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Mapping the intellectual structure of Industry 4.0, circular economy, and sustainable performance: A bibliometric review of knowledge evolution, emerging themes, and future research directions

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ABSTRACT

Objective: Research at the nexus of Industry 4.0, the circular economy (CE), and sustainable performance (SP) has gained considerable momentum within the broader fields of industrial transformation and sustainable development. To address this gap, the present study systematically maps the intellectual structure underlying the convergence of Industry 4.0, CE, and SP, identifies major thematic clusters, pinpoints structural deficiencies in the literature, and outlines promising directions for future inquiry.

Methodology: A bibliometric analysis was conducted using VOS viewer software on 741 articles indexed in the Scopus database from 2016 to 2026, covering eight analytical dimensions.

Results: Keyword co-occurrence analysis shows that SP holds a central, highly connected position within the knowledge network. Accordingly, the existing literature frequently examines SP in tandem with Industry 4.0 and CE frameworks, typically treating SP as an outcome of adopting Industry 4.0 technologies and implementing CE practices.

Conclusion: The analysis reveals notable knowledge voids concerning "reverse logistics" and "smart manufacturing". Conversely, "social sustainability," "digital product passport," and "Industry 5.0" emerge as rising research trends. Scientific collaboration analysis further indicates that the United Kingdom plays a pivotal role in the international research cooperation network within this field.

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Introduction

Over recent decades, growing global concern over natural resource depletion, greenhouse gas emissions, and climate change has elevated sustainability to a central pillar of organizational strategy. Organizations must embrace a comprehensive, long-term approach integrating economic, social, and environmental dimensions—commonly referred to as the triple bottom line (Elkington, 1997). Rooted in the Brundtland Report, sustainable development emphasizes meeting present needs without compromising future generations' ability to meet their own needs (Brundtland & Mansour, 2010). In this context, "sustainable performance" reflects an organization's ability to maintain dynamic balance across these three dimensions over the long term. However, the traditional linear economic model—based on "extraction, production, consumption, and disposal"—has led to widespread resource depletion and environmental degradation, making its continuation environmentally unsustainable and economically unviable.

The circular economy (CE) has been proposed as a transformational approach to sustainability. Rooted in the 1970s, CE seeks to create a regenerative economic system where product, component, and material value is preserved, keeping material flows in closed cycles (Dwivedi & Madaan, 2020). Unlike linear economics, CE is based on "cradle-to-cradle" logic and emphasizes 10R strategies to reduce virgin resource extraction, minimize waste generation, and increase material and energy efficiency throughout the product life cycle (Kirchherr et al., 2017).A circular economy can be considered a closed-loop system where material and energy flows return to production through multiple cycles, leading to new business models, job opportunities, and increased economic resilience (Han et al., 2023). Many countries and international organizations are now formulating policies to facilitate this transition.

Simultaneously, extensive technological developments in production and industrial management—known as "Industry 4.0"—have emerged. First coined in 2011 as a German strategic initiative, I4.0 refers to the fourth industrial revolution, characterized by advanced digitization, cyber-physical systems integration, and intelligent connectivity of equipment and processes (Hofmann & Rüsch, 2017; Sung, 2018). I4.0 relies on technologies including IoT, big data analytics, AI, blockchain, additive manufacturing, and cloud computing (Han et al., 2023; Rizvi et al., 2023) Unlike Industry 3.0, which focused on automating individual machines, I4.0 emphasizes intelligent integration of the entire value chain, enabling real-time data collection, predictive decision-making, optimized resource consumption, and increased process quality and flexibility(Bourghani Farahani et al., 2026).

I4.0 technologies enable sustainability goals: IoT and big data allow real-time monitoring of energy and material consumption, reducing waste and optimizing processes (Rajput & Singh, 2019). AI optimizes production planning and resource allocation (Frank et al., 2019). Blockchain facilitates recycling and reverse logistics through supply chain transparency

(Hosseini Dehshiri & Amiri, 2026; Kouhizadeh et al., 2021). Additive manufacturing reduces material waste and enables custom production (Khan & Ali, 2022). Cloud computing provides coordination infrastructure (Kamble & Gunasekaran, 2023). Thus, I4.0 operationalizes CE principles through an intelligent digital platform, and their synergy is proposed as a complementary approach to promote sustainable performance.

A review of previous studies shows that existing research has examined parts of the relationship between CE, digital technologies, I4.0, and SDGs; however, limited studies simultaneously analyze the knowledge structure of CE, I4.0, and sustainable performance (SP) from a bibliometric perspective. Most available studies focus on one dimension (e.g., CE-AI, CE-digital technologies, or CE-SDGs), resulting in limited attention to their integrated convergence as a coherent research area. With emerging concepts such as Industry 5.0, Digital Product Passport, and Social Sustainability, examining new research trends is increasingly necessary. In response, this study uses bibliometric analysis and VOSviewer to examine 741 Scopus-indexed articles (2016-2026) through keyword co-occurrence, country co-authorship, journal bibliographic coupling, author co-citation, document co-citation, annual publication trends, and subject area analysis. The study aims to map the intellectual structure, identify thematic clusters, examine scientific collaboration patterns, and reveal emerging research trends through four research questions.

RQ1: What is the intellectual structure of the I4.0-CE-SP field based on keyword co-occurrence and document co-citation analyses, and what are the most important thematic clusters and their fundamental resources?

RQ2: What is the position and relevance of different concepts in the knowledge network, and which concepts and authors are more prominent in terms of scientific impact and network communication?

RQ3: What are the patterns of international cooperation, geographical distribution, and core journals, and which countries and journals play pivotal roles?

RQ4: What is the evolution of research topics, emergence of new concepts, and interdisciplinary characteristics of the I4.0-CE-SP field during 2016-2026?

Materials and Methods

The authors employed a bibliometric approach, widely recognized as one of the most objective methods for exploring emerging research trends, particularly when integrating different conceptual domains (Paul & Criado, 2020). Bibliometric methods provide a structured, systematic, and repeatable approach to evaluating research areas, offering a clear framework for quantifying publication patterns, identifying thematic clusters, and mapping scientific collaboration networks. Although bibliometric methodology dates back to the 1950s, the development of analytical software such as VOS viewer has dramatically expanded its application in interdisciplinary fields.

Figure (2) presents the general framework and research stages: In the first stage, bibliographic data were collected and refined from Scopus. In the second stage, data were prepared for analysis and visualization in VOS viewer. The third stage included bibliometric analyses across multiple levels. Finally, findings were interpreted to identify the knowledge structure, emerging trends, less developed areas, and future research directions.

Data Collection Strategy

The Scopus database was selected for its broader coverage in sustainability and industrial management. The search covered title, abstract, and keywords of articles published from 2016 to 2026, with data extracted on February 21, 2026. The search strategy was designed around three thematic clusters with comprehensive terminology covering synonyms and related concepts:

Cluster 1 (Industry 4.0 and digital technologies): "Industry 4.0" OR "Fourth Industrial Revolution" OR "smart manufacturing" OR "smart factory" OR "cyber-physical systems" OR "Internet of Things" OR IoT OR "artificial intelligence" OR AI OR "machine learning" OR "big data" OR "big data analytics" OR blockchain OR "additive manufacturing" OR "3D printing" OR "digital twin" OR "digitalization" OR "digital technologies" OR "cloud computing" OR "advanced robotics"

Cluster 2 (Circular Economy): "circular economy" OR "closed-loop economy" OR "circular manufacturing" OR "resource circularity" OR recycling OR remanufacturing OR "reverse logistics" OR "waste management" OR "resource efficiency" OR "cradle-to-cradle" OR "industrial ecology"

Cluster 3 (Sustainability and Sustainable Performance): sustainability OR "sustainable performance" OR "sustainability performance" OR "sustainable development" OR "triple bottom line" OR "environmental sustainability" OR "social sustainability" OR "economic sustainability" OR "corporate sustainability" OR "sustainable production" OR "sustainable manufacturing" OR "sustainable supply chain" OR "cleaner production" OR "carbon footprint"

The final search equation combined these three clusters with the AND operator, initially identifying 1,061 documents. After applying inclusion criteria—restricting document type to articles, reviews, and conference papers, and language to English—741 articles were finalized for bibliometric analysis. The screening process, illustrated in Figure 1 (PRISMA-inspired framework), followed a sequential exclusion process: 147 non-article/non-review/non-conference records, 89 non-English records, 52 duplicates, and 32 irrelevant records were removed. The final dataset comprises 741 records (78.4% articles, 13.7% reviews, and 7.9% conference papers).

