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A Bibliometric Analysis of Industry 4.0 Literature in the Operations Management Domain

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ABSTRACT

It has been exactly a decade since the term "Industry 4.0" was coined. Researchers have been fascinated with this term and have since explored different areas of Industry 4.0. This study uses bibliometric tools to conduct an in-depth, year-wise analysis of Industry 4.0 literature in operations management. A detailed year-wise keywords cluster analysis highlights the evolution of the intellectual structure of Industry 4.0. Two new aspects namely the morphological study of keywords and the year-wise new keywords analysis are included in the keyword analysis. The analysis identifies the most significant studies, influential contributors (authors), and the countries that have majorly contributed to the body of knowledge of Industry 4.0. Since the research on Industry 4.0 is relatively new and attracts the heightened focus of scholars worldwide, the timely in-depth bibliometric review provided in this study will help future scholars explore multiple research directions in Industry 4.0.

Keywords: *bibliometric analysis, cluster analysis, industry 4.0, keywords analysis, literature review*

1. INTRODUCTION

The term "Industry 4.0" was initiated by the German government as "Industrie 4.0" at the Hannover Fair in 2011. Over the last decade, it has become a global phenomenon. Different terms such as "Factories of Future", "Smart Factory", "Industry 4", "Industrial Internet", and "Intelligent Manufacturing", etc. are used simultaneously (Kamble *et al.*, 2018; Liao *et al.*, 2017).

Industry 4.0 accentuates the current emphasis on digital technology with the help of interconnectivity through the Internet of Things (IoT), access to real-time data and the introduction of cyber-physical systems (CPS) (Paksoy *et al.*, 2020). It connects the physical with the digital and allows for better collaboration and access across departments, partners, vendors, products, and people. The Boston Consulting Group has identified nine technologies as the building blocks of Industry 4.0: big data analytics, autonomous robots and vehicles, additive manufacturing, augmented and virtual reality, horizontal/vertical system integration, IoT, cloud, blockchain and cyber-security (Erboz, 2017). Industry 4.0 has a noticeable impact on business models, markets, financial performance, product lifecycle management, supply chain management, workforce empowerment, production systems, productivity and efficiency (Kagermann, *et al.*, 2013; Pereira & Romero, 2017; Rosa *et al.*, 2020).

It has been exactly a decade since the term "Industry 4.0" was coined. Researchers have been fascinated with this term and have explored it in different areas. By 2016, literature review papers on Industry 4.0 started appearing in publications; for example, Liao *et al.* (2017) performed a rigorous keywords cluster analysis that generated five clusters: Industry 4.0 (127 keywords), CPS (61 keywords), Manufacturing (44 keywords), Smart Factory (30 keywords) and IoT (25 keywords). The authors also recognized the most important Industry 4.0 citations through the references, authors, institutions and their geographical locations. The literature review by Strozzi *et al.* (2017) focused only on particular aspects of smart manufacturing in the timeframe 2007–2016. Adams and Mpofu (2018) and Osterrieder *et al.* (2020) reviewed papers on Industry 4.0 and smart factories. Stentoft & Rajkumar (2020) performed a literature analysis on Industry 4.0 from 2013 to April 2018 to identify Industry 4.0 attributes and to provide a comprehensive idea of the success and failure factors concerning the implementation of Industry 4.0. Hoyer *et al.* (2020) performed a systematic literature review to identify a list of potential factors that influence the implementation of Industry 4.0 and adopted a systems-thinking perspective to understand the complexity of the implementation of Industry 4.0.

The aforementioned literature reviews have studied Industry 4.0 as an independent topic; other literature review studies have explored the links between Industry 4.0 and allied topics of Operations Management such as lean manufacturing (Bittencourt *et al.*, 2021; Núñez-Merino *et al.*, 2020; Pagliosa *et al.*, 2019; Kassem and Portioli, 2019); logistics (Bigliardi *et al.*, 2021); supply chain management (Zekhnini *et al.*, 2020; Tiwari, 2020); circular economy (Rosa *et al.*, 2020); Total Quality Management (Chiarini, 2020); work (Simões *et al.*, 2020); manufacturing (Zheng *et al.*, 2021); and sustainability (Beier *et al.*, 2020; Müller, 2021). Furthermore, studies have also conducted literature reviews on the application of Industry 4.0 in specific sectors such as the hospitality sector (Osei *et al.*, 2020); healthcare (Cavallone and Palumbo, 2020); plastics industry (Echchakoui and Barka, 2020); and port and maritime industry (de la Peña Zarzuelo, 2020).

Over the years, researchers have attempted to provide research perspectives and directions on Industry 4.0. However, a rigorous year-wise bibliometric study comprising keywords cluster analysis, new words analysis, morphological word analysis, citation analysis, co-authorship cluster analysis and co-citation cluster analysis till 2023 has not yet been reported in the extant literature. Using the latest available software such as Vosviewer, the aforementioned analyses have been performed in the present study to derive insights on year-wise research trends and to provide future research directions. The research objectives of this paper are as follows:

- RO1. Map the intellectual structure of Industry 4.0 topics using keyword analyses, provide year-wise evolution for the period 2011–2023, and identify future research directions.
- RO2. Identify key documents with influential contributions in the Industry 4.0 domain using citation analysis.
- RO3. Identify key authors and their clusters of collaboration networks that have contributed to the knowledge repository of Industry 4.0 using citation, citation cluster and co-citation cluster analyses.
- RO4. Identify research progress of Industry 4.0 research in countries worldwide.

