023).

The transition to Industry 3.0 introduced automation through electronic and information technology, which significantly transformed production processes (Bhat and Parvez 2024; Domenteanu et al. 2024). Innovations such as the programmable logic controller (Akinsolu 2023) developed in the late 1960s marked the early integration of digital technology into manufacturing and laid the groundwork for what would become a digital revolution in Industry 4.0. Today, humanity finds itself amid Industry 4.0 (I4.0), which integrates technologies as diverse as cyber-physical systems, the Internet of Things (IoT), and cloud computing to create smart factories (Abdirad and Krishnan 2020; AL-Khatib 2023). These advancements enhance efficiency through real-time monitoring and decision-making support, offering significant productivity and connectivity boosts (Abril-Jiménez et al. 2024; Atif 2023). The focus of I4.0 is on smart manufacturing, which leverages technologies like AI, big data, and IoT to enhance the manufacturing process's adaptability and efficiency (Fanoro et al. 2021; Hansen et al. 2024). However, the rapid advancements in I4.0 have also brought challenges, including socio-economic disparities, environmental concerns, and an increased complexity in technological integration (Akinsolu 2023; Bakon et al. 2022; Basulo-Ribeiro and Teixeira 2024; Bissadu et al. 2024). Although the integration of these technologies is promising, it has highlighted the limitations of a purely technology-driven approach, particularly in its tendency to marginalize the human component of manufacturing (Bhattacharya et al. 2023). This backdrop sets the stage for the emergence of Industry 5.0 (I5.0), which addresses the shortcomings of I4.0 by reintegrating the human element into the production process (Adel 2022; Agote-Garrido et al. 2023).

I5.0 extends the principles of I4.0 by emphasizing collaboration and coexistence between humans and machines in the industrial sector, aiming to balance automated and human-centric manufacturing processes (Abdel-Basset et al. 2024; Asad et al. 2023; Eriksson et al. 2024). Furthermore, this novel paradigm not only fosters creativity and analytical reasoning in conjunction with cutting-edge technology but also facilitates the development of more flexible, customized, and innovative manufacturing solutions (Ghobakhloo et al. 2023). While the definition of I5.0 is still emerging, this paradigm envisions a manufacturing landscape that leverages the strengths of both humans and machines to foster a more resilient, personalized, and sustainable production environment. In particular, technologies such as autonomous driving, IoT, blockchain, and green and renewable energy are pivotal to this transformation. For instance, Miao et al. (2022a, b), Zhou and Lund (2023) explore innovative approaches in electric vehicle services and peer-to-peer energy sharing. Similarly, the studies of Liu et al. (2021), Guo et al. (2024), and Wang et al. (2024) highlight the importance of AI and IoT in fostering sustainable industrial practices within the framework of I5.0. Therefore, the transition toward I5.0 is pivotal in addressing the limitations of purely technology-driven approaches and in paving the way for a future where human-centric and technologically advanced manufacturing coexist harmoniously.

The implications of I5.0 are transformative and meld the technological prowess of I4.0 with a renewed focus on human skills, sustainability, and quality of life. This new industrial paradigm seeks to revolutionize the work environment by enhancing the interaction between humans and machines (Dornelles et al. 2023; Gervasi et al. 2023). For instance, collaborative robots, or "cobots", are designed to handle tedious or physically demanding tasks. They not only reduce workplace injuries and ensure safety for human interaction but also allow human workers to engage in more creative and intellectually stimulating roles (Ciccarelli et al. 2024; Duarte et al. 2022; Enang et al. 2023). This shift is anticipated to lead to greater job satisfaction and retention by making work more rewarding. In addition to improving workplace conditions, I5.0 places a strong emphasis on environmental responsibility (Abuhasel 2023b). For example, Universal Robots and Continental have installed cobots on assembly lines in their manufacturing plants to perform repetitive tasks such as material handling, reducing human error, minimizing waste and reducing energy consumption by optimizing processes (Zaman et al. 2023).

The integration of advanced technologies such as AI and IoT optimizes resource use and energy consumption (Rejeb et al. 2020; Rejeb, Suhaiza, Rejeb et al. 2022a, b, c, d), which helps to reduce the carbon footprint of manufacturing activities. This approach is aligned with the principles of the circular economy, aiming to minimize waste through recycling and reuse, thus promoting sustainability (Agrawal et al. 2023; Atif 2023; Garrido et al. 2024). Philips Lighting transitioned to a "lighting as a service" model, where customers pay for the light they use rather than owning the equipment. This model allows Philips to retain ownership of the materials, ensuring that they are recycled or repurposed at the end of their lifecycle. IoT sensors track usage, optimizing energy consumption, and reducing waste (Uçar et al. 2020). Similarly, ZenRobotics, a pioneer company in waste management technology, is able to enhance the efficiency and effectiveness of sorting recyclables by leveraging AI and robotics. Their system, with cameras and sensors feeding data into ZenBrain for real-time analysis, enables their robots to make informed decisions about which materials to prioritize for recycling (Uçar et al. 2020). Decentralized renewable energy systems, supported by smart grid technology, allow factories and communities to generate, store, and distribute their own renewable energy. This reduces reliance on fossil fuels and improves energy resilience. As an example, Tesla's Gigafactory in Nevada is powered by a combination of solar panels and wind turbines, making it one of the largest net-zero energy manufacturing facilities in the world. The factory's energy needs are managed through a smart grid system that optimizes the use of renewable energy and battery storage (Maradin et al. 2022).

Economically, I5.0 is poised to enhance production efficiency without sacrificing the quality of outputs (Basulo-Ribeiro and Teixeira 2024). For example, with the support of AI and digital twin, predictive maintenance aids in reducing downtime, while real-time data analytics ensure optimal operational performance. Siemens employs digital twin technology to create virtual replicas of its gas turbines. By feeding real-time sensor data from actual turbines into their digital twins, Siemens enables predictive maintenance, which is a proactive approach to managing the health of these complex machines (Soori et al. 2024). AI can optimize supply chain logistics by predicting demand, reducing excess inventory, and optimizing transportation routes, which in turn reduces carbon emissions. AI can also identify inefficiencies in the supply chain and suggest improvements. Unilever and P&G use AI and blockchain to analyze data across its supply chain to improve sustainability. By predicting demand more accurately, they reduce waste in production and packaging. Additionally, AI optimizes transportation routes, significantly reducing carbon emissions and fuel costs, while blockchain enhances transparency and traceability within the supply chain, ensuring that all parties involved can access real-time data, fostering accountability, and enabling more informed decisions (Rejeb et al. 2021). This transparency helps in verifying sustainable practices, as companies can track the origins of materials and ensure that their suppliers adhere to environmental standards (Ajwani-Ramchandani et al. 2021). Moreover, additive manufacturing, or 3D printing, allows for the creation of complex parts with minimal material waste. It also enables localized production, reducing the carbon footprint associated with transportation and logistics (Mourtzis et al. 2022). Siemens has adopted 3D printing in its gas turbine manufacturing process. By printing parts on demand, Siemens reduces waste, shortens lead times, and eliminates the need for large inventories. Additionally, using 3D printing allows for the creation of lighter and more efficient parts, leading to reduced energy consumption during operation (Avdovic et al. 2021; Soori et al. 2024). The agility afforded by these technologies enables manufacturers to swiftly adapt to market changes or consumer preferences (Aldoseri et al. 2024; Bendavid et al. 2024), which is crucial for businesses aiming to offer mass customization. The potential economic benefits extend beyond mere cost savings because companies can deliver products tailored to individual preferences, thereby enhancing customer satisfaction and loyalty.

1.2 Main review studies on I5.0

The topic of I5.0 has garnered significant attention from academia, leading to a proliferation of review papers that explore various facets of this emerging paradigm. For instance, Ghobakhloo et al. (2023) explore the core definitions, technologies, and values of I5.0, revealing that while a unified definition is still forming, there is a clear trend toward addressing socio-economic and environmental challenges previously exacerbated by I4.0. However, the study could further elaborate on how these technologies integrate with human-centric practices to foster more resilient industrial systems. Zizic et al. (2022) highlight the paradigm shift toward prioritizing human roles in production processes, which signals a movement from technology-centric to human-centric approaches in industrial settings. This study identifies a critical gap in understanding how these human-centric practices can be operationalized alongside advanced technologies like AI and IoT. Moreover, Gladysz et al. (2023) examine the transition from Operator 4.0 to Operator 5.0 and point out the current inadequacies in integrating human factors within I4.0 technologies. The authors suggest that addressing these gaps is essential for a smooth transition to Operator 5.0, yet there is still a need for a comprehensive framework that seamlessly blends these human elements with the technological advancements of I5.0. Similarly, Mourtzis (2021) discusses the broader transition from I4.0 to Society 5.0 and emphasizes the need for a human-centered, resilient, and sustainable framework to support this evolution.

However, the study could benefit from a deeper exploration of how specific technologies like blockchain and IoT can be leveraged to achieve these goals. In terms of specific applications, Baig and Yadegaridehkordi (2024) examine the impact of I5.0 on sustainability and identify key technologies like IoT and AI that are pivotal in promoting sustainable practices. The authors also note a growing research trend in this area, which underlines I5.0's potential in fostering sustainable industrial processes. Despite this, the study does not fully address how these technologies can be integrated into existing industrial systems to maximize their impact on sustainability. Lastly, Madhavan et al. (2022) analyze the effects of the pandemic on I4.0 and I5.0 adoption among small and medium enterprises (SMEs) and propose a model for digital transformation that integrates SMEs into global value chains. The role of human-centric approaches and open innovation during the pandemic is highlighted. However, the study lacks a detailed discussion on how these approaches can be sustained post-pandemic.

Collectively these reviews contribute to a nuanced understanding of I5.0, focusing on its conceptual foundations, transition challenges, and specific applications, thereby enriching the academic and practical discourse surrounding this next phase of industrial evolution. Table 1 provides a clear overview of the main contributions and identified gaps in prior I5.0-related review studies.

1.3 Research gap identification and current study's novelty

Although earlier review and bibliometric studies on I5.0 have made substantial contributions to knowledge of the subject (Table 1), they do have certain shortcomings that this present study aims to address. For instance, the work by Madsen and Berg (2021) offers an exploratory bibliometric analysis but primarily focuses on the early emergence of I5.0, providing a preliminary mapping without delving into the intricate interconnections or the evolution of specific themes within the literature. Similarly, the study by Ben Youssef and Mejri (2023) performs a bibliometric review but is limited by its reliance solely on co-citation and co-occurrence analysis, which restricts the depth of thematic exploration and overlooks the potential for more nuanced topic modeling. In contrast, our work offers a more extensive and updated bibliometric analysis that not only charts the field but also meticulously examines the themes through a blend of co-word analysis and topic modeling. The use of this dual methodology enables us to discern and investigate both the overt and underlying themes in the literature on I5.0, therefore facilitating a more comprehensive and intricate comprehension of the structure of the field. Through the inclusion of recent papers and a more extensive dataset, this analysis provides a more precise representation of the present research landscape, addressing the deficiencies of previous reviews.

In contrast to previous studies that emphasize descriptive statistics and basic network analyses, our research utilizes sophisticated bibliometric methods to reveal a more profound understanding of the development of research topics, the relationships between important concepts, and the emerging trends that anticipated to influence the future of I5.0 research. This methodology not only elucidates the present condition of the field but also establishes a strong basis for subsequent investigations to expand upon. In brief, our work distinguishes itself by providing a more extensive,

Table 1 Main review studies on I5.0

Study	Main contributions	Identified gaps
Ghobakhloo et al. (2023)	Explores core definitions, technologies, and values of I5.0; addresses socio-economic and environmental challenges.	Needs deeper integration of human-centric practices with technological advancements.
Zizic et al. (2022)	Highlights the shift from technology-centric to human-centric approaches in industrial settings.	Lacks operationalization of human-centric practices alongside AI and IoT.
Gladysz et al. (2023)	Examines the transition from Operator 4.0 to Operator 5.0; focuses on integrating human factors.	Requires a comprehensive framework that blends human elements with I5.0 technologies.
Mourtzis (2021)	Discusses transition from I4.0 to Society 5.0; need for human-centered, resilient, and sustainable frameworks.	Needs a deeper exploration of leveraging technologies like blockchain and IoT to achieve these goals.
Baig and Yadegaridehkordi (2024)	Examines I5.0's impact on sustainability; identifies IoT and AI as key technologies.	Lacks integration strategies for maximizing the impact of these technologies on sustainability.
Madhavan et al. (2022)	Analyzes the effects of the pandemic on I4.0 and I5.0 adoption among SMEs; proposes a digital transformation model.	Lacks discussion on sustaining human-centric approaches and innovation post-pandemic.
Madsen and Berg (2021)	Provides a comprehensive mapping of the emerging literature on Industry 5.0, offering an exploratory overview using bibliometric analysis.	Early-stage research with preliminary analysis, lacks critical analysis, limited to Scopus data, and ends with speculative future insights.
Ben Youssef and Mejri (2023)	Provides a holistic overview of I5.0 research through a bibliometric analysis of 300 publications.	Limited to Scopus data, lacks longitudinal analysis, and needs more critical evaluation of theoretical foundations.
Espina-Romero et al. (2023)	Highlights exponential growth in I5.0 research; identifies key industries and emerging research topics.	Limited to a specific time frame and industries; lacks deep theoretical analysis and regional/global focus.
Akundi et al. (2022)	Identifies five key research themes in I5.0; uses text mining and topic modeling to analyze 196 abstracts.	Limited dataset; lacks critical analysis of varying definitions and interconnections between themes.
Alves et al. (2023)	Focuses on human-centricity in I5.0; provides a systematic review of key technologies and strategies.	Lacks empirical validation; limited industry-specific analysis; potential overemphasis on human-centricity challenges.

detailed, and methodologically advanced analysis of the I5.0 domain while recognizing the contributions of prior bibliometric studies. This analysis addresses the limitations of earlier efforts and facilitates a more comprehensive understanding of this developing field.