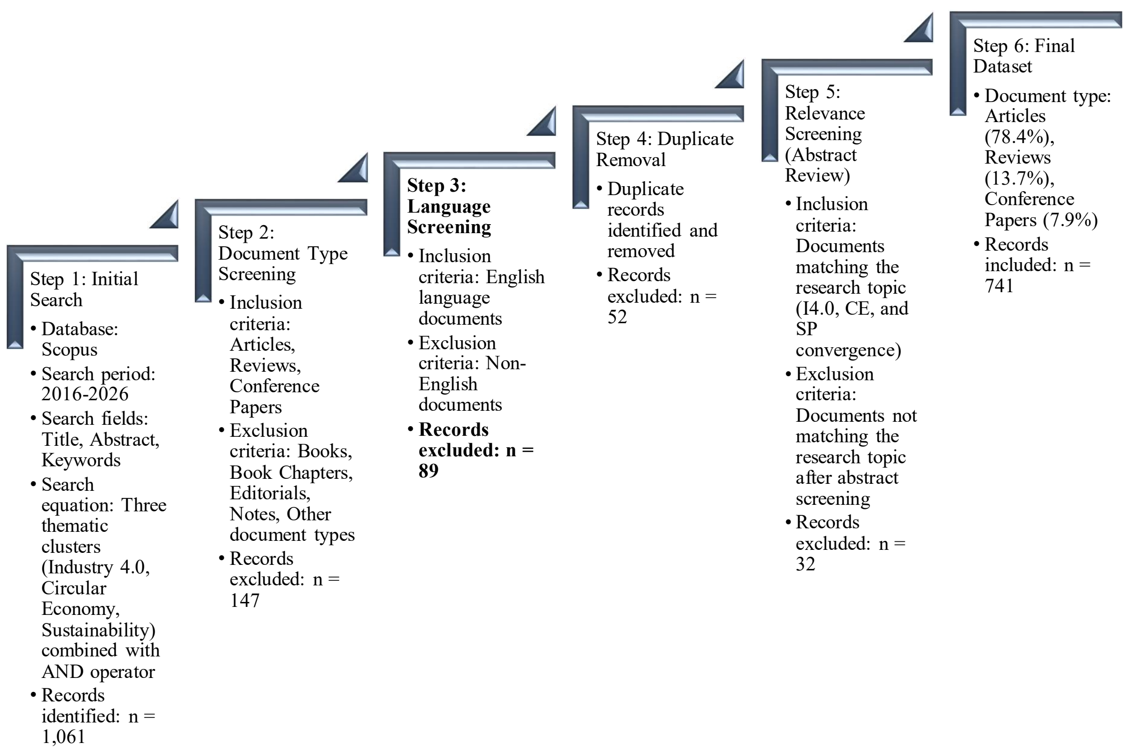

Figure 1. PRISMA-Inspired Flow Diagram of Document Screening Process

Data Output and Visualization

After extracting the data from the Scopus database, bibliographic information was stored in CSV and RIS formats to allow processing and analysis in specialized bibliometric software. In this study, VOSviewer software (version 1.6.20) was used to analyze and visualize scientific networks. Prior to analysis, bibliographic data underwent systematic cleaning and standardization. Author names were disambiguated using VOSviewer's thesaurus function, combining variants such as 'Bocken' and 'Nancy M.P.' into 'Bocken, N.M.P.', and similarly for other authors with multiple name variants. Publication sources were excluded from the author co-citation analysis, as this analysis is intended to examine citation relationships among individual authors rather than journals or proceedings.

Bibliometric analyses were performed at eight complementary levels. First, co-occurrence analysis of keywords was performed using the authors' keywords, the full counting method, and a minimum threshold of five repetitions to identify the conceptual structure of the field, thematic clusters, and the relationships between the concepts. Second, the co-authorship analysis of countries was carried out in order to investigate the patterns of international scientific cooperation and to determine the leading countries in knowledge production. Third, bibliographic pairwise analysis of journals was used to identify the core journals and evaluate the degree of intellectual closeness between scientific sources. Fourth, co-citation analysis of authors was performed in order to identify influential researchers and examine the thought structure formed based on common citation patterns. Fifth, the co-citation analysis of the documents was used to identify the fundamental references and reveal the knowledge foundations of the research field. Sixth, the annual trend of publication of articles was reviewed to determine the pattern of growth and development of the research field over time. Seventh, the distribution of thematic areas was analyzed to explain the interdisciplinary nature of this research field. Eighth, the analysis of document types was conducted to examine the structural characteristics of the literature.

The following parameters were applied for keyword co-occurrence analysis: Counting method: Full counting; Minimum occurrence threshold: 5 (selected to balance between capturing sufficiently frequent concepts and maintaining a manageable network size; this threshold was determined through sensitivity analysis, as reported in Supplementary Table 1); Normalization method: Association strength (default in VOSviewer); Clustering resolution: 1.00 (default value; sensitivity analysis with resolutions 0.80 and 1.20 yielded similar cluster structures); Minimum cluster size: 1; Random seed: Fixed seed for reproducibility; Thesaurus-based term merging: Synonyms and term variants were merged using a custom thesaurus file to ensure accurate representation of concepts. Sensitivity analysis using alternative thresholds (minimum occurrences of 4, 6, and 7) confirmed that the main cluster structure remained stable, with minor variations in the composition of smaller clusters. Detailed results of the sensitivity analysis are presented in Supplementary Table 1.

The results of these multilevel analyses provided a basis for identifying knowledge clusters, emerging trends, research gaps, and mapping potential paths for future research. Figure 2 shows the general framework of the research and the relationship between the different stages of analysis.

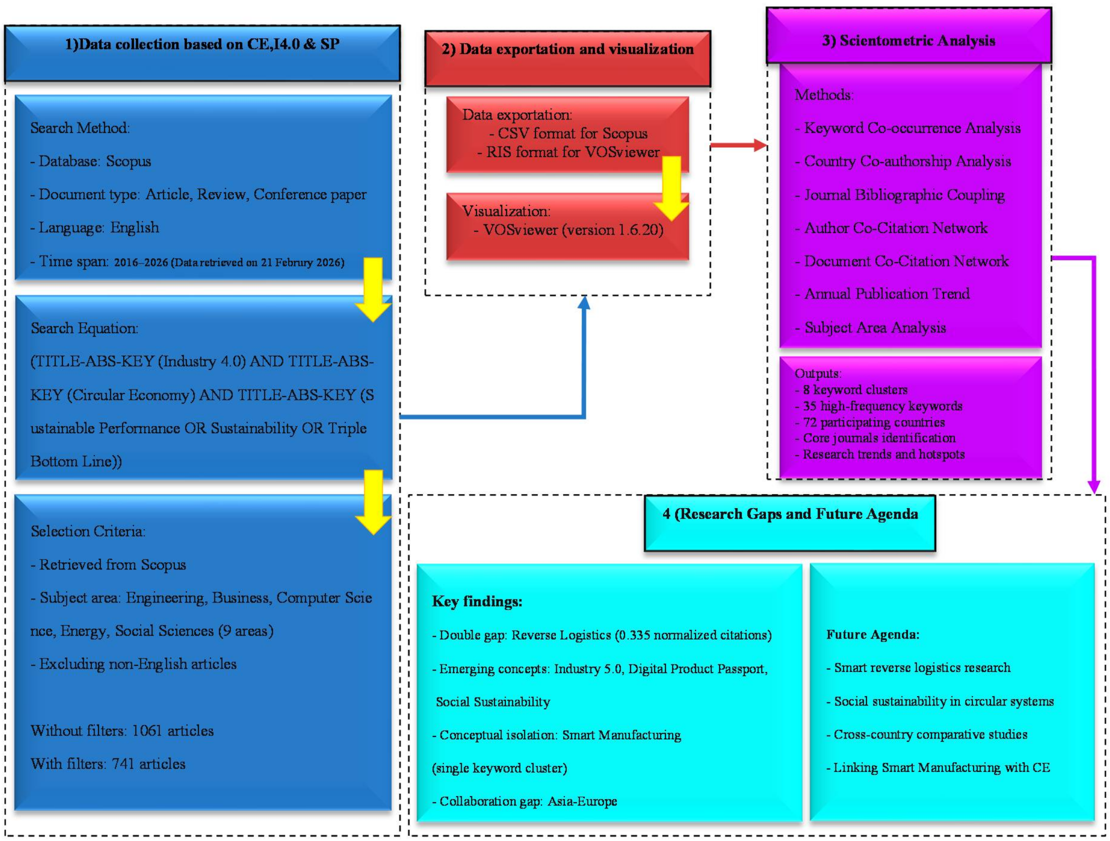

Figure 2. Methodological Framework of Research and Bibliometric Outputs

Detailed results of the sensitivity analysis are presented in Supplementary Table 1.