Our work on Industry 4.0 contributes to the literature in the following four ways. To the best of our knowledge, this is the first research to engage in a year-wise review of Industry 4.0 spanning a wide timeframe of over a decade, from the first appearance of the term "Industry 4.0" in 2011 to 2023. Second, unlike existing studies that compartmentalized their focus to a specific dimension of Industry 4.0, such as smart manufacturing, IoT or CPS, or to a specific sector (Raj *et al.*, 2020; Zheng *et al.*, 2021; Kamble *et al.*, 2018; Liao *et al.*, 2017), the current study offers a holistic perspective, covering all the aspects of Industry 4.0 research and without any sectoral specificity (i.e. including all sectors such as pharma, logistics, manufacturing, tourism and several others). The third contribution stems from the morphological study of keywords and the year-wise new keywords analysis, which have not been attempted by any other study. Furthermore, the multi-layer cluster formation in co-citation and citation analysis identifies five distinct clusters with research themes. The analysis also identifies the most influential and cited authors and documents. Finally, since the research on Industry 4.0 is relatively new and attracts the heightened focus of scholars worldwide, the timely in-depth bibliometric review provided by this study will help future scholars with details of significant authors and papers.

The remainder of the paper is organized as follows: Section 2 provides the methodology of the study and data aggregation steps. Sections 3, 4, 5, 6, and 7 delineate the findings of keywords analysis, citation analysis, co-citation analysis of co-cited authors, country-wise analysis and source analysis respectively. Section 8 presents the discussion and implications. Finally, Section 9 concludes the paper's future research direction.

2. RESEARCH METHODOLOGY

Research articles on Industry 4.0 were collected from the Scopus database. The database was chosen due to its wide coverage and access to critical, high-quality research. It is the "largest single abstract and indexing database ever built" and the largest searchable citation and abstract source (Ahmi *et al.*, 2019). The following search terms were used for data collection: "Industry 4.0", "Industrie 4.0", "Industry 4" or "Fourth Industrial Revolution". Since the search word "Industry 4.0" does encompass the complete literature, the keyword "Fourth Industrial Revolution" was also used because of its interchangeability with Industry 4.0. The results were refined by applying filters wherein the "subject area" was restricted to "business management, accounting, economics, operations management and decision sciences". The document types were limited to "conference papers", "articles" and "reviews". The search resulted in a total of 7866 documents published from 2011 to 2023. **Figure 1** shows the year-wise distribution of the number of papers.

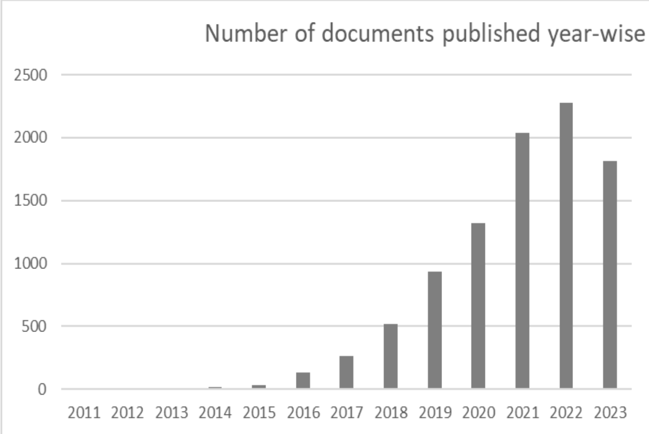

Figure 1 Number of documents published year-wise

The growth of the literature in Industry 4.0 in terms of publications, research domains, research productivity and citations is analysed using bibliometric analysis. It is defined as "the application of mathematics and statistical methods for the analysis of books and other media of communication" (Pritchard *et al.*, 1969). It is a quantitative method used to examine the knowledge, intellectual structure and evolution of research fields based on the analysis of related publications (Ahmi *et al.*, 2019; Tahai and Rigsby, 1998; Small, 1999; Arora and Chakraborty, 2020). According to Cobo *et al.* (2015), science mapping is a robust bibliometric technique to understand and monitor the structure and evolution of the field of research to identify how authors, disciplines and studies are related to one another, while performance analysis helps capture the effectiveness of the scientific documents based on citations. Researchers in the past have applied this technique to different management research areas, such as supply chain and logistics (Fahimnia *et al.*, 2015; Wang *et al.*, 2017), marketing (Samiee and Chabowski, 2012; Arora and Chakraborty, 2020), strategy, entrepreneurship (Etemad and Lee, 2003) and aviation (Dixit and Jakhar, 2021; Tanrıverdi *et al.*, 2020).

To visualize the bibliographic data, VOSviewer version 1.6.15 software was used. It can construct a network of co-authorship, co-occurrence of keywords, citation, bibliographic coupling, or co-citation links and is capable of providing a range of innovative visualizations (Thelwall, 2008). Three main bibliometric techniques were employed: keywords analysis, citation analysis and co-citation analysis (Zupic and Čater, 2015). A few generic algorithms in Microsoft Excel were also used for data analysis to generate additional insights. Each type of analysis is elaborated in the sub-sections below.

2.1 Keyword Analysis

'All keywords', the combination of 'author keywords' and 'index keywords', were considered for the keyword analysis. Three types of keyword analyses, namely cluster analysis, new words analysis and morphological analysis, were performed year-wise (i.e. from 2011 to 2023). For cluster analysis, a minimum cut-off value of the frequency of occurrence of a keyword was set for each year. Special attention was given to the most frequently occurring words. VOSviewer's cluster analysis generated coloured clusters based on the word co-occurrence networks and relationships associated with different research topics. Thereafter, a thematic analysis of each cluster was performed that detected their research themes. This resulted in year-wise thematic networks of the keywords.

For new words analysis and morphological analysis, no frequency cut-off criteria were set. The entire keyword table provided by VOSviewer was considered. New words introduced each year signify the new directions of Industry 4.0 research. Furthermore, the morphological analysis identified keywords with common roots but with new prefixes and suffixes being added every year. This divulges how a particular subject matter has enriched itself with additional aspects being incorporated into it every year. Section 3 presents the year-wise findings of all three types of keyword analyses.

2.2 Citation Analysis of Authors

Citation analysis identifies authors who have high citations for their publications. Furthermore, citation analysis shows co-authorship and citation links between the authors to reveal their collaboration networks. Section 4 presents the findings of the year-wise citation and co-authorship analyses.