This study contributes significantly to the existing literature in several ways. Initially, it presents a detailed examination of the I5.0 literature from its inception, broadening the understanding of advanced manufacturing technologies and human-machine collaboration. As I5.0 increasingly permeates discussions in both industry circles and academia, the analysis of the academic landscape helps deepen our understanding of how these innovative practices could reshape manufacturing paradigms and their societal implications. Moreover, this study highlights the technical, organizational, and ethical challenges that emerge as industries transition toward more human-centric and sustainable practices. By performing a bibliometric analysis of scholarly articles related to I5.0, this research not only broadens the scope of bibliometric inquiries but also furnishes valuable insights into the evolution of this field, the main themes and knowledge structures present in the literature, and the connections between different research areas. It identifies key authors, pivotal studies, and the primary institutions driving collaboration in the I5.0 realm.

This paper is structured as follows: Sect. 2 outlines the four-step methodology used for the bibliometric analysis. Section 3 discusses the results of the research, while Sect. 4 suggests potential directions for future research based on the findings. Finally, Sect. 5 presents the conclusions drawn from the study, discussing both the implications and limitations of the research findings.

2 Methodology

To carry out this bibliometric analysis, we adopted a structured four-step methodology (Fosso Wamba and Mishra 2017). Initially, we determined the appropriate databases and keywords to frame our search criteria effectively. Following this initial step, a preliminary analysis of the data was carried out to establish a baseline understanding of the dataset. Subsequent steps involved a detailed examination of bibliometric networks, where we mapped the relationships and interconnections among various scholarly works within the field of I5.0. The final step encompassed a thematic and conceptual structure analysis to uncover prevailing themes and the underlying conceptual frameworks in the literature.

The choice of bibliometric and topic modeling approaches was motivated by their capacity to offer a thorough understanding of the current state of I5.0 research (Rejeb, Rejeb, Appolloni, Kayikci, et al., 2023). Bibliometric analysis is highly efficient in managing extensive datasets, allowing scholars to map the structure and evolution of research fields throughout time, pinpoint key studies, and identify main publication outlets (Abedin et al. 2021; Alnajem et al. 2021; Donthu et al. 2021). In the context of I5.0, which is experiencing fast growth and includes a wide range of interdisciplinary contributions (Ben Youssef and Mejri 2023; Ghobakhloo et al. 2023; Ghobakhloo, Iranmanesh, Foroughi, Ghobakhloo et al. 2024a, b, c, d), this approach is well-suited for capturing the expansive and intricate nature of the literature (Rejeb et al. 2020). Topic modeling, however, provides a potent method for revealing concealed patterns throughout extensive text collections (Chen et al. 2022; Egger and Yu 2022; Williamson et al. 2021). The application of this approach enabled us to discern and examine the fundamental themes present in the literature on I5.0, which may not be readily evident only using conventional bibliometric methods (Rejeb et al. 2023). Through this combination, we are able to surpass superficial examination and gain a profound understanding of the interconnections and historical development of various themes and concepts.

To support and enhance the robustness of our analyses, we utilized a suite of analytical tools. The R software, along with specific packages like bibliometrix for bibliometric analysis, ggplot2 for data visualization, rentrez for accessing biometric data, and wordcloud for visual representation of text data, were integral to our methodology (Rejeb et al. 2023). Additionally, we employed VOSviewer (Eck and

Waltman 2009), which is a specialized software renowned for its capability to integrate text mining with visualization techniques. This tool was particularly valuable in effectively managing and depicting network visualizations, allowing scholars to present a coherent and insightful exploration of the academic landscape surrounding I5.0. These tools were specifically chosen for their proven effectiveness in previous studies related to emerging technologies and their ability to handle the complexity and scale of I5.0 research. By combining these methodologies and tools, we ensured a comprehensive analysis that not only maps the existing literature but also reveals deeper insights into the thematic structure and conceptual evolution within I5.0 research. This approach provides a more nuanced understanding of the I5.0 field, setting the stage for future research directions.

2.1 Database and search keywords selection

We selected Scopus as our primary database due to its extensive coverage of peer-reviewed publications, including journal articles and conference proceedings (Singh and Rejeb 2024). Scopus, owned by Elsevier, is favored for its user-friendly features that facilitate bibliometric analyses and is often considered more comprehensive and reliable than other databases like PubMed and Web of Science (WoS) (Rejeb et al. 2022a, b, c, d). Notably, Scopus includes 84% of the titles indexed by WoS and provides a more curated and reliable indexing system than Google Scholar (Fahimnia et al. 2015; Gorraiz and Schloegl 2008). The search terms included "Industry 5.0" OR "Fifth Industrial Revolution" OR "5th Industrial Revolution" OR "Society 5.0" OR "Society Five," applied within the title, abstract, and keywords fields in Scopus (Ghobakhloo et al. 2023; Madsen et al. 2023). The selection of these keywords was meticulously based on the methodologies described in two notable reviews by Ghobakhloo et al. (2023) and Madsen et al. (2023), which offered comprehensive overviews of I5.0 and its emerging trends. Furthermore, in order to enhance the pertinence and precision of the keyword selection, we sought advice from two experts in the domain of I5.0. Their contributions enhanced the validation of the selected keywords, thereby verifying their efficacy in capturing the core themes and topics relevant to I5.0 research. The search was conducted on 6 May 2024, and initially, we retrieved 1159 documents. We then meticulously reviewed titles and abstracts, discarding 217 articles that did not directly relate to our study focus, leaving us with a robust sample of 942 articles. These were transferred to a CSV file for further detailed analysis.

To ensure the comprehensiveness of our dataset, we cross-verified our findings by conducting a parallel search using the WoS database. The search conducted on WoS resulted in a moderate number of publications, namely 1032 documents. Out of these, around 84% were already included in the Scopus dataset. The presence of this overlap between WoS and Scopus suggests that Scopus offers a more comprehensive range of the pertinent literature covering I5.0. The decision to rely primarily on Scopus is reinforced by the fact that the majority of WoS publications were already included in Scopus, which provides a more comprehensive and representative sample of I5.0 research. Although this method may appear to be somewhat limited, it is specifically intended to guarantee a high level of academic rigor and relevance. It involves concentrating on English-language journal articles and reviews to preserve uniformity and comparability in our dataset (Ramos-Rodríguez and Ruíz-Navarro 2004). Incorporating this cross-verification process ensures that our analysis accurately includes the most important and pertinent publications, reducing the possibility of omitting crucial studies and establishing a strong foundation for our bibliometric and topic modeling analyses.

2.2 Preliminary analysis of the selected sample

To carry out an initial analysis of the selected I5.0 publications, we downloaded a BibTeX version of all relevant articles' metadata. This included the author names, titles, abstracts, and keywords of the articles identified in our search. The information was summarized in Table 2 to provide an overview of the key data from the publications. The collaboration index for these publications, calculated based on a methodology introduced by Ajiferuke et al. (2005) following the ideas of Price (2019), was found to be 3.7385. This index measures the average number of authors per article and offers insights into the collaborative nature of the research field. A higher index value often indicates significant collaborative efforts, which is important in fields that are inherently multidisciplinary. In the context of I5.0, this high collaboration index suggests that research typically involves multiple scholars, possibly from diverse

Table 2 Main information about the selected publications

Description	Results
Main information about data	
Timespan	2016:2024
Sources (Journals)	411
Documents	942
Average years from publication	1.39
Average citations per documents	15.76
Average citations per year per doc	5.087
References	59,769
Document types	
Article	802
Review	140
Document contents	
Keywords Plus (ID)	4020
Author's Keywords (DE)	3012
Authors	3253
Author Appearances	3804
Authors of single-authored documents	78
Authors of multi-authored documents	3189
Authors collaboration	
Single-authored documents	89
Documents per Author	0.2895
Authors per Document	3.4532
Co-Authors per Documents	4.0382
Collaboration Index	3.7385

fields such as engineering, computer science, organizational studies, and sustainability. This multidisciplinary approach is crucial for exploring the complex and varied aspects of I5.0, which integrates advanced technological systems with human-centric and sustainable manufacturing processes (Ghobakhloo et al. 2024). The relatively high collaboration index signifies that I5.0 research is likely a collective effort among scholars, leading to more integrated and holistic research outcomes. Such collaboration could be essential for addressing the nuanced challenges of implementing and optimizing I5.0 strategies across different sectors and regions.

2.3 Analysis of social networks

Social network analysis (SNA) is a robust approach that integrates methodologies from diverse disciplines like statistics, mathematics, and computer science, and it has become increasingly popular for analyzing complex networks within academic research. This analytical technique is especially valuable for uncovering hidden patterns, aiding theory development, and steering future research directions (Rejeb et al. 2022a, b, c, d). Collaborative networks are instrumental in visualizing co-authorship relationships among researchers, academic institutions, or countries, revealing patterns of international collaboration (Rejeb, Rejeb, Abdollahi, et al., 2022). As Zou et al. (2018) indicate, such collaborative efforts often foster research innovation, enhance the quality of research, and facilitate the diffusion of knowledge, providing various mutual benefits. To deepen our understanding of collaboration within the I5.0 field, we conducted both an institutional collaboration network and a national collaboration network analysis. These analyses are essential for identifying the key players and the dynamics of collaboration that drive research in the I5.0 domain. Ding (2011) underscores that collaborations between academic institutions can significantly enhance research partnerships, thereby supporting policymaking efforts and accelerating the global diffusion of I5.0 technologies. Moreover, we conducted a keyword co-occurrence analysis to delve into the structure of I5.0 research (Mostafa 2021). Keyword co-occurrence networks offer a valuable tool for identifying the core research themes or thematic areas within a specific knowledge domain (Soriano-Pinar et al. 2023). This data mining technique, which has proven effective in understanding the evolution of several academic fields, uses a visual representation where each keyword is depicted as a node. The color of a node indicates the cluster it belongs to, suggesting thematic grouping, while the size of the node reflects the frequency of the keyword's occurrence. The thickness of the edges between nodes represents the strength and significance of the relationships between different keywords. This provides insights into how concepts are interconnected and which themes are most prevalent within the field. Such visualizations not only help in mapping the intellectual structure of a field but also in spotting emerging trends and potential areas for future research.

2.4 Knowledge visualization maps

Strategic and thematic maps, utilizing centrality and density metrics (Callon et al. 1991), provide researchers with advanced tools for analyzing key themes in a field. Introduced by Law et al. (2005), these maps draw from methodologies similar to those used in keyword co-occurrence networks and financial portfolio analyses (Zong et al. 2013). These maps are particularly adept at differentiating between the centrality and density of research topics across multiple categories. Here, density relates to the internal development of a subject, while centrality indicates how interconnected a subject is within the wider research landscape (Singh and Rejeb 2024). By clustering frequently used keywords, thematic maps enable researchers to gain objective insights that surpass those offered by mere conceptual structure maps (Bajaj et al. 2022). This approach identifies the core themes and facilitates a deeper exploration of them across various categories, setting a foundation for further academic inquiry. Thematic maps have become a staple in academic research, widely recognized for their effectiveness in providing clear visual representations of the knowledge structure and dynamics within a field (Hanaa and Abdul 2023).