Table 1. Sensitivity Analysis Results for Keyword Co-occurrence with Different Thresholds

Threshold (minimum occurrences)	Number of keywords retained	Number of clusters	Key observations
4	48	9	Additional small clusters emerged; core structure remained stable
5	35	8	Main analysis (reported in manuscript)
6	28	8	Some minor keywords merged into larger clusters
7	22	7	Loss of some peripheral but relevant concepts

Results

Bibliometric Findings: Knowledge Structure and Research Trends

To understand the intellectual structure of the field of circular economy (CE), Industry 4.0 (I4.0), and sustainable performance (SP), Bibliometric analysis was performed at seven levels, which are described below:

Co-occurrence analysis of keywords

The conceptual structure of a research area can be examined through the keywords used by the authors. (Callon et al., 1983) state that words that often appear together tend to share a thematic relationship, making keyword co-occurrence analysis an effective tool for creating semantic maps that represent the cognitive structure of a research field.

This technique enriches thematic analysis derived from other methods, such as co-citation or bibliographic coupling. (Chang et al., 2015)note that these methods can sometimes identify overly general themes, whereas co-occurrence analysis allows for a more accurate understanding of thematic clusters. In addition, co-occurrence analysis helps interpret existing data and provides valuable insights into future research directions. In this study, co-occurrence analysis of keywords was performed to identify the main thematic clusters, relationships among concepts, and research gaps. The data of 741 articles extracted from Scopus were entered into VOSviewer software (version 1.6.20). Among 1,321 extracted keywords, 35 keywords had at least five occurrences and were categorized into eight clusters by the software. In addition to frequency, Table 2 also provides measures of total link strength, average year of publication, average citations, and normalized citation, which allows for a more detailed analysis of the maturity, impact, and emergence of each cluster.

Keyword Clustering in VOSviewer

Figure 3 shows the analysis of the most frequent keywords in 8 categorized clusters:

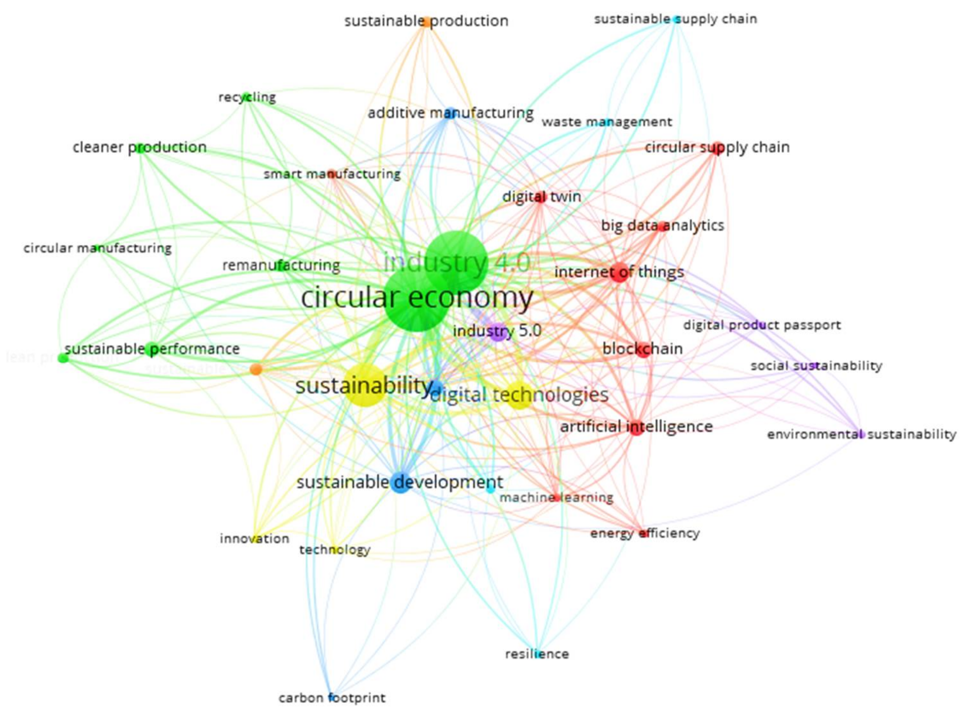

Figure 3. Keyword Co-occurrence Analysis

Table 2 presents the eight thematic clusters identified through keyword co-occurrence analysis, along with their constituent keywords and key bibliometric indicators—frequency, total link strength (TLS), average publication year (APY), and normalized citation score—enabling integrated assessment of each cluster's thematic composition and scientific impact.

Table 2: Final Co-occurrence Analysis of Keywords

Cluster	Dominant theme	label	weight<Total link strength>	weight<Occurrences>	score<Avg. pub. year>	score<Avg. citations>	score<Avg. norm. citations>	Preliminary analysis
Cluster 1	Digital technologies in the circular	artificial intelligence	109	33	2024.303	40.8485	1.1567	The simultaneous presence of IoT, Big Data, AI, and Digital Twin shows that this cluster encompasses a range of digital technologies from more established to newer technologies.
		big data analytics	56	16	2022.8125	119.375	1.324	
		blockchain	101	33	2023.5455	79.1515	1.7963	

Cluster	Dominant theme	label	weight<Total link strength>	weight<Occurrences>	score<Avg. pub. year>	score<Avg. citations>	score<Avg. norm. citations>	Preliminary analysis
	supply chain	circular supply chain	41	21	2023.619	35.5238	0.6383	
		digital twin	58	20	2024.45	14.45	0.44	
		energy efficiency	22	8	2023.625	31.125	1.2832	
		internet of things	126	47	2022.7872	89.4894	0.9894	
		machine learning	29	9	2024.2222	17.3333	0.7968	
Cluster 2	The core of integrating the circular economy, Industry 4.0 and sustainable performance	circular economy	999	510	2023.1784	54.6686	1.1173	The focus on the main keywords of circular economy, industry 4.0, and sustainable performance shows that this cluster constitutes one of the main foci of the literature in the field.
		circular manufacturing	17	7	2023.1429	17.8571	0.6097	
		industry 4.0	926	459	2023.0654	59.1699	1.1275	
		cleaner production	36	15	2022.3333	84.9333	1.33	
		lean production	38	15	2024.2	20.3333	1.2659	
		recycling	27	13	2022.3077	63.6923	0.7798	
		remanufacturing	46	17	2022.4706	36.1176	0.4635	
		sustainable performance	59	25	2023.68	62.36	1.7136	
Cluster 3	Sustainable Production and Carbon Footprint	additive manufacturing	45	18	2022.9444	66.1667	1.0568	The lower average publication year of Additive Manufacturing compared to other technologies indicates that the concept entered the literature earlier than some new technologies.
		carbon footprint	13	7	2023.2857	42	1.3319	
		sustainable development	124	57	2023.1053	61.614	1.2207	
		sustainable manufacturing	81	34	2023.1176	59.2941	1.3144	

Cluster	Dominant theme	label	weight<Total link strength>	weight<Occurrences>	score<Avg. pub. year>	score<Avg. citations>	score<Avg. norm. citations>	Preliminary analysis
Cluster 4	Technology and innovation in sustainability	sustainability	499	212	2023.2783	44.2217	0.8906	The difference between high frequency and average normalized citation of Sustainability shows that high frequency of a concept does not necessarily correlate with higher scientific impact.
		digital technologies	238	99	2023.6162	47.4545	1.5745	
		innovation	30	10	2023.6	33.5	0.7321	
		technology	25	10	2022.7	44.6	0.7598	
Cluster 5	Emerging Concepts: Industry 5.0 and the Digital Product Passport	environmental sustainability	20	10	2023.5	34.1	1.2144	The simultaneous presence of Social Sustainability and Environmental Sustainability reflects the increasing attention of research to various dimensions of sustainability within the framework of Industry 5.0.
		digital product passport	21	7	2024.8571	8.5714	0.4924	
		industry 5.0	107	44	2024.5227	17.25	1.0197	
		social sustainability	16	7	2023	56.1429	1.4305	
Cluster 6	Resilience, reverse logistics, sustainable supply chain and waste management	sustainable supply chain	20	9	2022.5556	103.1111	2.3211	Sustainable Supply Chain, despite its relatively low frequency, has the highest normalized citation among keywords, indicating significant scientific attention to the topic. In contrast, Reverse Logistics is at a lower level in terms of frequency and normalized citation and can be considered as one of the areas in need of research development.
		waste management	17	9	2022.5556	36.5556	0.8407	
		resilience	20	10	2023.2	47.5	1.2046	
		reverse logistics	35	11	2023.0909	16.2727	0.3358	
Cluster 7	Sustainable development and production	sustainable development goals	54	20	2023.25	59.7	1.0781	The limited number of keywords and their relatively low link strength indicate that this cluster is less connected to other parts of the network than the main clusters.
		sustainable production	24	14	2022.1429	131.3571	1.7916	

Cluster	Dominant theme	label	weight<Total link strength>	weight <Occurrences>	score <Avg. pub. year>	score <Avg. citations>	score<Avg. norm. citations>	Preliminary analysis
Cluster 8	smart manufacturing	smart manufacturing	33	12	2023.3333	112	0.858	The formation of this cluster around a single keyword indicates that Smart Manufacturing has a distinct communication pattern compared to other network concepts and its links to other clusters are more limited.