2.3 Co-citation Analysis of Cited Authors

A co-citation link is a link between two items that are both cited by the same document. VOSviewer's co-citation analysis reveals a connected network visualization with coloured clusters. In the present paper, co-citation analysis is done on the aggregated data from 2011 to 2023, which has 102040 authors. To limit the analysis to prominent authors, a cut-off criterion of 1449 citations was implemented which resulted in 1000 authors. Thereafter, a thematic analysis of coloured clusters was performed to identify the broad research themes and prominent authors within these clusters. Section 5 presents the findings of the co-citation analysis.

2.4 Country Analysis

The country analysis demonstrates the geographical division of the research on Industry 4.0. For this, a citation analysis of countries based on the number of documents published and citations received was performed.

3. KEYWORD ANALYSIS

For 2011 and 2012, only four articles were obtained in the data collection; thus, it did not reveal significant clusters. This is mainly because, even though the term was coined in 2011, most of the papers were published only after 2013. Therefore, keyword analysis was carried out from 2013 to 2023. **Figure 2** (**2.1** to **2.6**), **Figure 3**, **Figure 4**, **Figure 5**, **Figure 6** and **Figure 7** present the keywords clusters for the years 2013–2023.

In 2013, keyword analysis revealed two clusters: green and red (**Figure 2.1**). The green cluster includes terms like disruptive event, uncertainty analysis, roadmap, and strategic approaches, highlighting uncertainty in adapting business strategies to Industry 4.0. The focus was on developing IT capabilities and recognizing Industry 4.0's disruptive potential. The red cluster includes keywords such as industrial revolution, manufacturing equipment, operations planning, and smart manufacturing, emphasizing manufacturing and operations.

In 2014 and 2015, two similar themed clusters (red and green) were identified, as shown in **Figures 2.2** and **2.3** respectively. The red cluster featured new keywords related to enabling technologies such as cyber-physical systems, embedded systems, Internet of Things, big data, and automation. The green cluster included keywords like engineering, management, manufacturing companies, and production planning and control. In 2014, the keyword 'cyber-physical system' appeared for the first time (Wiesner *et al.*, 2014; Thoben *et al.*, 2014). Issues related to 'security and privacy' in a production setting were first mentioned by Müller (2013). Also, 'supply chain' was introduced in the Industry 4.0 context (Kemmner & Capellmann, 2014). These keywords highlight the early research on applying Industry 4.0 in supply chains and mark the transition from the third to the fourth industrial revolution.

The new words analysis for 2015 revealed that 'cloud-based computing' was mentioned for the first time this year (Röschinger *et al.*, 2015; Pisching *et al.*, 2015). Research into applying cloud-based computing in Industry 4.0 also began in 2015. Morphological analysis of 2013 and 2014 showed Industry 4.0 was discussed in relation to equipment, manufacturing, production, and technology. However, in 2015, the impact of Industry 4.0 expanded to encompass the entire value chain rather than being limited to these areas (Hurt *et al.*, 2017; Adeyeri *et al.*, 2015).

In 2016, the keywords were divided into three clusters (**Figure 2.4**). The red cluster includes terms like embedded systems, cloud computing, RFID, and cyber-physical system, related to Industry 4.0 enabling technologies. The green cluster features keywords such as digital transformations, digital factories, fourth industrial revolution, and production process, indicating the revision of business processes into digital factories. The blue cluster comprises terms such as information management, information systems, big data, data handling, lean production, and smart manufacturing, highlighting the role of big data and information systems in transforming traditional manufacturing into smart manufacturing.

In 2016, additive manufacturing as a disruptive technology was first mentioned in the industry 4.0 context (Zawadzki & Żywicki, 2016; Moradlou & Backhouse, 2016; Monostori *et al.*, 2016). Additionally, keywords such as 'agile manufacturing systems' (Gröger *et al.*, 2016; Golovatchev & Schepurek, 2016) and 'project management' (Rauch *et al.*, 2016) appeared for the first time. This shows that researchers began applying Industry 4.0 concepts to agile manufacturing and project management. Furthermore, the concept of a maturity model for assessing Industry 4.0 implementation maturity emerged in 2016 (Ganzarain & Errasti, 2016; Prinz *et al.*, 2016; Leyh *et al.*, 2016).

In 2017 and 2018 showed three similar clusters (red, green and blue), as shown in **Figures 2.5** and **2.6**. The keywords in the red cluster, such as big data, data analytics and digital transformation, highlight a better awareness of data in the context of engineering research, manufacturing and supply chain for sustainable development. The green cluster contains keywords such as IoT, industrial internet, industrial research and smart manufacturing. These studies focussed on industrial research and the application of IoT in transforming traditional manufacturing into smart manufacturing. The blue cluster shows studies that contributed to converting embedded systems into IoT and CPS.

In 2017, keywords like augmented reality, 5G, and blockchain emerged, highlighting researchers' focus on Industry 4.0 applications (Ahram *et al.*, 2017; Holland *et al.*, 2017; Zeidler *et al.*, 2017). The digital twin concept was also introduced (Rodič, 2017; Bottani *et al.*, 2017; Blum & Schuh, 2017), along with terms like Lean 4.0 (Mrugalska & Wyrwicka, 2017), energy-aware manufacturing, and wisdom manufacturing (Zhou *et al.*, 2017). These suggest a holistic application of Industry 4.0 in sustainable and lean manufacturing (Frolov *et al.*, 2017; Ferrera *et al.*, 2017). Analysis of 2016 and 2017 emphasized elementary automation, data, digital, intelligent, cloud, and virtual technologies as key enablers of Industry 4.0 (Petrasch & Hentschke, 2016; Yao *et al.*, 2017; Zhou *et al.*, 2017; Langfinger *et al.*, 2017; Ferry *et al.*, 2017; Kim-Hung *et al.*, 2017; Kolberg *et al.*, 2017; Cattaneo *et al.*, 2017; Schroeder *et al.*, 2017).