Conceptual structure maps provide a unique visual approach to dissecting knowledge within a scientific field. These maps function by categorizing the field into distinct research clusters, which illustrate keywords as points on the map. The spatial arrangement of these points—how close or far apart they are—reflects the frequency with which related concepts are discussed in the literature. Points that are grouped closely suggest a high volume of published literature on those topics, whereas points that are more dispersed indicate areas with less scholarly focus. Conceptual structure maps are particularly useful for detecting citation bursts associated with specific keywords, which can help identify emerging research trends (Cobo et al. 2011). By employing these maps, researchers can gain a clearer understanding of the dominant topics within a field such as I5.0, allowing for a more strategic exploration of where the field is most active and where potential gaps in knowledge may exist. Therefore, this method aids in mapping the current landscape of research and guides future studies by highlighting areas ripe for further investigation.

3 Findings

3.1 Descriptive statistics

Upon examining the dataset detailing the annual number of publications that address I5.0, a distinct pattern of exponential growth emerges (see Fig. 1). This trend is particularly pronounced from 2020 onward, culminating in the most recent figures from 2024. Initially, the data reveals a relatively modest increase in I5.0-related publications between 2016 and 2019, averaging approximately 6 articles per year. This period was characterized by the nascent stages of I5.0 research, with scholars and technologists beginning to explore the integration of advanced technological systems with human-centric and sustainable manufacturing processes (Mihardjo et al. 2019; Nahavandi 2019).

The subsequent years, 2020-2021, exhibited a modest but noticeable uptick in I5.0-related publications, averaging 56.5 publications per year. This acceleration is likely attributable to the increasing recognition of I5.0 as a critical area of research and development, which is driven by advancements in AI, robotics, and IoT (Agrawal et al. 2023). In 2021, the number of publications surged to 78, marking a substantial

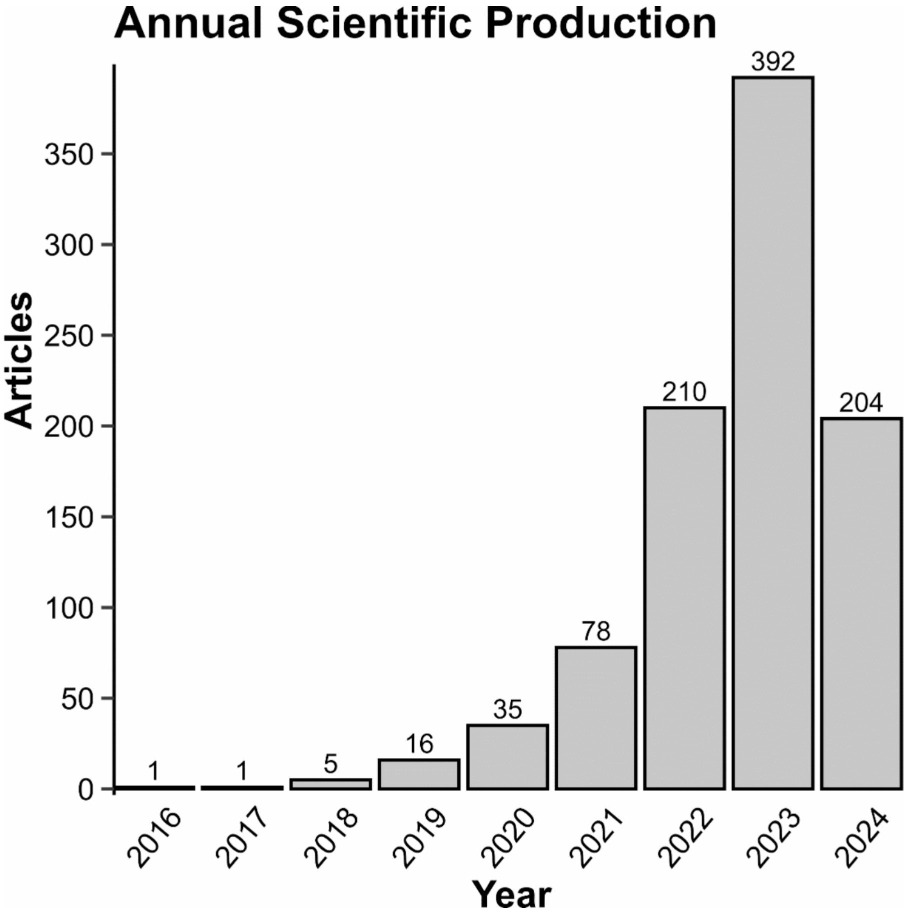

Fig. 1 Annual number of articles dealing with I5.0 (until May 2024)

increase in scholarly interest. This spike may be ascribed to the growing adoption of I5.0 principles in various sectors due to the need for more resilient and adaptive manufacturing systems. However, it is the period from 2021 to 2024 that truly exemplifies a burgeoning fascination with I5.0. In 2023, the number of publications skyrocketed to 362, representing a significant 365% increase from the previous year. By 2024, this upward trajectory continued with 234 publications. This unprecedented growth in I5.0-related research highlights the increasing prominence of the concept in both academia and industry. This significant interest can be attributed to several factors, including technological advancements, the need for sustainable and human-centric manufacturing processes, and the impact of global events such as the COVID-19 pandemic (Chatterjee and Chaudhuri 2024; Javaid et al. 2020), which accelerated the adoption of innovative manufacturing technologies. Overall, the data reflects a rapidly evolving academic landscape characterized by an exponential surge in I5.0-related publications.

Fig. 2 Word cloud of the most influential journals in the I5.0 field

The analysis of the dataset on I5.0 publications reveals preferred journals based on citation counts (Fig. 2). The Journal of Manufacturing Systems, with 1,679 citations, leads the field, reflecting its pivotal role in disseminating I5.0 research. Following are Sustainability and the Journal of Industrial Information Integration, with 1,639 and 860 citations, respectively, highlighting their focus on sustainable practices and industrial information systems. Other significant journals include Applied Sciences (540 citations) and IEEE Transactions on Industrial Informatics (452 citations), which contribute substantially to applied sciences and industrial informatics. The Journal of the Knowledge Economy and Sensors feature prominently with 430 and 397 citations, respectively. The International Journal of Production Research and International Journal of Production Economics, with 362 and 358 citations, underscore the importance of production research and economics in I5.0.

Bradford's law is a useful tool for evaluating scholarly output (Kumar and Dora 2011). Burrell (1989) states that this law helps identify key journals that publish relevant articles on a specific subject over a given time frame. According to the law, if journals are ordered by decreasing productivity on a subject, they can be divided into a core group of periodicals highly focused on the subject and several groups with the same total number of articles as the core group.

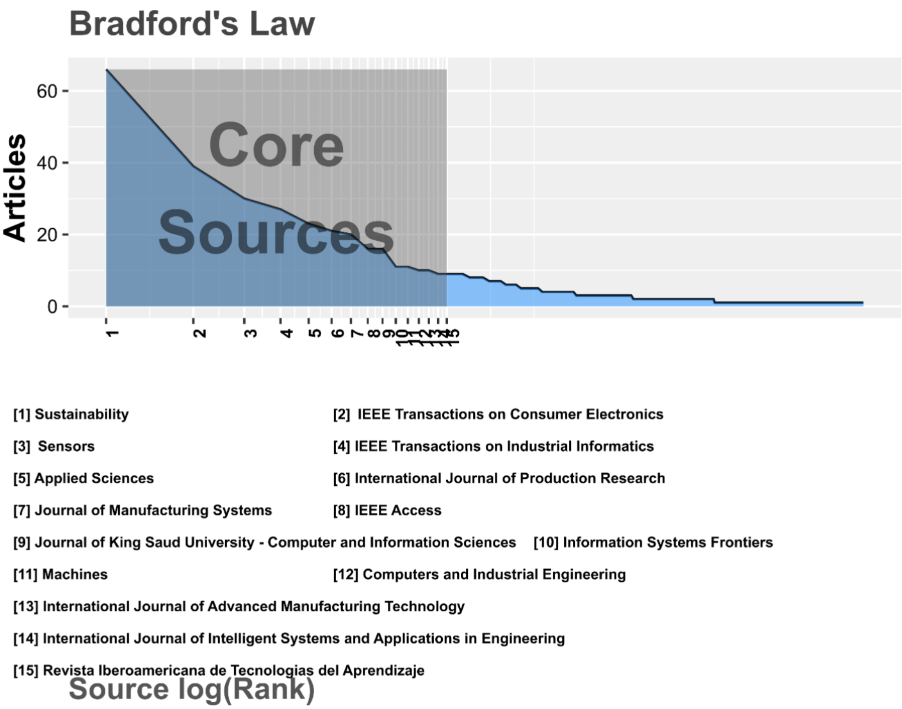

Fig. 3 Distribution of I5.0-related publications across the core Bradford zone

Figure 3 shows the distribution of academic articles on I5.0 within the primary Bradford zone. This central zone, comprising the most prolific journals, includes 17 key journals that publish the majority of I5.0 articles. The figure demonstrates an inverse relationship between the number of journals and citation frequency. It also indicates that a small number of top-tier journals publish most of the research in the I5.0 field. This information aids researchers in pinpointing the most productive journals for their studies.

3.2 Analysis of collaboration networks

Figure 4 illustrates the collaborative network among institutions in the I5.0 field, featuring 30 nodes, a density of 0.207, and a diameter of 7. This network provides a detailed view of the inter-institutional collaboration dynamics. The network density of 0.207 indicates a relatively low level of collaboration among institutions, with only about 20.7% of potential connections being realized. Despite this low density, the transitivity rate of 0.768 suggests that when institutions are connected, they tend to form tightly knit groups. The network diameter of 7 reveals that the longest path between any two institutions in the network is relatively long, implying some degree of separation between distant nodes. Notable institutions, such as the Hong Kong Polytechnic University, Zhejiang University, and the Chinese Academy of Sciences, emerge as central hubs within the network, connecting with multiple other institu-

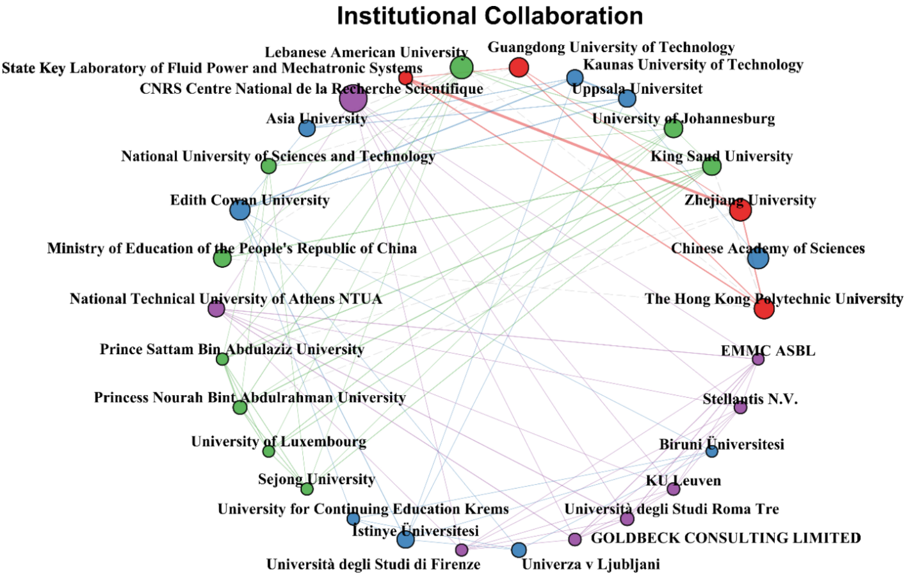

Fig. 4 Institutional collaboration network in the I5.0 field

tions. These key players facilitate collaboration and resource sharing, thereby driving forward I5.0 research. The network does not show isolated clusters, indicating that all institutions are part of a connected whole, albeit with varying degrees of connectivity. This structure highlights the need for increased inter-institutional partnerships to enhance the integration and dissemination of knowledge. Promoting collaborations between more institutions can bridge existing gaps, foster innovation, and accelerate advancements in I5.0 research.

The map of the national collaboration network in the I5.0 research field effectively illustrates a significant digital divide between the Global North and Global South (Fig. 5). Most collaborations occur between countries in North America, Europe, and Asia, with a special emphasis on China, demonstrating a strong mutual sharing of expertise and resources in these regions. In contrast, the Global South, which incorporates regions of Africa and South America, exhibits far less cooperation, suggesting an inequality in the availability and involvement in the cutting-edge research and technological advancements linked to I5.0. The existence of the divide highlights the necessity for more comprehensive and fair international research collaborations to guarantee that the advantages of I5.0 are accessible to all countries worldwide.