Cluster 1 (Red) - Digital Technologies in the Circular Supply Chain

This cluster comprises AI, IoT, Blockchain, Digital Twin, Machine Learning, and Big Data Analytics. IoT and Big Data Analytics represent established technologies with older average publication years, while AI, Machine Learning, and Digital Twin are emerging concepts. Blockchain demonstrates the highest scientific impact (normalized citation: 1.796), and IoT exhibits the strongest network connectivity (TLS: 126), highlighting their central roles in digital technology communication within circular supply chains.

Cluster 2 (Green) - The Core Integration of Circular Economy, Industry 4.0, and Sustainable Performance:

This cluster forms the intellectual backbone of the knowledge network, with 'Circular Economy' (510 occurrences, TLS 999) and 'Industry 4.0' (459 occurrences, TLS 926) serving as the most influential and highly connected concepts. The strong linkages around these two keywords indicate that most research has examined the role of I4.0 technologies in achieving CE goals. Sustainable Performance (normalized citation: 1.736) appears alongside CE, I4.0, Cleaner Production, and Lean Production, suggesting it is conceptualized as an outcome of implementing I4.0 technologies and CE practices, with its growing citation impact reflecting increasing scholarly attention.

Cluster 3 (Blue) - Sustainable Production and Carbon Footprint:

This cluster focuses on sustainable production and environmental impact assessment, with keywords including Sustainable Manufacturing, Sustainable Development, Carbon Footprint, and Additive Manufacturing. The lower average publication year of Additive Manufacturing (2022.94) suggests earlier entry into the literature and possible saturation. Sustainable Manufacturing serves as a key connecting concept (TLS: 81), while Carbon Footprint (normalized citation: 1.331) reflects research attention to measuring and mitigating environmental impacts of manufacturing activities.

Cluster 4 (Yellow) - Technology and Innovation in Sustainability:

This cluster encompasses broader concepts including Sustainability, Digital Technologies, Innovation, and Technology. Sustainability is among the most frequently used keywords (212 occurrences), while Digital Technologies exhibits the highest scientific impact in this cluster (normalized citation: 1.574). The cluster structure confirms that technology and innovation remain pivotal themes in sustainability-related studies.

Cluster 5 (Purple) - Emerging Concepts: Industry 5.0 and Digital Product Passport:

This cluster represents the latest research frontiers, featuring Industry 5.0, Digital Product Passport, Social Sustainability, and Environmental Sustainability. The Digital Product Passport is the newest keyword in the entire network (APY: 2024.85). The simultaneous presence of Industry 5.0 and Social Sustainability indicates a gradual expansion of research attention from technological efficiency toward human-centric and social dimensions of sustainability.

Cluster 6 (Turquoise) - Resilience, Reverse Logistics, Sustainable Supply Chain, and Waste Management:

This cluster addresses operational execution of circular supply chains, incorporating Reverse Logistics, Resilience, Waste Management, and Sustainable Supply Chain. Despite low occurrence frequency, Sustainable Supply Chain achieves the highest normalized citation score (2.321) among all keywords, indicating significant scientific impact. In contrast, Reverse Logistics records the lowest normalized citation (0.335), revealing a structural gap and critical need for further empirical development.

Cluster 7 (Pink) - Sustainable Development and Production:

This small cluster contains two keywords: Sustainable Development Goals and Sustainable Production. Sustainable Production demonstrates significant scientific impact (normalized citation: 1.791), while the relatively low TLS values (54 and 24) indicate limited connectivity with other network concepts, suggesting this cluster functions relatively independently.

Cluster 8 (Brown) - Smart Manufacturing:

This single-keyword cluster contains only Smart Manufacturing (12 occurrences, TLS: 33, normalized citation: 0.858). Its formation as an independent cluster indicates a distinct communication pattern compared to other topics. Despite the importance of smart manufacturing in I4.0 literature, its linkages with CE and sustainable performance concepts remain underdeveloped, representing a potential area for future research integration.

Co-occurrence map analysis of keywords based on overlay visualization

Figure 4 shows the co-occurrence map of keywords based on overlay visualization in VOSviewer software.

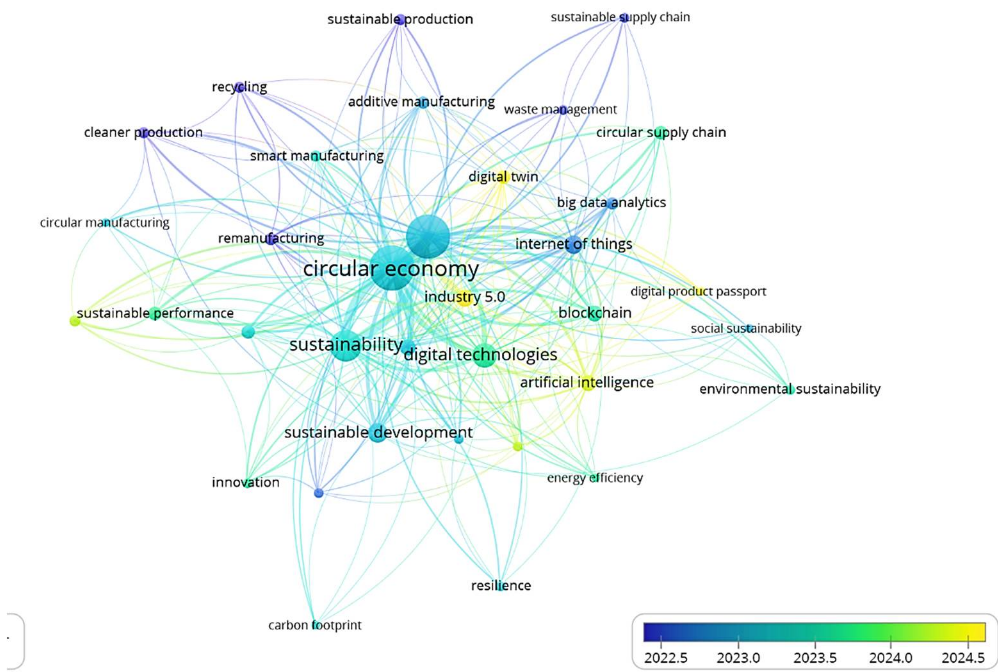

Figure 4. Overlay Visualization

In this map, the size of the nodes indicates the frequency of keyword occurrence, the thickness of the links indicates the intensity of the co-occurrence, and the color range from blue to yellow indicates the average year of publication of the keywords, so that the blue colors refer to the older concepts and the yellow colors refer to the newer concepts.

As illustrated in the figure, the keywords Circular Economy, Sustainability, and Digital Technologies reside at the center of the network, maintaining the highest volume of links with adjacent concepts. The coloration of these nodes' rests predominantly within the greenish-blue band, confirming that these themes have firmly established themselves as the core baseline of the I4.0-CE–SP literature over recent years. Conversely, in the newer zones of the network, keywords such as Artificial Intelligence, Digital Product Passport, Digital Twin, and Industry 5.0 are colored yellow. The more recent average publication years for these concepts reveal that contemporary academic attention has pivoted sharply toward intelligent technologies and next-generation digital solutions designed to operationalize the circular economy and elevate sustainable performance.

On the other hand, keywords such as Recycling, Cleaner Production, Sustainable Production, and Sustainable Supply Chain are placed in the peripheral parts of the network with bluer colors, which indicates the earlier presence of these concepts in the research literature. Despite their longer history, these concepts are still linked to the central core of the network through multiple links and play an important role in the development of the field's literature. Overall, the temporal overlay analysis shows that the evolution of research is moving from basic concepts related to cleaner production, recycling, and sustainable supply chain toward smart technologies, Industry 5.0, the digital product passport, and the social dimensions of sustainability. This trend indicates the gradual development of the field from operational and technological approaches toward more comprehensive perspectives in the circular economy and sustainable performance.