The 2018-word analysis highlighted new technology-related keywords such as cognitive systems (Serrano *et al.*, 2018; Luetkehoff *et al.*, 2018), green computing (Ferrer *et al.*, 2018; Pham & Ahn, 2018), edge computing (Mishra *et al.*, 2018; Seitz *et al.*, 2018), and drones (Beke *et al.*, 2018). Keywords like workforce 4.0 (Kazancoglu & Ozkan-Ozen, 2018), society 5.0 (Riminucci, 2018), procurement 4.0 (Bienhaus & Haddud, 2018), and logistics 4.0 (Schmidtke *et al.*, 2018) indicate Industry 4.0's influence on operations management and the logistics sector's technological transformation. Morphological analysis emphasized future research on human-machine interaction.

For the year 2019, four clusters were identified, as shown in **Figure 3**. The red cluster comprises keywords such as *automation, blockchain, digital transformation* and *IoT*. It shows that research studies focussed on the development of technological aspects of Industry 4.0. The green cluster contains keywords such as *artificial Intelligence, machine learning, decision-making, information management* and *manufacturing industries*. This cluster consists of research studies that utilized artificial intelligence and machine learning for decision-making in manufacturing companies. The blue cluster contains keywords such as *embedded system, CPS* and *smart manufacturing*. These studies emphasized the role of embedded systems and CPS in achieving smart manufacturing. The yellow cluster consists of the keywords *digitalization* and *digital twins*. The studies in this cluster emphasized the requirement of digitization for formulating the digital twin of systems.

In 2019, research highlighted smart contracts (Dai *et al.*, 2019), eye tracking applications (Borgianni *et al.*, 2019), face recognition (Rahman *et al.*, 2019), and Cobots in Industry 4.0. Studies from 2019 also focused on AI and machine learning for manufacturing decision-making. Advanced technologies included 3-D printing, 4G, and 5G (Atmojo *et al.*, 2019; Yli-Ojanperä *et al.*, 2019; Le Grand & Deneckere, 2019).

In 2020, five clusters were identified (**Figure 4**). The yellow cluster emphasizes transforming traditional manufacturing into smart manufacturing. The purple cluster focuses on connectivity and integration in Industry 4.0. The green cluster highlights digital transformations, innovations, and digitalization. The red cluster centers on big data analytics, artificial intelligence, machine learning, and digital twins for manufacturing decision-making. The blue cluster explores blockchain applications in supply chains for sustainable development.

In recent literature, new terms like construction 4.0, healthcare 4.0, maintenance 4.0, pharma 4.0, port 4.0, tourism 4.0, education 4.0, circular industry 4.0, and globalization 4.0 illustrate the expansion of the fourth industrial revolution beyond manufacturing (Osunsanmi *et al.*, 2020; Noran *et al.*, 2020; Aceto *et al.*, 2020; Tortorella *et al.*, 2020; Nissoul *et al.*, 2020; Baritto *et al.*, 2020; Saidy *et al.*, 2020; Reinhardt *et al.*, 2020; Jiang *et al.*, 2020; de la Peña Zarzuelo *et al.*, 2020; Stankov & Gretzel, 2020; Soni *et al.*, 2020; de Sousa Jabbour *et al.*, 2018; Damiani *et al.*, 2020; Ali & Mahboob, 2020). Additionally, advanced technologies such as enhanced cognitive twins, net neutrality, port connectivity, positioning and tracking, and travelling cranes (Singh *et al.*, 2020; Dev *et al.*, 2020; Halawa *et al.*, 2020) have emerged, representing evolved forms of Industry 4.0 innovations. Notably, 'COVID-19' has become a significant research focus in 2020, exploring applications of Industry 4.0 in managing the pandemic (Javaid *et al.*, 2020).

In 2021, six clusters were identified, as shown in **Figure 5**. The red cluster denotes research on the use of blockchain to increase the security, efficiency, and transparency of supply chains. The green cluster's researchers look at how the pandemic has affected efforts at digital transformation, expedited the use of Industry 4.0 technologies, and encouraged sustainability practises in the industry. Blue cluster explores the application of AI and machine learning techniques in optimizing manufacturing processes, improving decision-making, and enabling smart and autonomous manufacturing systems. The yellow cluster presents how IoT and big data analytics may improve industrial process innovation, allow predictive maintenance, and improve operational efficiency. Purple cluster explores how Industry 4.0 technologies can facilitate the transition towards a circular economy model, where resources are used more efficiently and waste is minimized. Lastly, the sky-blue cluster links the two concepts of circular economy and digital twin.

In 2022, five clusters were identified. The red cluster focused on digital technology's transformative impact, integrating Industry 4.0 and 5.0 in manufacturing, and promoting sustainable practices. The green cluster explored blockchain in supply chain management, circular economy principles in Industry 4.0, COVID-19's effects on supply chains, and sustainability. The blue cluster studied synergies among AI, machine learning, big data analytics, and digital twin technology for smart industrial environments. The yellow cluster delved into smart manufacturing technology issues, digitalization implementation, and outcomes. The purple cluster aimed to aid SMEs in their digital transformation efforts.

In 2023, seven research clusters emerged. The red cluster studies COVID-19's impact on digital technologies, supply chain resilience, and disruption management. The green cluster explores technology integration, simulation for industrial process enhancement. The blue cluster delves into smart manufacturing's role in the fourth industrial revolution and quality management. The Yellow Cluster focuses on blockchain in digital innovation and sustainability solutions. The purple cluster examines blockchain's impact on organizational performance and transparency. The sky-blue cluster explores digitalization's role in the circular economy. The orange cluster centers on smart factory development and advanced production technologies.