3.3 Analysis of keywords frequency and keyword co-occurrence

Keywords are crucial for understanding the core themes and trends in a research field (Soriano-Pinar et al. 2023). By examining the frequency of terms in abstracts, we gain insights into the current state and future directions of I5.0 research. Figure 6 presents a word cloud generated from I5.0 abstracts, highlighting dominant terms such as “AI,” “IoT,” and “Digital Twin,” which emphasizes the importance of advanced technologies (Aldoseri et al. 2024; Alimam et al. 2023b; Cummins et

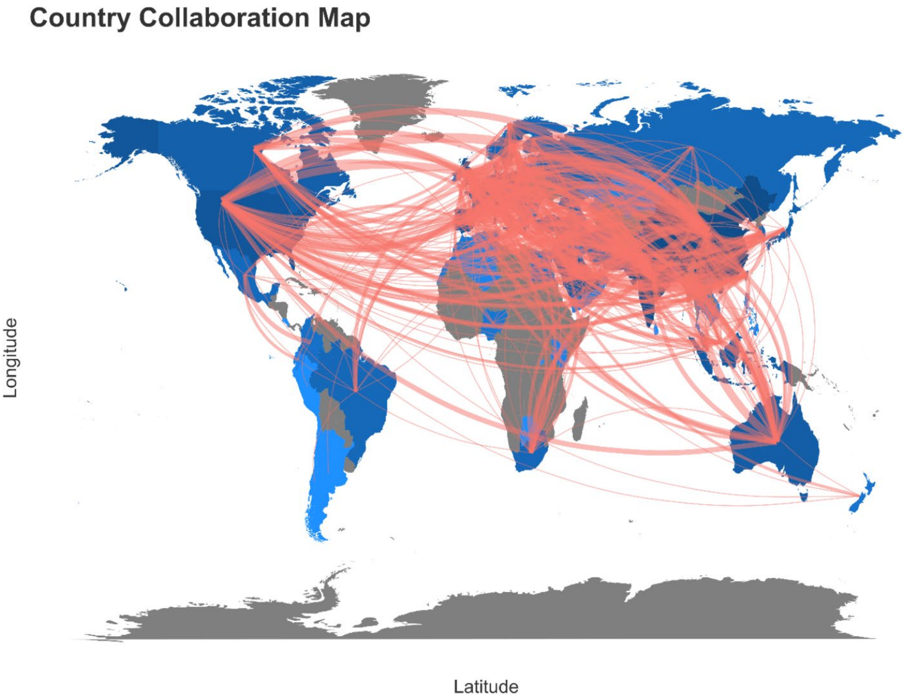

Fig. 5 National collaboration network in the I5.0 field

Fig. 6 A word cloud of the most common terms in the abstracts of selected publications

al. 2024). Keywords like “Sustainability,” “Human-Centric,” and “Resiliency” show a significant focus on sustainable, resilient, and human-centered processes. Other frequently appearing terms include “Machine Learning,” “CPS” (Cyber-Physical Systems), and “Blockchain,” underscoring the technological innovations driving this field (Alimam et al. 2023b; Asad et al. 2023; Fraga-Lamas et al. 2022). The presence of “Digitalization,” “Cobots” (Collaborative Robots), and “HRC” (Human-Robot Collaboration) suggests a trend toward greater digital integration and human-machine collaboration (Ciccarelli et al. 2024; Dornelles et al. 2023; Duarte et al. 2022). Additionally, terms like “SDGs” (Sustainable Development Goals) and “S5.0” (Society 5.0) reflect the alignment of I5.0 initiatives with global sustainability goals (Basulo-Ribeiro and Teixeira 2024; Bonello et al. 2024; Dovleac et al. 2023). These keywords illustrate the interdisciplinary and innovative nature of I5.0 and highlight its potential to transform traditional manufacturing through advanced technologies and human-centric approaches.

Using Keyword Plus, Fig. 7 displays the dynamics of keyword growth. Sharp increases in keywords’ popularity reveal priorities and trends in I5.0 research. In 2024, the most frequent terms are 4IR, AI, Digital Twin, SDGs, Sustainability, Blockchain, and Machine Learning. These keywords highlight emerging priorities and trends, representing potential new directions or hotspots in I5.0 research (Ghobakhloo et al. 2022).

Using Bibliometrix software, we constructed a keyword co-occurrence network through six key steps: (1) Data collection: We compiled all keywords from the

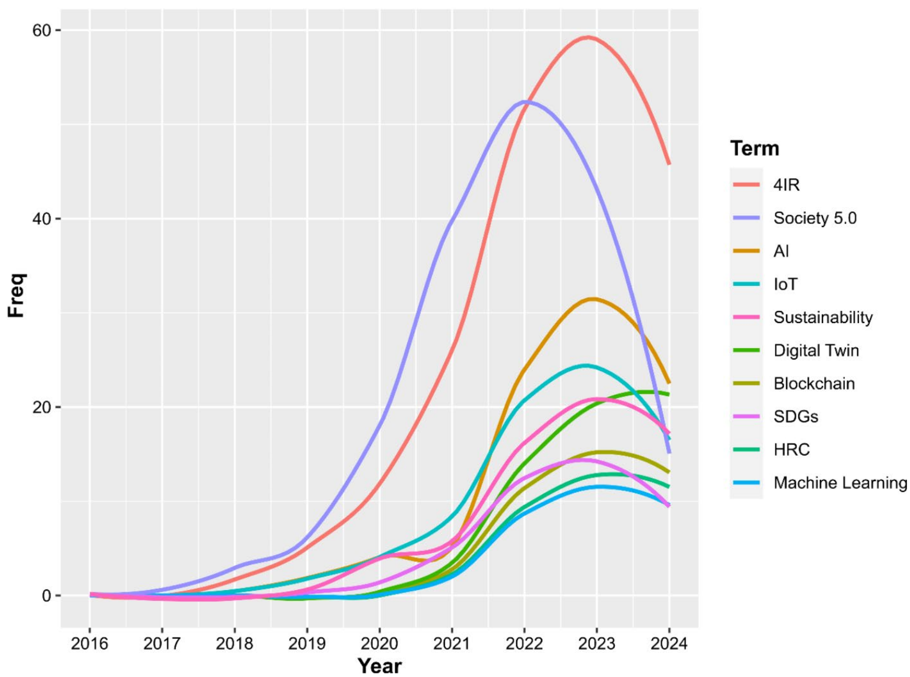

Fig. 7 Growth dynamics of the main keywords in I5.0 research

selected studies; (2) Keyword frequency analysis: We identified and selected the top 56 most frequently occurring keywords; (3) Network construction: These selected keywords were used to create a network, mapping their co-occurrences; (4) Network analysis: We assessed the network to identify critical parameters such as its size, density, and diameter; (5) Cluster identification: By applying advanced algorithms, we discovered three distinct clusters within the network, each representing different thematic areas; (6) Visualization: We used Bibliometrix's tools to visualize the network, which resulted in a figure showing the network with a size of 56 nodes, a density of 0.3935, and a diameter of 2 (Fig. 8). This visualization clearly depicts the three distinct clusters and highlights major thematic areas in the I5.0 research domain.

As seen in the network, the red cluster positioned near the center exhibits the most influence. This cluster focuses on various aspects of I5.0 and its integration with advanced technologies. The primary keywords in this cluster include 5IR, 4IR, AI, IoT, digital twin, blockchain, machine learning, IIoT, CPS, industry, manufacturing, edge computing, security, deep learning, decision making, federated learning, 6G, etc., all of which are semantically interconnected. The red cluster underscores the interplay between these emerging technologies and their applications in modern industry settings. For instance, 5IR and 4IR (Fifth and Fourth Industrial Revolutions) are closely tied to advancements in AI, IoT, and Blockchain (Agostinho et al. 2023; Alberti et al. 2024; Bassir et al. 2023; Drissi Elbouzidi et al. 2023). According to Fanoro et al. (2021), these technologies are crucial for the development of smart factories where IoT and AI facilitate real-time data processing and decision-making, thereby enhancing efficiency and productivity.

The inclusion of digital twin and IIoT (Industrial Internet of Things) emphasizes their roles in creating virtual replicas of physical systems, allowing for predictive maintenance and optimization of manufacturing processes (Alimam et al. 2023a; Awouda et al. 2024; Coito et al. 2022; Dobaj et al. 2023). Dobaj et al. (2023) argue that digital twin technology significantly reduces downtime and operational costs

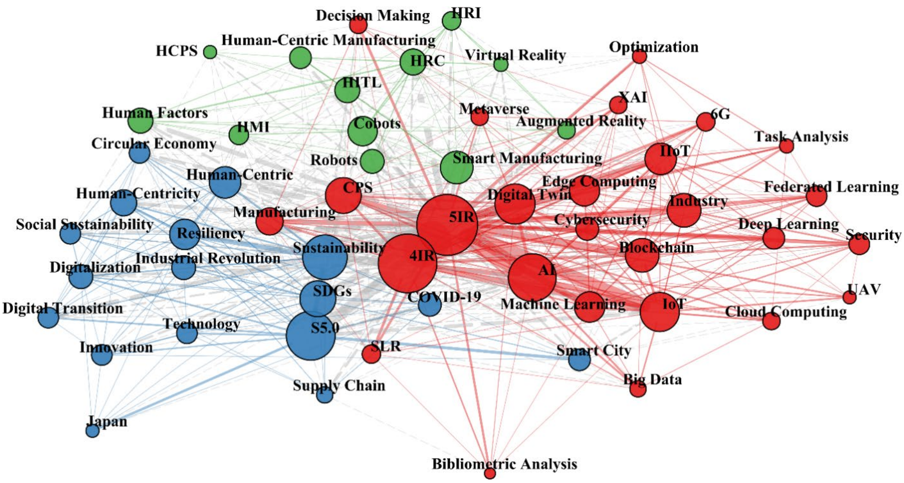

Fig. 8 Keyword co-occurrence network of I5.0 research

by enabling continuous monitoring and simulation of industrial equipment. Moreover, machine learning and deep learning are pivotal for analyzing large datasets generated within these smart environments (Abuhasel 2023b; Alimam et al. 2023b; Chourasia et al. 2023). Federated learning and XAI (Explainable AI) are emerging fields that ensure data privacy and transparency in AI-driven decision-making processes (Agostinho et al. 2023; Alsamhi et al. 2024; Cummins et al. 2024; Habbal et al. 2024). According to several recent studies (e.g., Alsamhi et al. 2024; Berguiga et al. 2023; Habbal et al. 2024), federated learning facilitates collaborative training of machine learning models without compromising data security, which is vital in highly regulated industries like manufacturing and healthcare. Edge computing and cloud computing are also key components of I5.0 due to their ability to provide the necessary infrastructure for processing and storing vast amounts of data (Bajic et al. 2023; Fraga-Lamas et al. 2022). In particular, edge computing reduces latency by processing data closer to the source (Rejeb et al. 2022), which is essential for real-time applications in manufacturing and autonomous systems (Domenteanu et al. 2024). The work of McEnroe et al. (2022) highlights how edge computing can enhance the performance of UAVs (Unmanned Aerial Vehicles) used for inspection and maintenance tasks in industrial settings.

Cloud manufacturing is a concept that is both emerging and becoming increasingly important in I5.0 (Maddikunta et al. 2022; Zhang et al. 2023). It represents a paradigm transition in the design, management, and execution of manufacturing processes (Bhat and Parvez 2024). Through the incorporation of cloud computing technologies into the manufacturing ecosystem, cloud manufacturing facilitates the development of production environments that are more robust, scalable, and adaptable (Liu et al. 2024; Ren et al. 2017). This approach leverages the extensive computing capabilities, storage capacity, and interconnectedness of cloud systems to facilitate various industrial operations, including design, simulation, production, and supply chain management. Within the context of I5.0, cloud manufacturing serves a crucial function in promoting cooperation among disparate networks of manufacturers, suppliers, and customers, going beyond mere process optimization (Hu et al. 2024; Yin et al. 2024). This is accomplished by facilitating the smooth exchange of resources, data, and services via cloud technology, thereby enabling enhanced adaptability and timely reaction in production. For instance, manufacturers have the ability to deploy resources in real-time according to the current demand, adjust production levels as necessary, and quickly adapt to market fluctuations or disruptions in the supply chain (Chiappa et al. 2023; Gharibvand et al. 2024).