Density Visualization

In VOSviewer density visualization, yellow colors represent the points with the highest research density and blue colors represent the points with the lowest research density (Figure 5).

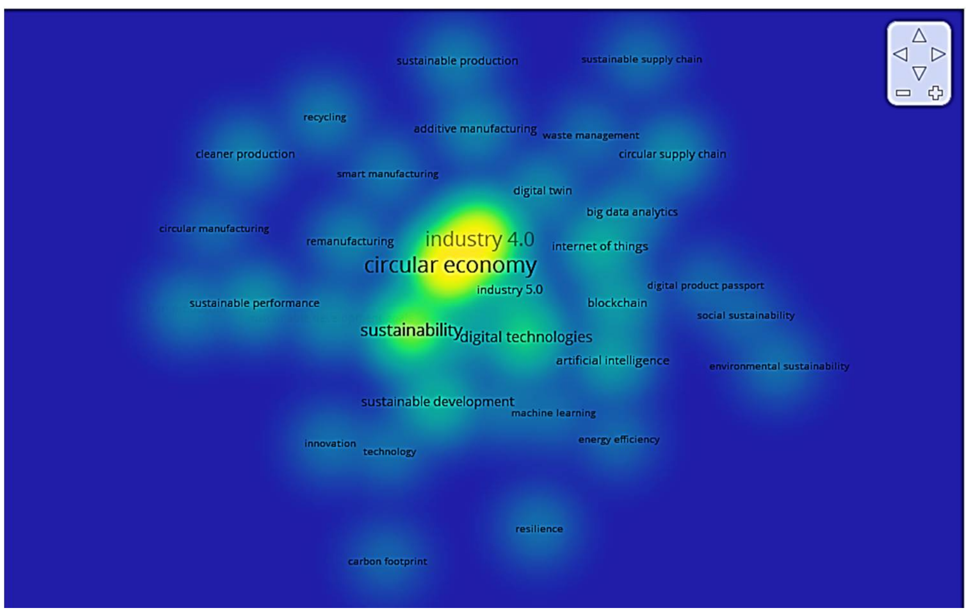

Figure 5. Density Visualization

The results of keyword density analysis show that most of the studies focus around the concepts of "Circular Economy", "Industry 4.0", "Sustainability", and "Digital Technologies", which are represented in bright yellow and green colors in the center of the map. This indicates that most of the research literature is devoted to the study of the interaction of the circular economy with Industry 4.0 technologies and its sustainability implications.

In contrast, concepts such as "Social Sustainability", "Environmental Sustainability", "Resilience", "Carbon Footprint", "Sustainable Supply Chain", and "Digital Product Passport" have been placed in areas with lower density. This model shows that although these topics are present in the knowledge network, the volume of studies related to them is smaller than the core of the field.

Annual Publication Trend Analysis

Based on the data extracted from the Scopus database and the output of the "Documents by year" analysis, the trend of publishing articles in the field of Circular Economy (CE), Industry 4.0 (I4.0) and Sustainable Performance (SP) in the period 2016 to 2026 (February 21, 2026) is as follows (Figure 6):

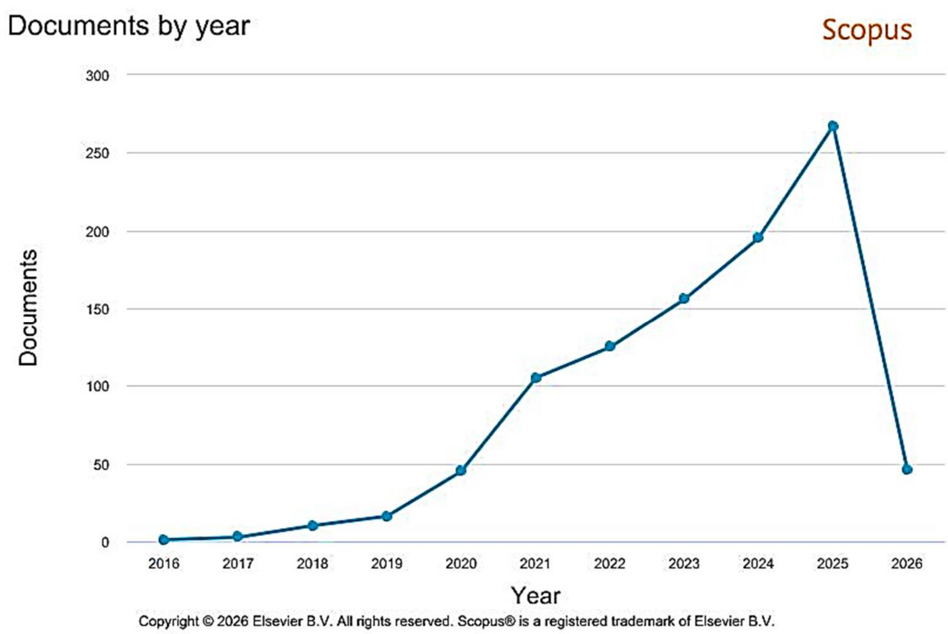

Figure 6. Annual Publication Trend

The publication trend (Figure 6) reveals a clear growth trajectory. Between 2016 and 2018, the field was in its infancy, with only a handful of studies exploring the link between sustainability, CE, and I4.0. From 2019 onward, however, publications surged—a reflection of growing academic and practical interest in this intersection. The upward momentum continued through 2023–2025, peaking in 2025, indicating that the field has matured into a well-established and active research domain. Although the 2026 data appear lower at the time of extraction, this simply reflects incomplete indexing rather than a decline in scholarly activity. Overall, the steady upward trend confirms that this interdisciplinary area has moved beyond its early stages and remains a vibrant and expanding field of study.

Country Co-authorship Analysis

The analysis of the co-authorship network of countries (Figure 7 and Appendix A) shows that the I4.0-CE-SP research area is global in nature and 72 countries have participated in its knowledge production. According to the data presented in Appendix A, India with 143 documents, the United Kingdom with 108 documents, and Italy with 87 documents ranked first to third respectively in terms of the number of documents.

It is noteworthy that the United Kingdom is a major hub for international cooperation. With a total link weight of 150 (the highest value among all countries) and having links with 45 other countries, it plays the role of a bridge between different geographical clusters. In terms of scientific quality, the United Kingdom ranks second after China (2.20) with a normalized citation of 1.59. The visualization of the co-authored network in Figure 7 shows the seven main clusters:

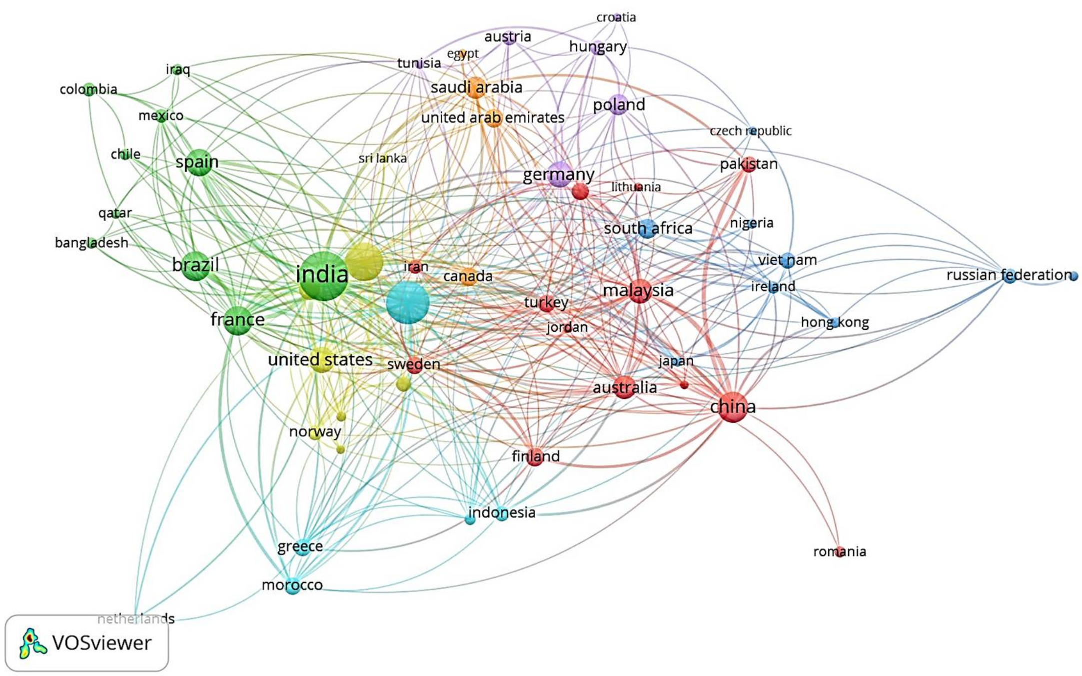

Figure 7. Country Co-authorship Analysis

Red Cluster: Includes China, Malaysia, Pakistan, Australia, Japan, Canada, Sweden, Turkey, and Iran. Iran is in this cluster with the weight of links 20 and 11 documents and has had the most cooperation with China and Malaysia.