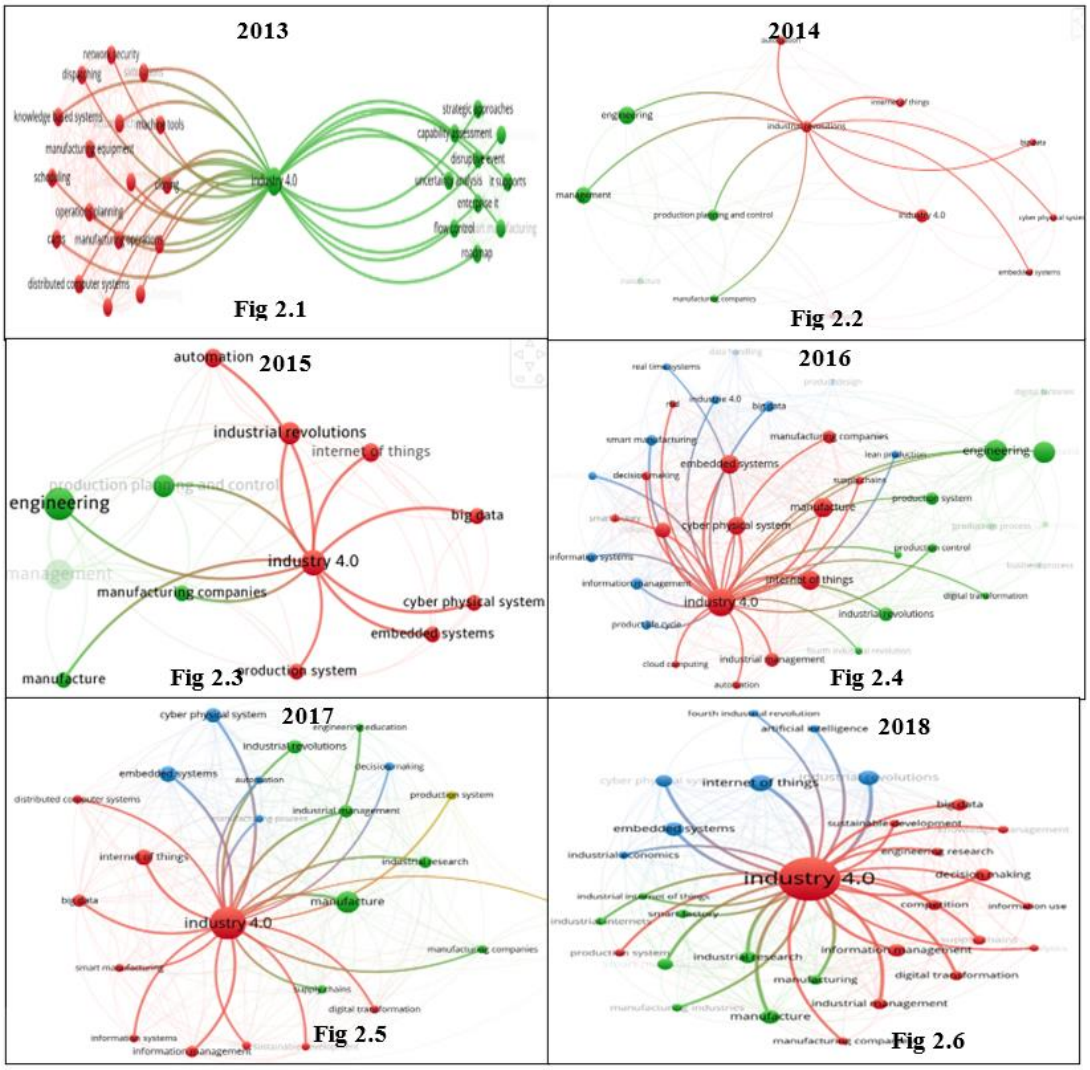

Figure 2 Keywords' clusters for the years 2013 to 2018

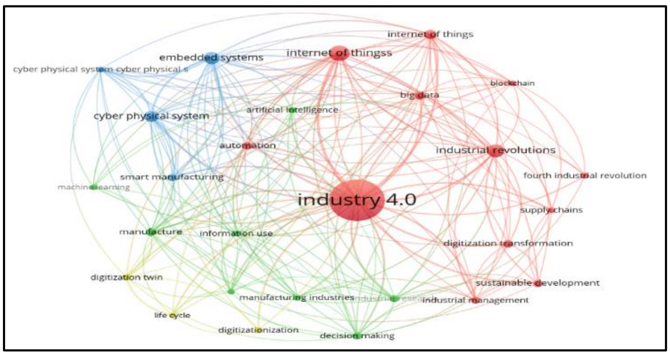

Figure 3 Keywords' clusters for the years 2019

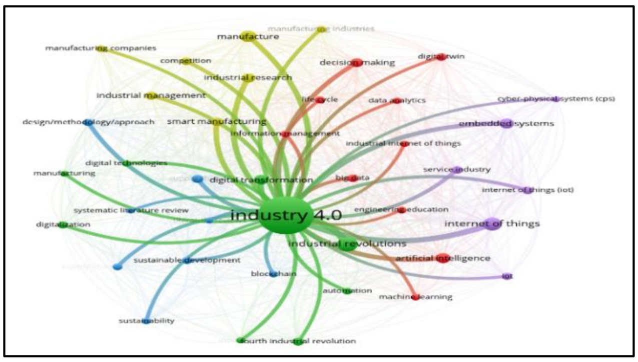

Figure 4 Keywords' clusters for the years 2020

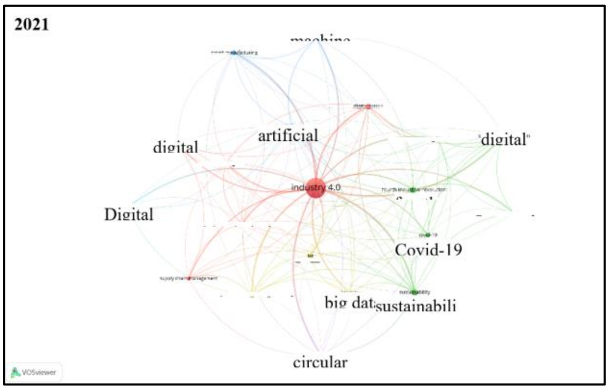

Figure 5 Keywords' clusters for the years 2021

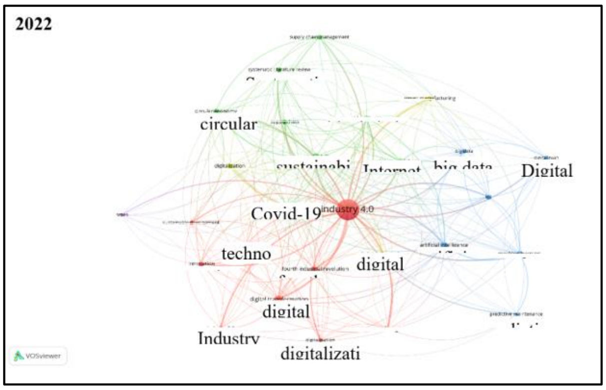

Figure 6 Keywords' clusters for the years 2022

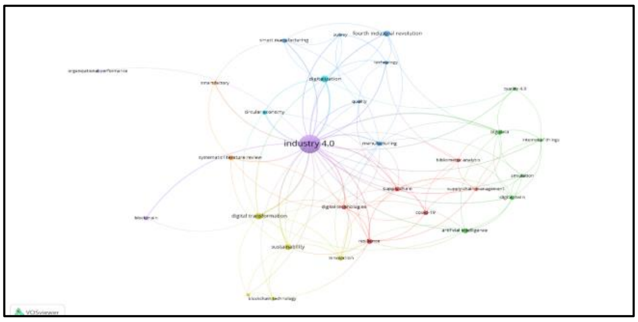

Figure 7 Keywords' clusters for the years 2023

Table 1 below presents the year-wise account of the most important and influential keywords relating to Industry 4.0. It represents the year of first appearance; for example, 'IT support' and 'Enterprise IT' first appeared in 2013 and continued to be important areas in the coming years. Similarly, 'smart contracts' was first used only in 2019. Thus, the table helps identify the general trend of research every year based on the new keywords. It is interesting to observe that in the initial years of research, Industry 4.0 found application in processes such as support systems, transportation, etc., while in the later years, focus on sectors as a whole was evident, giving rise to terms like 'healthcare 4.0', 'transportation 4.0', etc. Post-Covid disruption the concept of Resilience with digital transformation was introduced.

Table 1 Chronological analysis of keywords

Year	Keywords
2013	IT support, enterprise IT, engineering, management, manufacturing companies, production planning and control, and smart manufacturing.
2014	Supply chain, RFID, big data, cyber-physical systems, security and privacy-related issues.
2015	Cloud-based computing.
2016	Digital transformation, additive manufacturing, agile manufacturing systems, project management, maturity model.
2017	Sustainable development in the supply chain, blockchain, artificial intelligence, machine learning, digital twin, augmented reality, 5-G, energy-aware manufacturing, wisdom manufacturing, and Lean 4.0.
2018	Embedded systems, IOT and CPS, cognitive systems, green computing, edge computing, drones, workforce 4.0, society 5.0, procurement 4.0, logistics 4.0, and human-machine interaction.
2019	Smart contracts.
2020	Construction 4.0, healthcare 4.0, maintenance 4.0, enhanced cognitive twins, net neutrality, port connectivity, COVID-19 pandemic.
2021	Industry 4.0, sustainability and fourth industrial revolution.
2022	Digital transformation, artificial intelligence and circular economy.
2023	Resilience, human-centricity.

4. COUNTRY-WISE ANALYSIS