Recent literature, including the study of Shahab et al. (2024), emphasizes the significance of cloud manufacturing in the realization of the interconnected, resilient, and flexible systems that are envisioned in I5.0. This work, along with others (e.g., Dong et al. 2020; Liu et al. 2023; Zhang et al. 2022), emphasizes the potential of cloud-based platforms to improve system resilience by utilizing sophisticated algorithms such as reinforcement learning to optimize network configurations, efficiently manage resources, and guarantee uninterrupted operations even in the presence of obstacles like network failures or unforeseen peaks in demand. Moreover, cloud manufacturing facilitates the incorporation of other cutting-edge technologies, including AI, big data analytics, and IoT, into manufacturing operations. When integrated with cloud computing, these technologies facilitate the development of intelligent factories in which machines, sensors, and systems are linked and have the ability to make decisions independently. Not only does this increase efficiency, but it also significantly strengthens the capacity to tailor products, minimize waste, and attain sustainability objectives (Bhat and Parvez 2024). Given the ongoing adoption of I5.0 concepts, cloud manufacturing is expected to emerge as a fundamental component that stimulates innovation and empowers businesses to effectively address the needs of a swiftly evolving global market (Gharibvand et al. 2024).

Furthermore, cybersecurity and optimization are critical to protect and enhance these complex systems (Adel 2023; Chakir et al. 2023; Clim et al. 2023). Ensuring robust cybersecurity measures is paramount to safeguarding sensitive industrial data and maintaining operational integrity (Introna et al. 2024). In this regard, Adel (2023) emphasizes the importance of integrating advanced cybersecurity protocols to mitigate the risks associated with cyber threats. Additionally, the cluster's focus on big data and metaverse suggests a broader scope of I5.0, where data analytics and virtual environments play significant roles (Bai et al. 2024). The concept of the metaverse is increasingly being explored for virtual collaboration and training in industrial contexts (Alimam et al. 2023). Zhou et al. (2024) discuss how immersive metaverse environments can facilitate remote training and prototyping, leading to improved innovation and workforce development. In conclusion, this cluster encapsulates the diverse and interconnected nature of I5.0 research and highlights how advanced technologies and innovative methodologies are driving the transformation of modern industries. The integration of AI, IoT, blockchain, and other cutting-edge technologies has the potential to enhance operational efficiency and pave the way for a more resilient and adaptive industrial ecosystem.

The second cluster is centered around sustainability and human-centric approaches within the I5.0 landscape. The cluster focuses on how these themes intertwine with digital transformation and resilience (Abuhasel 2023a; Chabane et al. 2023; Ismail et al. 2024). Key terms in this cluster include S5.0 (Society 5.0), sustainability, SDGs, resiliency, digital transition, human-centric, digitalization, COVID-19, human-centricity, smart city, innovation, circular economy, etc. These keywords reflect the increasing emphasis on integrating sustainable practices and human-centered design in industrial innovations (Bonello et al. 2024; Chabane et al. 2023; Gualtieri et al. 2024). This cluster highlights the synergy between sustainability and digital advancements in I5.0 (Ghobakhloo et al. 2024). For example, the keyword "sustainability" is closely linked with "SDGs" (Sustainable Development Goals), underscoring the commitment to aligning industrial practices with global sustainability targets (Ghobakhloo, Iranmanesh, Foroughi, Ghobakhloo et al. 2024a, b, c, d). According to Ghobakhloo et al. (2022), I5.0 aims to achieve these goals by leveraging technologies that promote resource efficiency and reduce environmental impact, such as through the adoption of circular economy principles and innovations in supply chain management. The inclusion of "resiliency" and "digital transition" suggests a focus on building robust and adaptable industrial systems. Studies like those by Agrawal et al. (2023), Jankowska et al. (2023), and Frutos-Bencze et al. (2022) discuss how the COVID-19 pandemic accelerated the need for resilient supply chains and digitalization, driving industries to adopt more flexible and responsive approaches. This transition involves technological upgrades and a shift toward more human-centric and sustainable practices.

Human-centric approaches are emphasized through keywords like "human-centric," "human-centricity," and smart city." These terms indicate a move toward designing technologies and systems that prioritize human well-being and societal benefits. Adel (2023) highlight that smart city initiatives driven by human-centric design aim to improve urban living conditions through innovative solutions in transportation, energy management, and public services, contributing to overall social sustainability. The cluster also reflects on the importance of innovation and digitalization in achieving these goals. "Innovation" and "digitalization" are crucial for advancing technologies that support sustainable and resilient industrial practices. Drissi Elbouzidi et al. (2023) argue that digital tools and platforms are vital for monitoring and optimizing industrial processes, thereby enhancing efficiency and reducing waste. Furthermore, the term "circular economy" indicates a shift toward systems that reuse, recycle, and regenerate materials, minimizing the environmental footprint of industrial activities (Atif 2023; Camarinha-Matos et al. 2024; Garrido et al. 2024). Research by Rejeb et al. (2022a, b, c, d) suggests that integrating circular economy principles with advanced digital technologies can lead to significant reductions in resource consumption and waste generation. The keyword "social sustainability" highlights the need to consider social impacts alongside environmental and economic factors (Bonello et al. 2024; Ciccarelli et al. 2023). This encompasses fair labor practices, community engagement, and equitable access to technological benefits (Foltynowicz et al. 2024). According to Izui and Koyama (2017), industries in Japan are pioneering efforts in social sustainability, balancing technological advancement with societal well-being. Overall, the second cluster illustrates the interconnectedness of sustainability, human-centric design, and digital transformation within I5.0. The integration of these elements is crucial for developing resilient, efficient, and socially responsible industrial systems. The ongoing research and innovations in this area are paving the way for a more sustainable and human-centric industrial future.

Finally, the third green cluster centers on the integration of human-robot collaboration (HRC) and advanced manufacturing technologies within the I5.0 framework. The key terms in the cluster include HRC, human factors, cobots, smart manufacturing, HRI, human-centric manufacturing, augmented reality, etc. These keywords illustrate the focus on enhancing manufacturing processes through the collaboration between humans and robots, emphasizing the importance of human-centric design and advanced interaction technologies (Apraiz et al. 2023; Duarte et al. 2022; Gervasi et al. 2023). The term "HRC" is pivotal in this cluster, and it highlights the cooperative interaction between humans and robots in industrial settings. In this context, Borchardt et al. (2022) argue that integrating HRC into manufacturing can significantly improve productivity and safety by leveraging the strengths of both human workers and robotic systems. Cobots, or collaborative robots, are designed to work alongside humans, ensuring safety and efficiency in tasks that require both precision and adaptability (Adriaensen et al. 2023). "Human factors" and "HRI" (Human-Robot Interaction) stress the importance of considering ergonomic and psychological aspects when designing collaborative systems (Abdous et al. 2023). Apraiz et al. (2023) found that addressing human factors in HRI can enhance user acceptance and performance, leading to more effective implementation of robotic systems in manufacturing environments.

The high frequency of the keywords "smart manufacturing" and "human-centric manufacturing" emphasizes the transition towards more intelligent and adaptive production systems that prioritize human involvement. Smart manufacturing leverages advanced technologies like IoT, AI, and robotics to create more flexible and responsive production processes (Bhattacharya et al. 2023). Garrido et al. (2024) discuss how human-centric manufacturing focuses on designing systems that improve worker satisfaction and well-being, thereby enhancing overall productivity. The inclusion of "augmented reality" (AR) and "virtual reality" (VR) indicates the role of immersive technologies in training, maintenance, and operational support (Ariansyah et al. 2024; Ciccarelli et al. 2023). AR and VR provide interactive and intuitive interfaces for workers, facilitating better understanding and execution of complex tasks. For example, Rejeb et al. (2021a, b) demonstrate that AR can be used to overlay digital information onto physical equipment, aiding in maintenance procedures and reducing downtime. "HMI" (human-machine interface) and "HCPS" (human-cyber-physical systems) point to the integration of user-friendly interfaces and cyber-physical systems in manufacturing. Effective HMIs are crucial for seamless interaction between human operators and automated systems (Caiazzo et al. 2023; Gualtieri et al. 2024). Bajic et al. (2023) argue that HCPS frameworks enhance the synergy between humans and machines, leading to more resilient and adaptable manufacturing processes. "Robots" and "HITL" (human-in-the-loop) further emphasize the collaborative nature of modern manufacturing systems (Cortés-Leal et al. 2022). Robots perform repetitive and precise tasks, while human workers provide oversight, decision-making, and adaptability. Coronado et al. (2024) highlight the HITL approach, where humans are integral to the control and monitoring of robotic systems, ensuring flexibility and robustness. In summary, the third cluster illustrates the convergence of human-centric design, advanced robotics, and immersive technologies within I5.0. The integration of these elements aims to create more efficient, flexible, and user-friendly manufacturing environments.

Overall, the keyword co-occurrence analysis of I5.0 research reveals three distinct clusters, each focusing on critical aspects of the field: the integration of advanced technologies, the emphasis on sustainability and human-centric approaches, and the collaboration between humans and robots in manufacturing environments. Table 3 summarizes these clusters, highlighting their main contributions to the literature and providing illustrative studies that exemplify the key themes within each cluster.

3.4 Topic modeling using latent Dirichlet allocation

3.4.1 Identification of topics in industry 5.0 research

Given that abstracts typically encapsulate the key content of publications, topic modeling was employed on the abstracts of selected articles to gain deeper insights into the main themes within I5.0 research. In the realm of machine learning, topic modeling identifies patterns in word usage and assigns new meanings to common terms by grouping them together. This method streamlines the analysis of extensive volumes

Table 3 Detailed overview of thematic areas in I5.0 research, main contributions, and key studies

Cluster	Summary	Main contributions	Key studies
Red cluster	Focuses on the integration of advanced technologies in I5.0, including AI, IoT, digital twin, blockchain, machine learning, and more. This cluster emphasizes the development of smart factories and the role of technologies like edge computing and cloud manufacturing in enhancing operational efficiency and resilience.	Highlights the pivotal role of emerging technologies in transforming industrial operations, particularly through real-time data processing, predictive maintenance, and enhanced cybersecurity. Discusses how these technologies support the development of intelligent and resilient manufacturing ecosystems.	(Brunetti et al. 2022; Cotta et al. 2023a; Fatima et al. 2022; Maddikunta et al. 2022; Nguyen and Tran 2023; Özdemir & Hekim, 2018; Peruzzini et al. 2023; Sarkar et al. 2024; Zhang et al. 2023)
Blue cluster	Centers around sustainability and human-centric approaches, exploring how these themes intersect with digital transformation and resilience. Key topics include Society 5.0, sustainability, SDGs, digitalization, and circular economy.	Discusses the integration of sustainable practices and human-centered design in I5.0, focusing on how digital transformation drives innovation and resilience. Highlights the importance of aligning industrial practices with global sustainability goals.	(Aheleroff et al. 2022; Ali and Johl 2024; Baig and Yadegaridehkordi 2024; Grabowska et al. 2022; Kasinathan et al. 2022; Martini et al. 2024; Panza et al. 2023; Sharma and Gupta 2024; van Erp et al. 2024)
Green cluster	Explores HRC and the role of advanced manufacturing technologies within I5.0. Key topics include HRC, cobots, AR, human-centric manufacturing, and human-machine interaction.	Emphasizes the collaborative interaction between humans and robots in industrial settings, focusing on enhancing productivity and safety through advanced technologies. Discusses the use of immersive technologies like AR and VR in training and maintenance.	(Coronado et al. 2022; Demir et al. 2019; Marinelli 2023; Ohueri et al. 2024; Panagou et al. 2024; Pizoń and Gola 2023; Ramírez-Gordillo et al. 2024; Rožanec et al. 2023; Yang et al. 2022; Zafar et al. 2024)

of unlabelled texts by clustering words with similar meanings and differentiating between words with multiple meanings. Generally, topic modeling is a standard practice for uncovering hidden themes or topics within a collection of texts or corpus (Zrelli et al. 2024). It interprets each theme in a given text as a combination of several topics. In this study, the Latent Dirichlet Allocation (LDA) approach was utilized to uncover latent topics within the abstracts of selected I5.0-related publications. This technique has been widely applied in research examining international trade, public sentiment during the COVID-19 pandemic, and Industry 4.0 (Rejeb et al. 2023). Initially, text preparation was conducted to enhance the quality of the collected data. This included tokenization to split abstracts into individual words, normalization to convert all capital letters to lowercase, and stemming to reduce words to their base forms. Additionally, numbers, punctuation, and stop words were removed due to their lack of useful information (Ligorio et al. 2022). The LDA approach identified six overarching themes in I5.0 research. In Fig. 9, the vertical axis lists the keywords representing different themes, while the horizontal axis displays the values of beta, indicating the relevance of each keyword to its corresponding theme. By employing topic modeling on the abstracts of I5.0 research, we were able to distill key themes and insights from a vast amount of data, facilitating a better understanding of the