Green cluster: Includes India (the most productive country), Brazil, France, Spain, Mexico, and Bangladesh. India's presence in this cluster, and not alongside the United Kingdom, reflects the country's pattern of independent cooperation. Despite the large presence of countries, cooperation between clusters is limited. As the only country in Cluster 6, the United Kingdom plays the role of a bridge between the clusters. This collaboration gap creates an opportunity for future research with a comparative inter-country approach.

Journal Bibliographic Coupling Analysis

The top 24 journals in the Scopus database are in Appendix B, respectively. With 71 articles, Sustainability has the highest number of articles published on the topic of sustainable performance, circular economy, and Industry 4.0. Journal of Cleaner Production ranked second with 47 articles and BUSINESS STRATEGY AND THE ENVIRONMENT ranked third with 45 articles. Table 3 presents the performance of these 24scientific journals.

A review of the publication trends of the top five journals (Figure 8) shows that the number of articles published in most selected journals has increased since 2020.

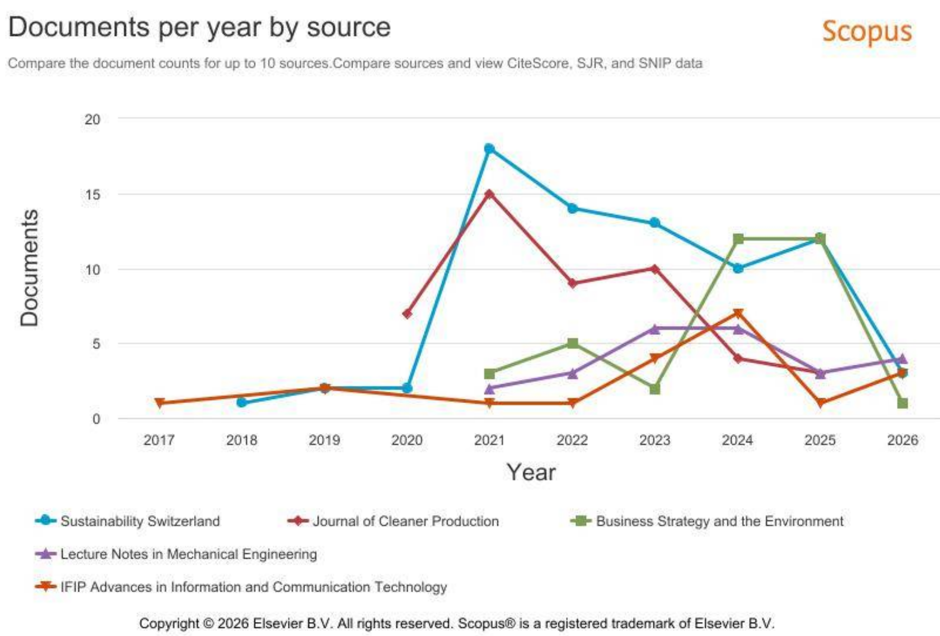

Figure 8. Number of Articles Published in 5 Journals in the Period 2016-2026

Journals such as Sustainability, the Journal of Cleaner Production, and Business Strategy and the Environment have had the largest share in the publication of articles in this field, although their publication rate also fluctuates in different years. The decrease in the number of documents in 2026 is due to this year's indexing being incomplete at the time of data extraction and should not be interpreted as a real reduction in research activity.

Table 3. Journal Bibliographic Coupling Analysis

label	cluster	weight<Total link strength>	weight<Documents>	score<Avg. norm. citations>
annals of operations research	2	143	6	1.98
business strategy and the environment	2	1106	35	1.79
computers and industrial engineering	2	275	11	2.2202
international journal of production economics	3	204	7	2.7252
journal of cleaner production	3	890	46	1.8849
production planning and control	3	229	9	2.2208
resources, conservation and recycling	3	88	10	1.6058
sustainability (Switzerland)	1	512	75	0.7233
sustainable production and consumption	2	296	10	3.1811
technological forecasting and social change	2	116	10	2.6858

Journal analysis reveals distinct patterns of scientific impact and knowledge dissemination. The Journal of Cleaner Production (46 documents, TLS: 890, normalized citation: 1.88) occupies a central position in the bibliographic coupling network, indicating its pivotal role in shaping knowledge flow. Conversely, Sustainability leads in publication volume (75 documents) but exhibits lower citation impact (0.72). Business Strategy and the Environment demonstrate strong scholarly influence (35 documents, TLS: 1,106, normalized citation: 1.79), while Sustainable Production and Consumption achieve the highest normalized citation rate (3.18) among peer-reviewed journals, underscoring the high scientific impact of its publications despite a smaller article count (Table 3).

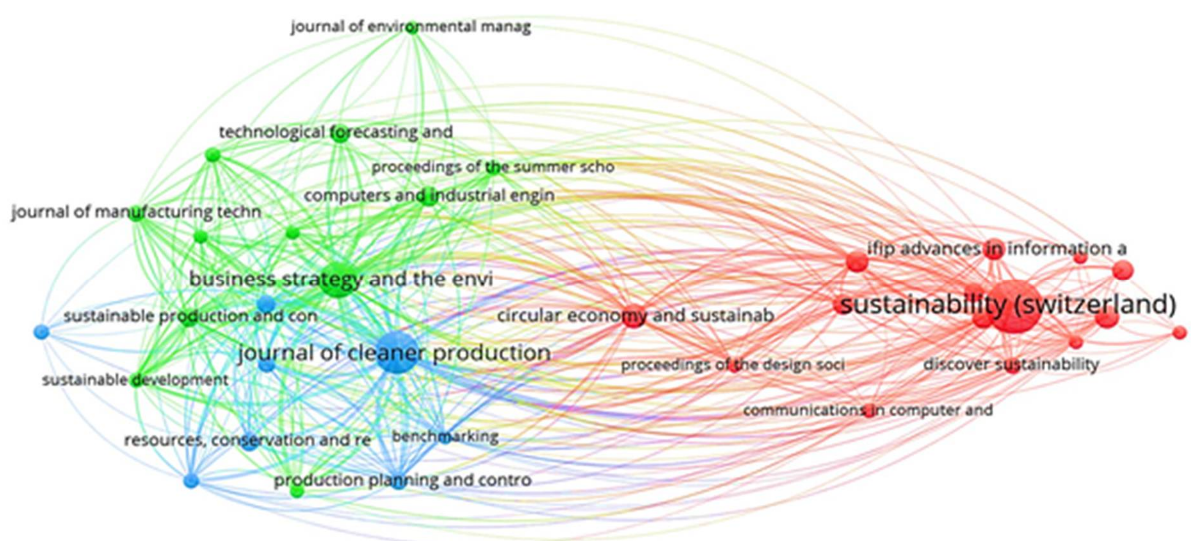

Figure 9. Visualization of Bibliographic Pairs Network of Journals

I Regarding citation impact, Sustainable Production and Consumption achieves the highest normalized citation rate (3.18) among peer-reviewed journals, indicating high scientific impact despite fewer publications. The bibliographic coupling network (Figure 9) reveals three main journal clusters: sustainability and digital technologies; management, strategy, and innovation; and sustainable production and resource efficiency. The high density of inter-cluster links and the central positioning of some journals confirm the interdisciplinary nature of I4.0-CE-SP research, demonstrating that thematic boundaries are not strictly segregated.

Author Co-Citation Analysis

To identify influential authors and the structure of scientific communication among them, co-citation analysis of authors was performed.