Figure 8 presents the country analysis diagram in overlay format from 2013 to 2023. In the early years (2013), the maximum number of articles came from Germany. However, in the following years (2014, 2015) contributions from Italy, Spain and Ireland were also reported. This shows that more countries started taking interest in Industry 4.0. In 2016, authors from Germany, the United Kingdom, South Korea and India wrote 78 (1055 citations), 10 (40 citations), 2 (499 citations) and 3 (55 citations) documents respectively. It can be inferred that over the years more countries became aware of Industry 4.0 and various authors started collaborating internationally and writing about the impact and benefits of this global phenomenon. In 2017, authors from Germany, the United Kingdom, the United States and the Netherlands wrote 104 (1050 citations), 19 (1222 citations), 13 (1055 citations) and 3 (106 citations) documents respectively. In 2018, authors from Germany, the United States and the United Kingdom wrote 113 (889 citations), 36 (1646 citations), and 31 (684 citations) documents respectively. In 2019, authors from Germany published 106 documents, which was less than the previous year, receiving 564 citations. Following it were authors from Italy and Bangladesh who wrote 91 (612 citations) and 70 (40 citations) documents respectively. It can be inferred that although authors from Germany are still actively writing about Industry 4.0, authors from other countries have equally contributed to writing papers about Industry 4.0. In 2020, papers published by Indian authors (160 documents, 418 citations) surpassed those of German authors (136 documents, 520 citations) and authors from the United Kingdom (106 documents, 358 citations). New countries such as Iran and Pakistan also joined them. By 2020, authors from 118 countries, individually or collaboratively, published 1321 articles on Industry 4.0. Around 168 countries were present in 2021. The majority of authors were from China, with 241 documents that were cited 3208 times. India followed with 197 documents cited 2693 times. Other notable contributors were the United States (152 documents cited 3504 times) and Germany (161 documents cited 1448 times). There were 213 countries in 2022, and Indian articles were cited the most with 1382 times. India contributed approximately 310 articles. Other top countries included Italy (206 documents cited 641 times), China (247 documents cited 1504 times), and the United Kingdom (201 documents cited 1163 times). In 2023, 73 countries were highlighted. The maximum number of cited articles came from India, with 49 citations. The United Kingdom had 36 documents cited 47 times. Italy, China, and Germany also made a significant impact in this year. This shows that Industry 4.0 is no longer restricted to only developed countries. Many developing countries have started researching, reviewing and analyzing Industry 4.0.