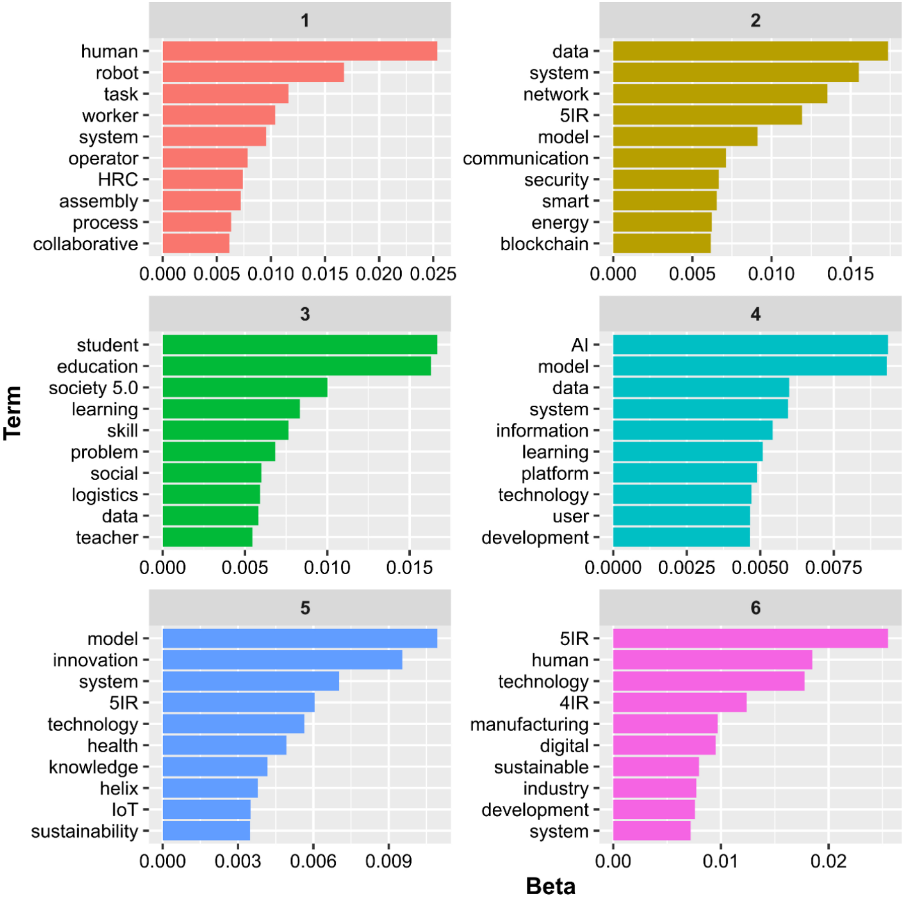

Fig. 9 Topic modeling in I5.0 research using LDA

field's core topics and trends. This method provides a powerful tool for researchers to explore and analyze complex datasets, revealing the underlying structure and key areas of focus within the burgeoning domain of I5.0.

The first theme deals mostly with human-robot collaboration in industrial processes. Key terms such as human, robot, task, worker, system, operator, HRC, assembly, process, and collaborative highlight the emphasis on seamless interaction between humans and robots (Apraiz et al. 2023; Di Marino et al. 2023). The goal is to enhance efficiency and safety in manufacturing environments. For instance, recent studies indicate that incorporating collaborative robots into assembly lines can improve productivity while maintaining high safety standards by allowing robots to handle repetitive tasks and humans to oversee more complex operations (Boschetti et al. 2023; Calzavara et al. 2023; Di Marino et al. 2023). The second topic revolves around the crucial role of data management and security in I5.0. The terms data, system, network, 5IR, model, communication, security, smart, energy, and blockchain suggest a focus on creating robust data systems that support smart manufacturing. Maintaining the security of these systems is paramount, particularly with the increased connectivity and reliance on real-time data (Adel 2023; Dobaj et al. 2023; Hansen et al. 2024). For example, blockchain technology is being explored to enhance data integrity and security across manufacturing networks (Alsamhi et al. 2024; Habbal et al. 2024; Lage et al. 2023).

The third topic addresses the intersection of education and societal advancement in the context of Society 5.0. The appearance of the terms student, education, society 5.0, learning, skill, problem, social, logistics, data, and teacher indicates a focus on equipping individuals with the necessary skills to thrive in a technologically advanced society. Educational initiatives are being developed to integrate technology and social innovation, preparing students for the challenges and opportunities of the future workforce (Borchardt et al. 2022; Darani et al. 2021). The fourth theme highlights the role of AI and technology in advancing I5.0. With terms such as AI, model, data, system, information, learning, platform, technology, user, and development, the focus is on leveraging AI to enhance data processing, decision-making, and system optimization (Cotta et al. 2023b). AI-driven platforms are being developed to streamline operations and improve user experiences, driving technological innovation across various industries (Agrawal et al. 2023; Akinsolu 2023; Caiazzo et al. 2023).

The fifth topic centers on innovation and sustainable practices within I5.0. Keywords such as model, innovation, system, 5IR, technology, health, knowledge, helix, IoT, and sustainability suggest a focus on developing innovative solutions that promote sustainability. The triple helix model, which involves collaboration between academia, industry, and government, is often cited as a framework for fostering innovation and sustainability in industrial practices (Carayannis and Campbell 2022; Ejaz 2023). The sixth theme focuses on the integration of human-centric technology and sustainable practices in manufacturing. The topic encompasses terms like 5IR, human, technology, 4IR, manufacturing, digital, sustainable, industry, development, and system. The emphasis is on developing manufacturing systems that prioritize human well-being and sustainability. Digital technologies are being leveraged to create more adaptable and resilient manufacturing processes that align with the goals of I5.0. Conclusively, the analysis of each topic illustrates a different facet of I5.0, from the integration of advanced technologies and human-centric design to the focus on education, innovation, and sustainability.

3.4.2 Evolutions and interconnections of key topics in industry 5.0 research

To analyze the evolution of topics over time in the context of I5.0 research, we have conducted a detailed analysis based on the results of Fig. 10. This analysis elucidates the development, prominence, and interrelation of the key topics highlighted in the study from 2016 to 2024, therefore enhancing the understanding of the trends and dynamics that are influencing the I5.0 landscape.

The first topic, focusing on human-robot collaboration (HRC) in industrial processes, has experienced a gradual yet substantial rise in importance over time. Commencing with limited focus in 2016, this topic acquired significant traction by 2018 and experienced a substantial upsurge from 2021 forward. By 2024, it has emerged

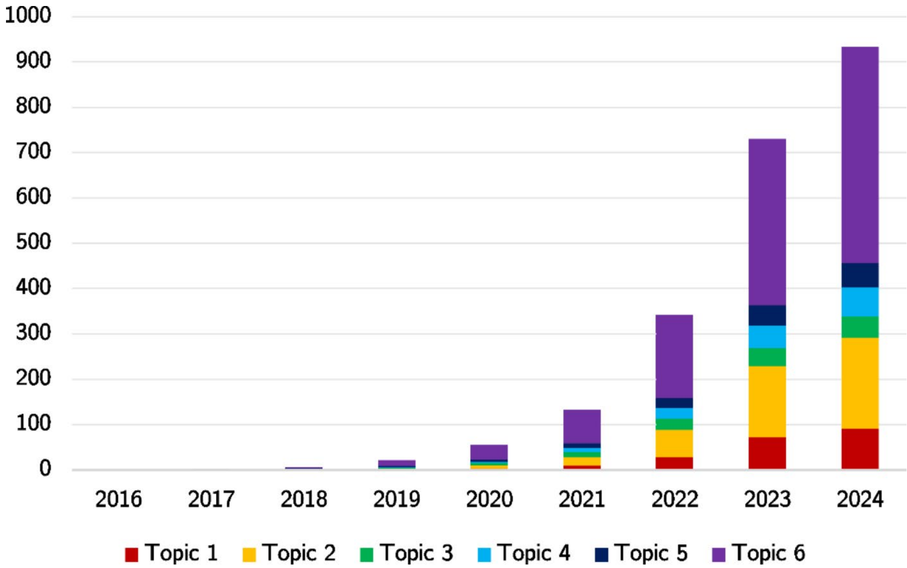

Fig. 10 Temporal evolution of LDA-derived research topics in I5.0 (2016–2024)

as a highly significant topic in the field of I5.0. This trend is driven by the increasing focus on incorporating collaborative robots in manufacturing environments to improve operational efficiency and safety (Doyle-Kent and Kopacek 2021; Prassida and Asfari 2022). Given the emphasis on human-centric technologies in I5.0, the seamless interaction between humans and robots, especially through HRC, is essential for the progress of contemporary industrial systems. The present topic is closely linked to Topic 4, which revolves around AI and technological advancements. This is because AI assumes a pivotal function in augmenting the capacities of robots, facilitating their efficient collaboration with humans (Borboni et al. 2023).

The second topic, centered on data management and security, demonstrates a consistent upward trend, with a notable surge commencing in 2020. This growth aligns with the extensive implementation of digital transformation strategies in several sectors, emphasizing the crucial need for robust data systems in facilitating intelligent manufacturing. The growing importance of this topic by 2024 underscores the persistent difficulties and possibilities associated with safeguarding industrial data in more networked settings, where technologies such as blockchain are being investigated for improving data integrity and security (Rejeb et al. 2023). This topic is interconnected with Topic 5, which centers on the concepts of innovation and sustainable practices. Secure data management is crucial for integrating cutting-edge, sustainable practices into I5.0 frameworks (Asif et al. 2023; Bhat and Parvez 2024). Education and societal advancement, the focus of the third topic, has also evolved, though at a more moderate pace compared to other themes. The rise in interest in this subject around 2019 indicates an increasing acknowledgment of the necessity to provide the labor force with the necessary abilities to navigate a technologically sophisticated society (Asif et al. 2023). The increasing focus on this topic highlights the need for combining technology and social innovation in education, hence equipping individuals to make valuable contributions to the changing requirements of I5.0. This topic overlaps with Topics 1 and 6, which focus on human-centric technology and sustainability in manufacturing. Education plays a vital role in acquiring the necessary skills to effectively implement and maintain these practices (Gürdür Broo et al. 2022; Poláková et al. 2023).

The fourth topic, focused on AI and technological advancements, demonstrates steady expansion, especially starting in 2019. By 2024, AI continues to be a primary area of interest, motivated by its ability to improve data processing, decision-making, and system optimization in many economic sectors (Ghobakhloo et al. 2024a; Leng et al. 2024). The proliferation of AI-powered platforms that optimize processes and enhance user experiences highlights the growing reliance on AI technology in driving I5.0 forward. This theme not only facilitates the progress in HRC (Topic 1) but also forms the foundation for the secure and effective data management systems emphasized in Topic 2. The fifth theme, innovation and sustainable practices, demonstrates consistent growth with a significant increase beginning around 2020. The observed pattern is indicative of the growing significance of sustainability in industrial operations, propelled by worldwide sustainability objectives and the incorporation of IoT and emerging frameworks such as the triple helix model (D. Liu and Zhu 2023). The synchronization of innovative endeavors with sustainable practices is crucial for the progress of I5.0 and the resolution of the environmental issues linked to modern manufacturing. This topic is intricately connected to Topic 6, as sustainable practices are a fundamental element of the human-centered approach that characterizes I5.0.

From 2020 onward, the sixth and last topic, which concentrates on human-centric technology and sustainability in manufacturing, has experienced the most significant expansion. More recently, it has become a prominent topic, emphasizing the worldwide transition toward sustainability and the crucial necessity for robust industrial systems that give priority to human welfare. A crucial driving force behind this trend is the incorporation of digital technologies in manufacturing to improve adaptability and sustainability (Ghobakhloo et al. 2024). The present theme consolidates the knowledge gained from the preceding topics underscoring the significance of human-centered, sustainable, and innovative approaches within the dynamic I5.0 environment. In conclusion, the examination of these topics across time demonstrates the dynamic development and interconnections of important themes in I5.0 research. The growing emphasis on HRC, data management, AI, and sustainability mirrors the wider transformative changes in industrial processes toward more cohesive, robust, and human-centered systems.