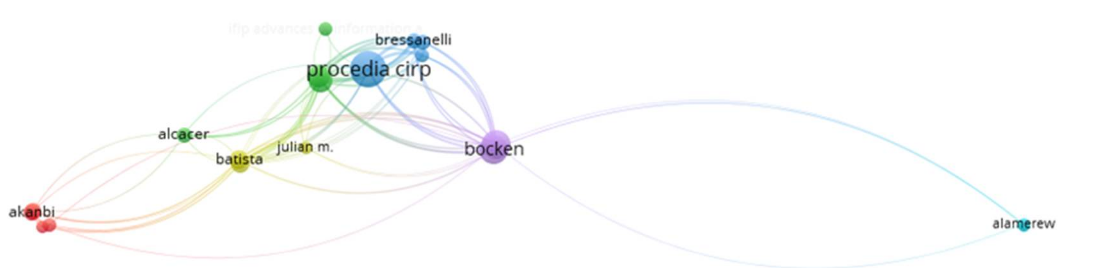

Figure 10. Co-citation network of authors in the field of Industry 4.0, circular economy and sustainable performance

The results showed (Figure 10) that the co-citation network consists of 19 authors and highly cited sources that are organized into six clusters. The total strength of network links is 509, which indicates significant citation connections among the reference authors in this field.

Table 4. Highly cited authors identified in authors' co-citation analysis

Author	Cluster	Total Link Strength	Citations
Adams	1	17	11
Akanbi	1	33	15
Alamerew	6	13	9
Alcacer	2	26	13
Antikainen, M.J.	2	89	29
Batista	3	58	21
Bocken, N.M.P.	5	104	47
Bressanelli, G.	4	67	14
Julian, M.	3	10	9
Luciano, C.	3	58	21
Richard, J.	1	15	10

In the second cluster, Antikainen and Maria J., with total link strength values of 89 and 29 and 31 citations, respectively, are considered the axial nodes of the network. The high number of links (11 links) and the significant communicative power of these authors demonstrate their prominent role in the thematic literature (Table 5).

In general, the results of the authors' co-citation analysis show that the citation structure of this field has been formed around a limited number of authors and pivotal sources. The high citation and link strength values for some nodes indicate their prominent role in the development and direction of research related to Industry 4.0, the circular economy, and sustainable performance. In addition, the existence of six distinct clusters indicates that the literature in this field consists of several related but distinct research streams that are connected to each other through citation relationships.

Document Co-Citation Analysis

To identify the central references and knowledge foundations of the field, co-citation analysis of documents was performed.

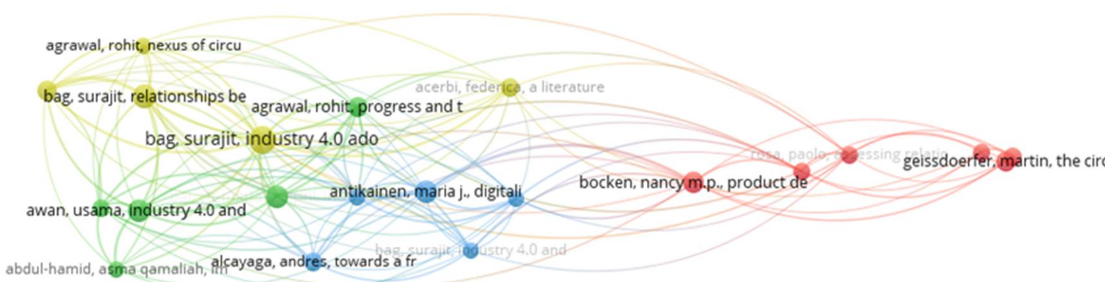

Figure 11. Co-citation network of influential documents and references

The results showed (Figure 11) that the co-citation network consists of 21 highly cited references that are classified into 4 clusters. The total strength of the network links is 278.

Bag et al. (2021) has the highest citation count (43) and total link strength (TLS = 73) in the co-citation network, serving as a pivotal reference connecting multiple research streams. Classical works—Geissdoerfer et al. (2017), Kirchherr et al. (2017), Ghisellini et al. (2016), Rosa et al. (2020), and Bocken (2016)—form a common cluster, reflecting close citation relationships. Overall, the field's intellectual development is anchored in a core set of highly interconnected references, with certain works exerting greater influence on research trajectories (Appendix C).

Subject Area Analysis

The distribution of thematic areas (Figure 12) shows that research related to the circular economy, Industry 4.0, and sustainable performance is interdisciplinary in nature.

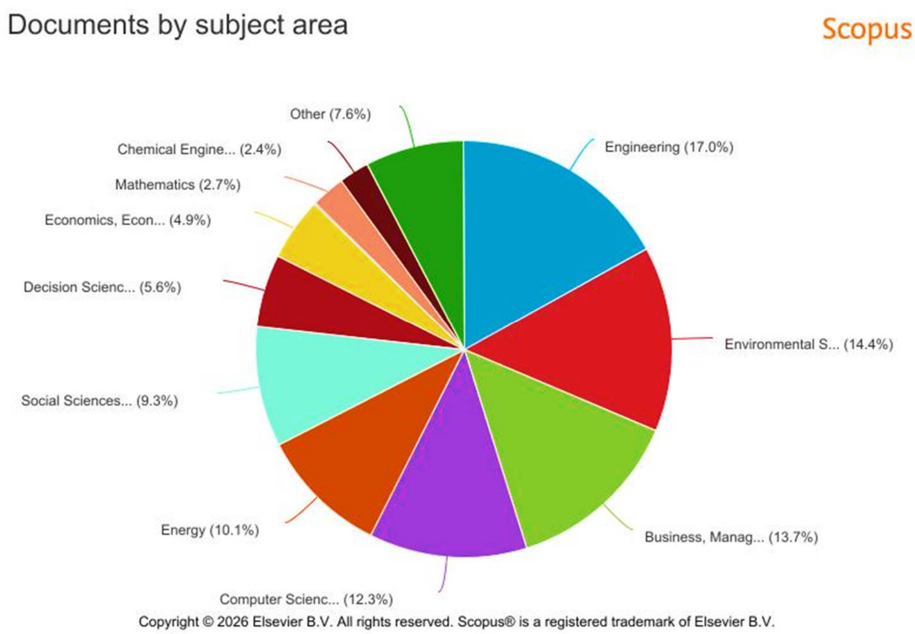

Figure 12. Subject Area Analysis

The distribution of subject areas (Figure 12) reveals that research on circular economy, Industry 4.0, and sustainable performance is inherently interdisciplinary. Although engineering holds the largest share of publications (17%), the considerable contributions from environmental sciences (14.4%), business, management and accounting (13.7%), computer science (12.3%), energy (10.1%), and social sciences (9.3%) indicate extensive interaction between this field and various scientific disciplines.

Document Type Analysis

The relatively high share of review articles (13.7%) along with a significant volume of research articles indicates that the literature in the I4.0-CE-SP field has passed the initial formation stage and has reached a level of development that allows for systematic review, classification, and integration of existing findings (Figure 13).

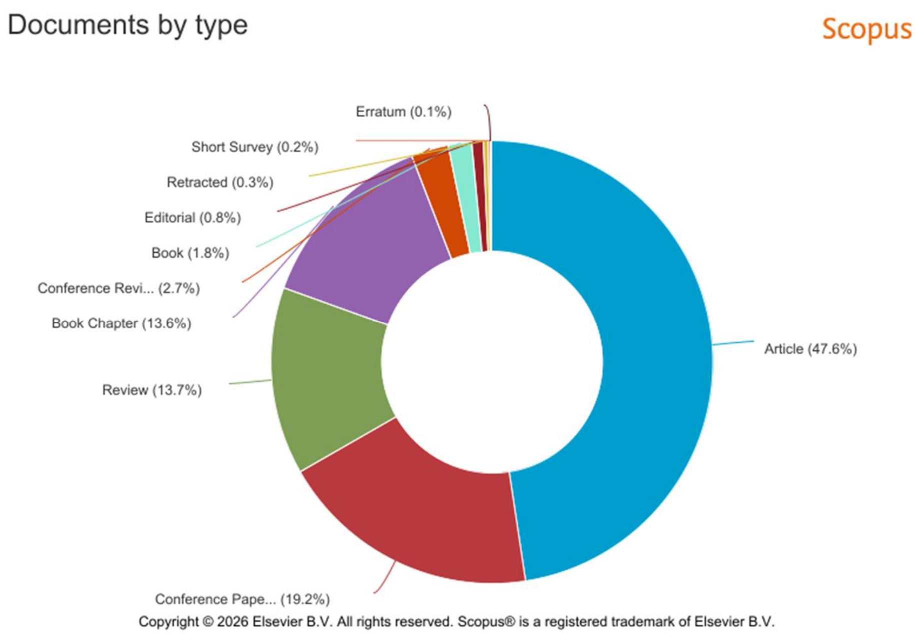

Figure 13. Document Type Analysis

Table 8 presents a summary of the most important Bibliometric findings of this research in 11 categories including frequent keywords, keyword gap, thematic structure, emerging concepts, low density points, temporal growth trend, leading countries, top journals, both authors' citations, and citations of documents and subject areas.