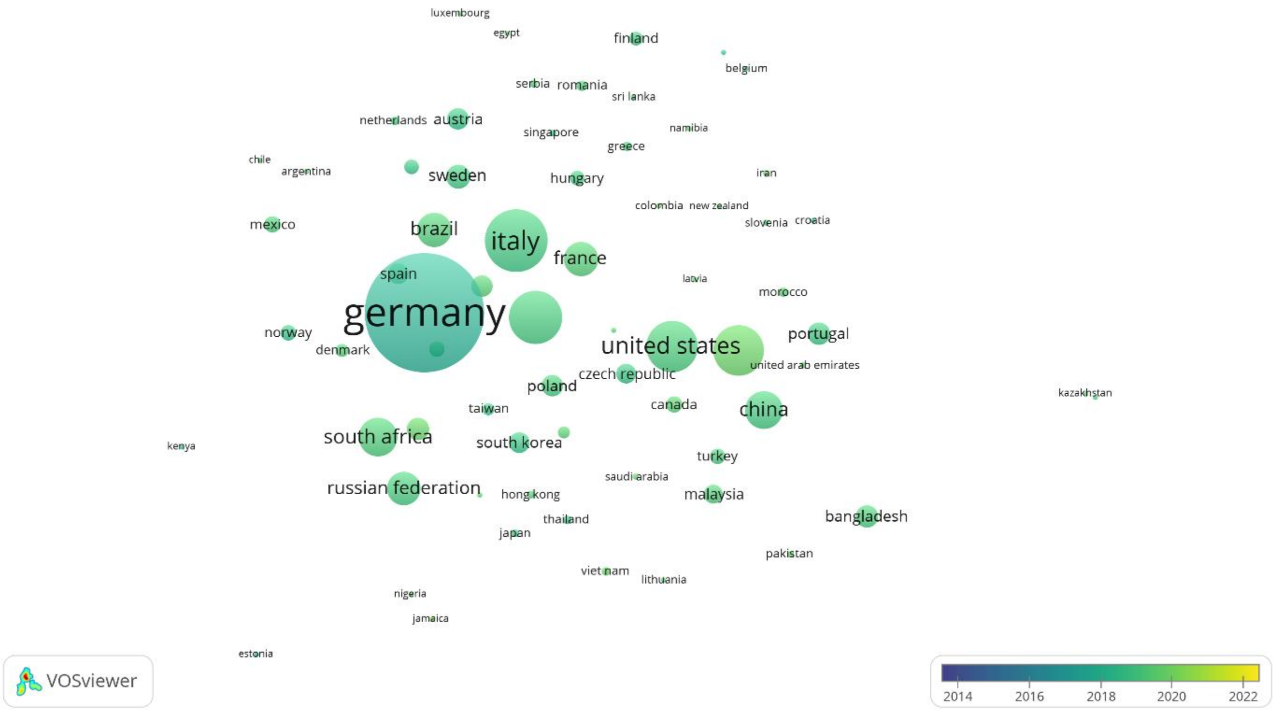

Figure 8 Country analysis

5. DISCUSSIONS AND IMPLICATIONS

This research was conducted with the motive of contributing meaningfully to the literature on Industry 4.0. The study makes its contribution by (1) highlighting and discussing influential works year-wise; (2) identifying knowledge groups while forming clusters of similar studies in the field; and (3) delineating earlier research while identifying future research opportunities. The implications derived from the bibliometric analysis are presented below:

1. The field has evolved from conceptualizing and defining the Fourth industrial revolution (in 2011–13) to incorporating multiple technological pillars of Industry 4.0 (in 2018–2023). **Figure 10** shows that the disruption caused by these new technologies has led to three parallel streams of research. The first stream focuses on advancement of manufacturing domain from automation□advanced manufacturing□smart manufacturing□additive manufacturing. The second stream focuses on development of integrative technologies from embedded systems□system integration□IOT□CPS. The third stream focuses on progression of data management technologies from information management□digitization□big data analytics□AI. These three streams together have culminated into an entirely new stream of research that utilizes Industry 4.0 forms of manufacturing, integration and data management systems in creating virtual models starting from simulation□ virtual reality□ augmented reality□block chain□digital twin that are used as decision-making models for complex business scenarios.

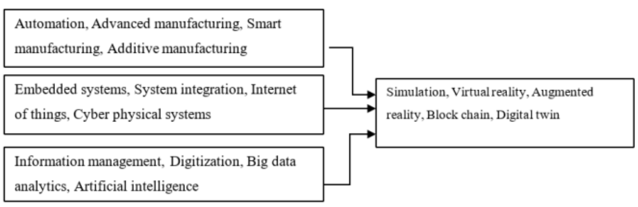

Figure 9 Streams of research in Industry 4.0

2. Careful evaluation of keywords clusters reveals that in the initial years (2013–2016), the focus of implementation of Industry 4.0 was only in the manufacturing sector. However, the clusters in the later

years (2018–2023) show that the Fourth industrial revolution has entered other service sectors, as evidenced by keywords such as pharma 4.0, tourism 4.0, society 4.0 and healthcare 4.0. Application of Industry 4.0 technologies in healthcare for fighting the COVID-19 pandemic, in enhancing supply chain resilience, and in sustainability are the evolving research areas. Furthermore, human-centricity is the budding research area popularised mainly in Industry 5.0.

3. Analyses of clusters at two different periods, 2013–2015 and 2016–2023, reveal the evolution of the intellectual design of the area. The period 2011–2015 marked the built-up phase of theory and concepts, and the scope of Industry 4.0 research was merely focused on equipment, production or manufacturing level. In the second period, the research expanded its focus to a holistic value chain level. Efforts were made to develop a scale to measure a firm's maturity (Industry 4.0 maturity models) and analyse human-machine interaction. Furthermore, Industry 4.0 research stretched its linkages to allied domains of operations management, as evident from keywords such as Lean 4.0, workforce 4.0, procurement 4.0 and maintenance 4.0.
4. Germany laid the foundation of Industry 4.0, leading to the inception of the fourth industrial revolution. It has also contributed the maximum to the body of knowledge. From the year 2016, authors from other developed countries such as Italy, the United Kingdom and the United States also started publishing in the Industry 4.0 domain. By 2023, authors from developing countries such as India, UK, Italy, South Korea and Bangladesh also contributed significantly.