3.5 Multiple correspondence and thematic analyses

Multiple correspondence analysis (MCA) was applied to examine the conceptual structure of I5.0 research. Using the R-Bibliometrix software, MCA was utilized to create a conceptual structure map by analyzing the proximity of keywords in selected publications (Singh and Rejeb 2024). On this map, keywords that are distributionally similar appear closer together. Additionally, the conceptualStructure function in R was used to extract authors' keywords. Considering the similarity of keywords on the map, k-means clustering was employed to generate clusters with shared themes. This combination of MCA and k-means clustering resulted in a two-dimensional graphic depicting the most significant keywords, their connections, and emerging trends in the field. The conceptual structure map of I5.0 research reveals four distinct clusters.

The red cluster includes keywords such as HITL, human-centric manufacturing, human-machine interaction, smart manufacturing, 4IR, HCPS, SLR, CPS, metaverse, industrial revolution, etc. (Fig. 11). This cluster focuses on the integration of advanced technologies and human-centric approaches in manufacturing. For example, Ciccarelli et al. (2024) demonstrate how human-centric manufacturing enhances worker satisfaction and productivity by leveraging technologies like human-machine interaction and collaborative robots. The inclusion of terms like digitalization and circular economy highlights the shift towards sustainable and efficient manufacturing processes, emphasizing the reduction of waste and resource optimization. The green cluster comprises keywords such as cybersecurity, IIoT, task analysis, industry, federated learning, deep learning, security, cloud computing, blockchain, machine learning, etc. This cluster underscores the critical role of data management, security, and advanced technologies in I5.0. Representative studies in the cluster include Alsamhi et al. (2024), Habbal et al. (2024), and Agostinho et al. (2023), who explore how federated learning and XAI (Explainable AI) are being used to enhance data security and transparency, ensuring robust and trustworthy AI applications in industrial settings.

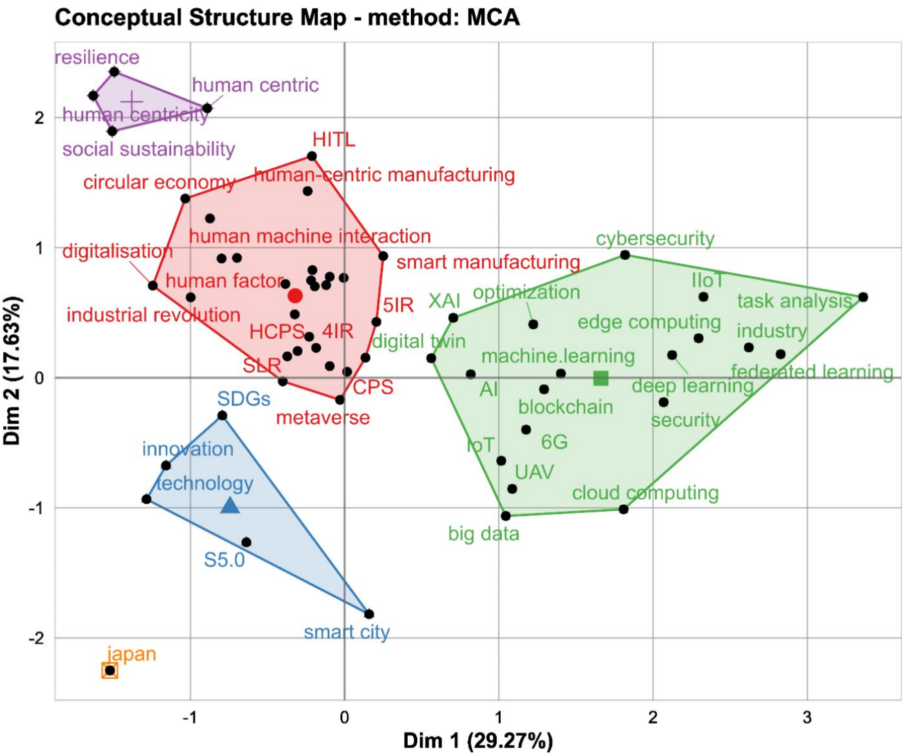

Fig. 11 Conceptual structure map of I5.0 research

The blue cluster includes keywords such as SDGs, innovation, technology, society 5.0, and smart city. This cluster highlights the alignment of I5.0 initiatives with broader societal goals and innovations. For example, research by Bonello et al. (2024) and Adel (2022) show how I5.0 supports the SDGs through technological advancements and smart city initiatives. These efforts aim to improve urban living conditions, promote sustainable practices, and foster innovation in various sectors, ultimately contributing to the development of Society 5.0 (Alimohammadlou and Khoshsepehr 2023; Althabhawi et al. 2022). The purple cluster encompasses keywords such as resilience, human-centric, social sustainability, and human-centricity. This cluster focuses on the importance of resilience and human-centered design in sustainable industrial practices. Studies like those by Camarinha-Matos et al. (2024) highlight how resilient manufacturing systems can adapt to disruptions, ensuring continuous operations while prioritizing human well-being and social sustainability. The emphasis on human-centricity accentuates the need for designing systems that enhance the quality of life for workers and communities.

The strategic thematic map of I5.0 research is illustrated in Fig. 12, with the size of the bubbles representing the frequency of each keyword in the selected articles. According to Cobo et al. (2011), the motor themes quadrant comprises topics that are both highly developed and central to the field, exhibiting strong internal and external

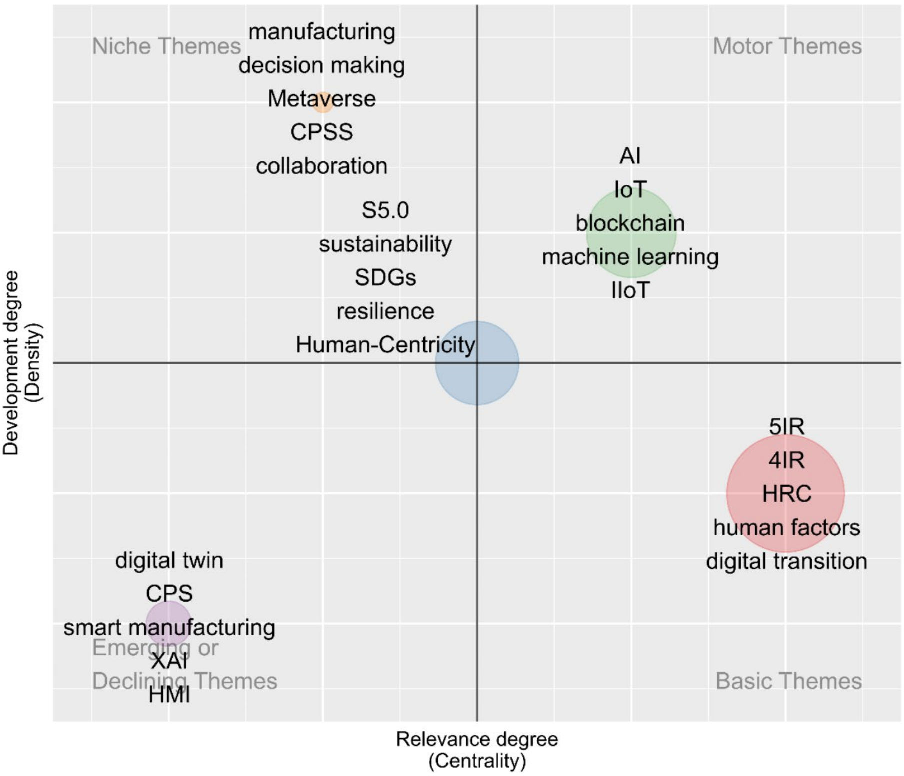

Fig. 12 Thematic map of I5.0 research

connections. In this quadrant, prevalent themes include AI, IoT, blockchain, machine learning, and IIoT, indicating that these technologies are well-established and critically important in driving I5.0 forward. The basic themes quadrant, characterized by high centrality but low density, features topics with significant external linkages but weaker internal cohesion. Keywords such as 5IR, 4IR, HRC, human factors, and digital transition fall into this category. These themes are foundational, connecting broadly with other topics and indicating their essential role in the broader research landscape, despite their current lower internal development.

Niche themes are located in the upper-left quadrant, which includes keywords that are densely interconnected internally but have fewer connections externally. These topics are specialized and complex, often representing unique areas of study. Manufacturing, decision-making, metaverse, CPSS (Cyber-Physical Social Systems), and collaboration are identified as niche themes in I5.0 research. These areas are well-developed within their specific context but have limited influence on the broader research field. The lower-left quadrant represents emerging or declining themes, characterized by low density and centrality, indicating that these topics are nascent or in decline and poorly developed. Keywords such as digital twin, CPS, smart manufacturing, XAI, and HMI fall into this category. These themes might be in the early stages of research development or losing prominence, signaling areas where future research might either revitalize interest or move away from them.

4 Discussion and future research

The review of I5.0 research reveals a rapidly growing field marked by exponential increases in publications, particularly from 2020 onward. This surge reflects the rising importance of integrating advanced technologies like AI, IoT, and robotics with human-centric and sustainable manufacturing processes. The significant uptick in publications can be attributed to several factors. Firstly, the advent of I5.0 marks a paradigm shift from the purely technology-driven approach of Industry 4.0 to a more balanced integration of technology and human elements (Ghobakhloo et al. 2022). This shift emphasizes not only efficiency and automation but also the enhancement of human well-being and environmental sustainability. The increasing recognition of this approach's value has driven both academic and industrial interest, leading to a surge in related research. Secondly, technological advancements have accelerated the adoption of I5.0 principles. Innovations in AI and machine learning have enabled more sophisticated and adaptive manufacturing systems (Akinsolu 2023). IoT has facilitated better connectivity and data exchange between devices, enhancing real-time monitoring and decision-making capabilities (Alimam et al. 2023b; Alsamhi et al. 2024; Habbal et al. 2024). Robotics has evolved to work more collaboratively with humans, leading to safer and more efficient production environments (Asad et al. 2023; Coronado et al. 2023, 2024). These advancements have created new research opportunities and challenges, fueling the exponential growth in publications. Additionally, global events such as the COVID-19 pandemic have highlighted the need for more resilient and flexible manufacturing systems. The disruptions caused by the pandemic reinforce the importance of having adaptable manufacturing processes that can quickly respond to changing demands and conditions. The emphasis of I5.0 on human-centric and sustainable practices offers a pathway to achieving this resilience, further driving research and development in this field. The increasing focus on sustainability is also a crucial factor. As industries face growing pressure to reduce their environmental impact, I5.0's principles of sustainable manufacturing have gained traction (Ghobakhloo et al. 2024). Research exploring ways to integrate eco-friendly practices with advanced technologies has become more prominent, contributing to the overall rise in publications.

The prominence of leading journals such as the Journal of Manufacturing Systems, Sustainability, and the Journal of Industrial Information Integration suggests more than just publication frequency. It hints at the strategic direction and influence these journals exert in shaping the discourse around I5.0. Are these journals pioneering new frameworks or emphasizing particular aspects of I5.0 that are driving the field forward? Their prominence could reflect broader shifts in research priorities toward sustainability and digital transformation. During the examination of the surge in publications, scholars must consider whether this growth genuinely reflects advances in knowledge or if it is partly driven by academic trends and funding opportunities. The increase in articles might be indicative of a bandwagon effect, where researchers focus on I5.0 due to its current popularity and funding availability, potentially leading to a saturation of redundant studies rather than novel contributions.

The analysis of social networks reveals that institutional collaboration is notably low, with a density of 0.207, though key institutions like the Hong Kong Polytechnic University and Zhejiang University serve as central hubs. This low collaboration rate may reflect a range of underlying factors, including socio-political dynamics, economic disparities, and varying levels of technological advancement across different regions. One interpretation of this finding is that the global North-South divide significantly impacts the nature and extent of research collaborations in I5.0. Institutions in more developed regions (often in the Global North) may have more resources, access to advanced technologies, and established networks, enabling them to lead and centralize research efforts (Muzaffar et al. 2024; Slavic et al. 2024). On the other hand, institutions in the Global South may have obstacles such as insufficient financial resources, access to less sophisticated technologies, or less established academic networks, which could hinder their capacity to participate in wider and more influential research partnerships (Alharbi 2023; Mukherjee et al. 2023).

Regional and cultural disparities also influence the adoption and development of I5.0 technologies. For example, cultural attitudes toward automation, human-centric technologies, and sustainability could vary significantly between regions, influencing how I5.0 is implemented (Cillo et al. 2021; Ghobakhloo et al. 2023). In some regions, there may be a stronger focus on human-centric approaches due to cultural values emphasizing community and social welfare (Hyz and Gikas 2024), while in others, the emphasis might be on technological efficiency and economic growth. Furthermore, the existing collaboration structure, characterized by tight-knit groups with limited broader interaction, suggests that while some institutions dominate the research landscape, this dominance might create barriers to more inclusive global collaboration. To overcome these barriers, there could be a need for targeted initiatives to promote inter-institutional partnerships, particularly those that bridge the gap between the Global North and South. This could involve collaborative funding opportunities, shared access to technological resources, and programs designed to foster intercultural exchanges in research. Through strengthening these partnerships and tackling regional inequalities, the worldwide research community can work more effectively toward advancing I5.0, ensuring a fairer distribution of its advantages among various regions and cultures.

The analysis of keyword co-occurrence network and topic modeling provides a comprehensive view of the I5.0 field's evolution and current trends. The exponential growth in publications from 2020 onward reflects the heightened interest and rapid advancements in integrating cutting-edge technologies such as AI, IoT, machine learning, and blockchain into industrial processes. However, this analysis also reveals critical insights into the thematic focus areas and potential gaps. The clustering of keywords indicates a strong emphasis on technological advancements, but it also highlights an imbalance. There is a predominant focus on developing and implementing these technologies without equally robust exploration of their broader socio-economic impacts. This narrow concentration could potentially stifle innovation by neglecting the diverse contexts and needs of different industries and regions.

The co-word clusters also suggest that while sustainability and human-centric design are acknowledged, they are often treated as secondary considerations rather than integral components of technological development. This separation may lead to fragmented approaches that fail to fully leverage the synergies between technology, sustainability, and human factors. For I5.0 to achieve its full potential, there needs to be a more holistic integration of these elements. Moreover, the clusters reflect a concentration of research efforts around well-trodden themes, potentially at the expense of exploring novel or interdisciplinary approaches. This could lead to redundancy and a slower pace of groundbreaking innovations. Therefore, diversity in research topics and methodologies should be encouraged as it is essential to foster a more dynamic and innovative research landscape.

The topic modeling of I5.0 research reveals key areas shaping the field. Human-robot collaboration is a major focus, aiming to enhance productivity and safety in industrial processes. However, this integration necessitates new skills and retraining programs for the workforce (Adel 2024). Data management and security are central, reflecting the reliance on real-time data and connectivity in smart manufacturing. Blockchain and other technologies are explored for data integrity, but robust cybersecurity measures remain a significant challenge. In addition, education and societal advancement raise the need for skills to thrive in a technologically advanced society, emphasizing the integration of technology and social innovation in education. AI also drives significant innovation and improves data processing and decision-making. Nevertheless, transparency and ethical use of AI are concerns necessitating responsible frameworks (Habbal et al. 2024). Similarly, innovation and sustainability focus on developing solutions aligned with sustainable practices, often involving collaboration between academia, industry, and government. Yet, practical implementation faces bureaucratic hurdles (Botti and Baldi 2024; Gavurova et al. 2023). Human-centric technology and sustainable manufacturing advocate for systems prioritizing human well-being and environmental sustainability. Consequently, the integration of these principles across diverse sectors remains challenging. Overall, the research underscores balancing technological advancements with workforce development, robust data security, effective collaborations, and ethical AI use to ensure I5.0's holistic advancement.

This study suggests several future research directions based on the analysis of the keyword co-occurrence network and topic modeling for I5.0. To provide clearer guidance, these directions are aligned with the importance of the topics as revealed in the analysis:

- Future research should prioritize a deeper exploration into the integration of HRC within industrial processes. While current research emphasizes productivity and safety enhancements through collaborative robots (Adriaensen et al. 2023; Dornelles et al. 2023; Espina-Romero et al. 2023), future investigations need to focus on the long-term implications for the workforce, particularly regarding the necessary skills and retraining programs. Understanding the socio-economic impacts of widespread robotic integration and how to mitigate potential job displacement will be critical (Almusaed et al. 2023; Ghobakhloo, Mahdiraji, Iranmanesh, et al., 2024). This area is prioritized due to its direct influence on workforce dynamics and the necessity of preparing industries for seamless human-robot collaboration.
- Data management and cybersecurity in I5.0 are also critical areas for future research. As manufacturing systems become increasingly reliant on real-time data and connectivity, robust cybersecurity measures are paramount (Adel 2023). Researchers should focus on developing advanced security protocols to protect against cyber threats and ensuring data integrity. The role of blockchain in enhancing data security and integrity across manufacturing networks warrants further exploration (Abdel-Basset et al. 2024; Ahamed and Vignesh 2022; Rejeb et al. 2023a). Given the increasing risks associated with data breaches and the critical role of secure data systems, this research direction is prioritized to ensure the safety and reliability of I5.0 infrastructures.
- Education and societal advancement within Society 5.0 are also important, but they are not prioritized as highly as HRC or data management. While these areas are vital for preparing the future workforce and ensuring societal readiness for I5.0, they are more foundational and support the broader adoption of I5.0 principles. The impact of education and societal advancement is more long-term and indirect, making it essential but not as immediately critical as the technical aspects (Hsu et al. 2024).
- The role of AI in advancing I5.0 is prioritized due to its direct impact on enhancing data processing, decision-making, and system optimization. While AI-driven platforms enhance data processing and decision-making, there is a need for research on the ethical use of AI and ensuring transparency in AI operations (Habbal et al. 2024). Developing frameworks for responsible AI implementation will be crucial as reliance on these technologies increases.
- Innovation and sustainable practices within I5.0 highlight the importance of developing solutions aligned with sustainability. Scholars should focus on practical strategies for implementing the triple helix model of collaboration between academia, industry, and government (Afzal et al. 2024). The mitigation of bureaucratic and operational hurdles to facilitate these collaborations is essential for

fostering sustainable industrial practices. The importance of this research area is acknowledged, but it is given somewhat lesser priority compared to AI and cybersecurity because of its wider scope, which necessitates cooperation across several industries.

- Human-centric technology and sustainable manufacturing are given significant priority because they embody the essence of I5.0's vision of creating systems that prioritize human well-being and environmental sustainability. As such, future research should explore methods to integrate human-centric design principles and sustainable practices more effectively across various industrial sectors. This includes investigating the practical challenges of implementing these principles and developing solutions to ensure that technological advancements benefit both human well-being and environmental sustainability.
- Finally, interdisciplinary and inter-institutional collaborations are essential but not prioritized as highly as the technical and human-centric aspects. Researchers should investigate the barriers to such collaborations and propose strategies to foster more integrated and cohesive research efforts. This will help bridge existing gaps and accelerate the development of holistic and innovative solutions in the I5.0 landscape. Although collaboration plays a crucial role in promoting innovation, its influence is more diffuse and relies on the successful progress of other priorities such as AI, HRC, and sustainable practices. Therefore, it is crucial for expediting development but is widely regarded as a supplementary rather than a primary focus.

5 Conclusions and research limitations

This study set out to explore the breadth and knowledge structure of I5.0 research over recent years. By employing bibliometric and topic modeling techniques, we examined 942 articles authored by 3253 researchers. Bibliometric methods, unlike subjective approaches such as systematic literature reviews, offer an objective means to map an entire research field. These methods avoid the biases that come from selective evidence and preferential treatment of certain articles, providing a more accurate representation of the current state of research. To the best of our knowledge, this study is among the first to investigate the bibliometric structure of I5.0 research comprehensively. Our analysis revealed significant trends, identified the most prolific authors, and pinpointed the leading journals contributing to this field. Notably, we discovered that the research networks often feature a hub-and-spoke configuration, with a few key scholars and institutions driving the majority of the advancements. These central figures and entities function as vital conduits of knowledge, facilitating the flow of information across the I5.0 research landscape.

It is notable that geographical proximity and cultural ties significantly influence research collaboration among countries and academic institutions. This finding is consistent with prior studies on scholarly collaboration patterns (Mostafa 2021; Rejeb et al. 2023c). Prominent contributors in this field include the Hong Kong Polytechnic University, Zhejiang University, and Guangdong University of Technology, with strong support from institutions like the Chinese Academy of Sciences and Uppsala University. These institutions play a crucial role in propelling I5.0 research forward. Our findings also highlight a lack of sufficient collaboration between developed and developing nations, which is a trend seen across various scientific fields (Rejeb et al. 2023). Bridging this gap could enhance the global reach and inclusivity of I5.0 research. Regarding the conceptual structure of I5.0, keyword co-occurrence and topic modeling analyses reveal key areas of focus, such as human-robot collaboration, data management and security, education and societal advancement, AI-driven innovation, and sustainable practices. These areas emphasize the transformative potential of I5.0 in manufacturing, blending advanced technologies with human-centered and sustainable approaches.

This study offers a range of insights and implications for both scholars and practitioners. It delivers a detailed bibliometric analysis that identifies, categorizes, and evaluates key elements of I5.0 research, emphasizing areas that need further exploration. The findings objectively present research performance related to I5.0 by identifying the primary topics and emerging trends. For practitioners, the review provides a deeper understanding of the core concepts within the I5.0 literature and its development over time.

To guide future research, the paper emphasizes numerous developing themes in I5.0, such as the importance of flexible services and manufacturing, as well as novel concepts such as resilience in cloud manufacturing. The incorporation of flexible manufacturing systems with robust cloud networks is crucial for improving flexibility, efficiency, and general robustness as the manufacturing industry progressively adopts I5.0. These adaptable systems enable quick adjustment and expansion of manufacturing operations in response to evolving requirements and unexpected disruptions. Through the effective application of cloud manufacturing, which offers scalable computing resources and facilitates real-time data sharing, these systems can attain a greater level of resilience.

Further investigation is warranted to explore the interconnections between flexible manufacturing systems and resilient cloud networks, with a specific emphasis on optimization strategies to enhance the responsiveness and efficiency of production environments. This entails examining the function of cloud-based platforms in facilitating decentralized decision-making processes, which are crucial for the reactive adaptation of industrial operations. Moreover, the capacity of these systems to resume operations after disruptions, such as interruptions in the supply chain or failures of equipment, could be improved by creating more advanced models that combine predictive analytics with real-time monitoring. In addition, exploring the impact of sophisticated analytics and machine learning on bolstering the robustness of cloud manufacturing systems could provide useful knowledge for strengthening the overall performance and reliability of the system. One possible application of machine learning algorithms is to forecast possible breakdowns and enhance maintenance plans, therefore minimizing periods of inactivity and enhancing the overall system availability. Furthermore, advanced analytics can be employed to enhance resource allocation in real-time, therefore guaranteeing maximum efficiency in industrial operations while preserving the necessary flexibility to changing circumstances.

Furthermore, research might investigate the possibilities of digital twins in cloud manufacturing, where virtual representations of physical assets are employed to simulate, forecast, and enhance manufacturing processes in real-time. This approach not only strengthens the ability of manufacturing systems to withstand challenges but also enables ongoing enhancement by examining data from previous operations to guide future decision-making. Finally, collaborative research between academia and industry could be crucial in creating and testing novel innovations, guaranteeing that theoretical advancements translate into practical solutions that manufacturers can easily embrace. Future research in these developing areas can make a substantial contribution to the progress of I5.0, facilitating the development of manufacturing environments that are not only more efficient but also more robust and flexible in addressing future issues.

The present investigation is subject to specific constraints. First and foremost, the usage of only Scopus and the focus on journal papers may have impacted the results, possibly leading to bias in the representation of the scientific discipline. In addition to journal articles, future research should consider incorporating other knowledge sources such as conference papers, books, and book chapters to capture a more comprehensive view of I5.0-related research. The selection of a database and the type of source can have a substantial impact on the scope and direction of research results. Further research could enhance these results by integrating more scientific databases, such as Web of Science (WoS), and conducting a comparative analysis to mitigate any biases arising from the selection of databases and sources. Furthermore, whereas techniques like topic modeling enable comprehensive coverage of a large number of publications, they are unable to completely replicate the precision of human reviewers in analyzing and interpreting article content. A consequence of this constraint is the possibility of bias in the identification and interpretation of themes. However, it is crucial to acknowledge that automated methods may fail to detect small nuances that human analysis could detect. Although keyword frequency and co-occurrence analyses can assist in identifying common themes and establishing links across texts, future research should investigate more sophisticated analytical approaches. These sophisticated techniques may provide enhanced clustering and more detailed analysis, thereby minimizing possible biases in theme identification. Ultimately, incorporating a wider range of methodologies, data sources, and journal selections could enhance the objectivity and thoroughness of the I5.0 research overview, reducing any biases inherent in this study.

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Declarations

Conflict of interest The authors state that there is no conflict of interest in this research work. The authors have followed all ethical guidelines of the journal.

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