6. FUTURE RESEARCH DIRECTIONS

Although scholars working under the Industry 4.0 umbrella have touched upon various domains in isolation, the results from the analysis clearly show that existing Industry 4.0 research is primarily derived from individual technology solutions. With the advent of large-scale data enabled by advanced technological infrastructure, there is a pressing need to integrate the data streams from these individual technologies to create a synergistic Industry 4.0 ecosystem. This integration will help address a broad spectrum of technology domains and transition from a shareholder to a stakeholder approach.

Industry 5.0, a term used to describe this shift, connects the avenues of sustainability, human-centricity, and resilience, facilitating the integration of all stakeholders for a more holistic and robust understanding of Industry 4.0 technologies. Accordingly, this section presents three promising research avenues along with potential research questions (see **Table 2** below).

Table 2 Research gaps and future research directions

No	Research Gap	Potential research questions
1	Develop a comprehensive understanding of Industry 4.0 by including diverse perspective	What are the different research directions in Industry 4.0 and the new related keywords?
2	Society/Customer-centric perspective	How can customer-centric needs be rapidly adopted in products and processes using Industry 4.0 technologies?
3	Value chain perspective	How can the value chain be reconfigurable to meet changing societal needs?
4	Enhance viability focus to incorporate sustainability in the business	How do Industry 4.0 technologies continuously innovate the products and processes with a focus on sustainability?
		How do Industry 4.0 technologies overcome the cost-benefit standpoint to include financial, digital and environmental barriers to include sustainability in business?
		How can Industry 4.0 technologies enhance the viability of circular supply chains?
5	Enhance reconfigurability of supply chains to increase service levels	How can digital twins be incorporated into diverse business scenarios, integrating synergies from advanced AI/ML technologies?
		How can Industry 4.0 technologies be coupled with human ingenuity to increase reconfigurability and flexibility in manufacturing systems?
		How can Industry 4.0 technologies be agile enough for multilevel enterprise adoption?
		How can industries can synergise operators' skills with advanced Industry 4.0 technologies to achieve mass customisation in resilient environment?

Develop a comprehensive understanding of Industry 4.0 by including diverse perspective

Research in the Industry 4.0 domain has predominantly adopted a shareholder approach, focusing only on the perspective of a single entity within the supply chain. To enable a holistic understanding of Industry 4.0, it is crucial to incorporate the perspectives of various supply chain entities for synergistic technology adoption efforts.

Society/Customer-centric perspective and Value chain perspective

Studies on Industry 4.0 have primarily addressed manufacturer concerns, aiming for cost-benefit gains by incorporating physical and digital technologies (Wiesner *et al.*, 2014; Röschinger *et al.*, 2015; Hurt *et al.*, 2017; Yao *et al.*, 2017). Few studies have considered customer-centric inclusion for Industry 4.0 adoption. Notably, the cluster of networks in **Figure 4** shows that the concept of organizational performance, which includes all supply chain entities, is not strongly connected with other themes.

Enhance viability focus in order to incorporate sustainability in business

Despite some successful implementations of Industry 4.0 technologies, real-life success stories are sparse. Studies have not sufficiently modelled financial performance, which directly influences the adoption of Industry 4.0 technologies for sustainable business. Environmental sustainability aspects have been introduced since 2020, as seen in **Figure 4**, and interest in this area has grown. However, the yellow cluster representing sustainability is not integrated with the strong green cluster of Industry 4.0 technologies (See **Figure 4**). Moreover, although circular supply chains have gained attention due to societal interest and financial value, their cluster remains aloof and not strongly connected with the Industry 4.0 technologies cluster. To achieve viable business, all entities should be interconnected with Industry 4.0 technologies, necessitating answers to the research questions presented in **Table 2**.

Enhance Reconfigurability of Supply Chains to Increase Service Levels

Bibliometric results show increased attention towards human-centricity and resilience in recent years, as seen in the keyword clusters of 2023 (**Table 1**). With increasing digitalization, customer voices are more prominent, leading to a shift from mass production to mass customization. Existing industrial infrastructure is inadequate for supporting mass customization, highlighting the need for reconfigurability in supply chains. Human skills, combined with advanced digital technologies, can address this need, as outlined in the research questions in **Table 2**.

Future research should focus on advancing human-centricity within Industry 5.0 by exploring the intersections between human-centricity and key operational domains. This paper underscores the transformative potential of integrating advanced technologies with human ingenuity. Future research should aim to integrate technological innovation with concepts of supply chain resilience and sustainability in the new era of Industry 5.

7. CONCLUSION

The present study conducted an in-depth, year-wise analysis of Industry 4.0 literature using bibliometric tools. It engaged in an integrative review of the Industry 4.0 domain using keywords, citations and co-citations analyses. A detailed year-wise keywords cluster analysis highlights the evolution of the intellectual structure of Industry 4.0. Furthermore, it identifies the most significant studies, influential authors, and countries that have majorly contributed to the body of knowledge of Industry 4.0.

Our analysis of the literature reveals that research in the Industry 4.0 domain has grown considerably and gained significant scholarly attention over the last decade, as evidenced by the increasing number of publications since 2011 (**Figure 1**). However, the domain is yet to reach its full maturity, as many questions remain unanswered, such as how long it would take Industry 4.0 to enter the less developed countries or the stage of implementation, they are currently in. Furthermore, many companies are uncertain about the financial investment required for implementing the Industry 4.0 technologies and their monetary impact on business strategies; hence, an effective roadmap for the implementation of various new Industry 4.0 technologies needs to be planned.

The bibliometric review of Industry 4.0, analyses and implications presented in this paper will provide a starting point for new researchers to explore multiple research directions in Industry 4.0. Scholars can also explore possible applications of Industry 4.0 on the social and environmental fronts, including the circular economy.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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