Table 6. Summary of Bibliometric Findings

Found category	Main finding
Frequent keywords	Circular Economy (510) ، Industry 4.0 (459) ، Sustainability (212)
Keyword gap	Sustainable Performance in Cluster 2 but not at the center; Reverse Logistics at the periphery (Cluster 6)
Thematic structure	The network is organized into 8 thematic clusters.
Emerging concepts	Industry 5.0, Digital Product Passport, Social (Sustainability Cluster 5 Purple)
Low density points	Reverse Logistics ،Social Sustainability ،Resilience
Growth trend	The number of articles has been on an upward trend from 2016 to 2025.
Leading countries	India (143), England (108), Italy (87); England is the main hub of cooperation with 45 countries
Top magazines	Sustainability and the Journal of Cleaner Production are the most important journals in the field.
Co-citation of authors	Identifying 18 highly cited authors and sources in 6 clusters; Procedia CIRP had the most citations and Bocken and Nancy M.P. had the highest total link strength.
Co-citation of documents	Identification of 21 highly cited references in 4 clusters; Bag et al. (2021) has the highest citation rate with 43 citations and in terms of total link strength (TLS), this article has the highest link strength in the network with a value of 73.
Subject areas	Engineering (17%), Environmental Sciences (14.4%), Business, Management and Accounting (13.7%), Computer Science (12.3%)

Discussion

In recent years, bibliometric studies have become one of the important approaches for understanding knowledge structure, conceptual evolution trends, and identifying research gaps in interdisciplinary fields. In the area of the circular economy and Industry 4.0, several research works have been conducted with the aim of identifying research trends, key technologies, and future development paths. In addition to identifying dominant concepts, bibliometric analyses make it possible to examine how connections among concepts, scientific actors, and knowledge streams are formed(Donthu et al., 2021).

This study employs bibliometric methods and VOSviewer to investigate the convergence of CE, I4.0, and sustainable performance. The results indicate significant growth over the past decade, establishing this as an interdisciplinary and mature research field.

Temporal Evolution of Key Concepts

The overlay visualization reveals a clear evolutionary trajectory within the I4.0-CE-SP research field. Concepts with earlier average publication years—Sustainable Production (2022.14), Recycling (2022.30), Cleaner Production (2022.33), Remanufacturing (2022.47), and Sustainable Supply Chain (2022.55)—indicate that initial research focused on operational CE strategies and resource recovery. Early digital technologies entering the literature included IoT (2022.78), Big Data Analytics (2022.81), and Additive Manufacturing (2022.94).

Subsequently, core concepts—Industry 4.0 (2023.06), Circular Economy (2023.17), Sustainable Development (2023.10), and Sustainable Manufacturing (2023.11)—positioned themselves at the network's center. Their high occurrence (CE: 510, I4.0: 459) confirms these as the field's primary pillars. More recent concepts like Blockchain (2023.54), Digital Technologies (2023.61), Circular Supply Chain (2023.61), and Sustainable Performance (2023.68) reflect an expanding focus on digital applications. The newest developments—Machine Learning (2024.22), AI (2024.30), Digital Twins (2024.45), Industry 5.0 (2024.52), and Digital Product Passport (2024.85)—signal a shift toward intelligent systems, human-centricity, and life-cycle tracking.

In summary, the field has evolved from operational CE concepts toward smart technologies and emerging themes, reflecting a maturation beyond efficiency toward sustainable value creation through advanced technologies.

Comparison with previous studies

Previous studies in this domain (see Appendix D) follow three methodological categories: SLR studies (Han et al., 2023; Magnano et al., 2024), quantitative SEM-based studies (Karmaker et al., 2023; Kamble & Gunasekaran, 2023), and mixed-method studies (Godinho Filho et al., 2022). Despite their contributions, none have provided a macro-level picture of the field's knowledge structure.

Recent bibliometric studies (see Appendix E) have examined specific aspects—AI-CE relationships (De Lucas López et al., 2026), digital enablers (Tankova et al., 2026), CE-digital integration (Mansouri et al., 2026), and CE-I4.0-SDGs (Baca-Neglia et al., 2025). However, each has focused on a specific technology, application, or outcome rather than the integrated convergence.

Unlike previous studies limited to bilateral linkages (e.g., CE-AI), this study treats CE, I4.0, and SP as a unified knowledge domain. Rather than merely identifying thematic clusters, it employs four complementary indicators—frequency, TLS, APY, and normalized citation—to simultaneously assess each concept's network position, scientific impact, and temporal dynamics.

Previous studies emphasize digital enablers (Tankova et al., 2026) or propose conceptual frameworks (Mansouri et al., 2026), but they do not position sustainable performance as central nor analyze emerging concepts like Industry 5.0. This study uncovers structural gaps—revealing that reverse logistics and smart manufacturing, despite operational importance, exhibit limited connectivity and lower impact. Country co-authorship analysis, absent in most studies, illuminates international collaboration patterns.

This study addresses four gaps: (1) examining the triadic convergence of CE, I4.0, and SP rather than bilateral relationships; (2) employing four complementary indicators for simultaneous assessment; (3) providing comprehensive structural analysis including country collaboration, journal coupling, and knowledge gap identification; and (4) explicitly analyzing emerging concepts (Industry 5.0, Digital Product Passport) that previous reviews have overlooked.

A methodological note: the centrality of core concepts is partly influenced by the search design requiring 'Industry 4.0' and 'Circular Economy' terms for inclusion, so absolute centrality should be interpreted cautiously. Unlike empirical studies in Appendix D, this study does not examine causal relationships—an inherent limitation of bibliometric approaches focused on mapping knowledge structure and evolution. The principal distinctions lie in integrated examination of CE, I4.0, and SP as a single field; use of complementary indicators; in-depth conceptual analysis; and comprehensive mapping of relationships, trends, and intellectual structure.

Conclusion

This study set out to map the intellectual landscape at the intersection of Industry 4.0, the circular economy, and sustainable performance. Using bibliometric methods, we analyzed 741 articles indexed in the Scopus database, examining keyword co-occurrence, country co-authorship, journal bibliographic coupling, author co-citation, document co-citation, publication trends, subject area distribution, and document type analysis. This multi-faceted approach offers an integrated perspective on the field's intellectual architecture and how it has evolved over time.

Our findings indicate that the circular economy, Industry 4.0, and sustainability constitute the core of this knowledge domain. The overall network is organized into eight thematic clusters, spanning from digital technologies in circular supply chains to emerging concepts associated with Industry 5.0. Despite substantial progress in developing macro-level concepts, the I4.0-CE-SP literature still struggles to effectively bridge certain operational and implementation issues with strategic frameworks. For instance, concepts such as reverse logistics and resilience reside in the network's periphery, receiving less research attention than pivotal constructs. This pattern suggests that several operational dimensions of the circular economy have yet to be fully integrated into mainstream research on Industry 4.0 and sustainable performance.

The keyword co-occurrence analysis reveals that sustainable performance occupies a prominent position within the conceptual network, frequently appearing alongside Industry 4.0 and the circular economy, indicating it has become a central theme examined across numerous studies. Temporal overlay analysis reveals that the literature has evolved from focusing on infrastructure technologies (e.g., IoT, big data) toward smarter technologies (e.g., AI, digital twins) and subsequently toward emerging concepts such as Industry 5.0, the Digital Product Passport, and social sustainability, signaling a shift from technology-driven approaches toward human-centered, value-creating perspectives.

From a scientific cooperation standpoint, interactions between certain geographical clusters—particularly between Asian and European nations—remain limited. Journal analysis indicates that knowledge production is concentrated within a relatively small set of specialized journals. Author co-citation and document co-citation analyses confirm that the field has experienced substantial scientific growth, moving toward a more coherent understanding of digital transformation and sustainability linkages.

This research offers a comprehensive mapping of the I4.0-CE-SP knowledge structure by identifying thematic clusters, conceptual relationships, and key actors. By combining indicators of frequency, link strength, average publication year, and normalized citation, it pinpoints underdeveloped areas and future research opportunities while providing empirical evidence of emerging concepts such as Industry 5.0, the Digital Product Passport, and social sustainability.

Future research should prioritize the following directions, each addressing specific gaps identified in our analysis: First, intelligent reverse logistics deserves greater scholarly attention given its lowest normalized citation score (0.335) among all concepts, despite its operational importance. Future studies should investigate how Industry 4.0 technologies can enhance reverse logistics efficiency and integration with circular supply chains. Second, social sustainability within circular systems requires further investigation given its peripheral network position. Research should examine the social implications of the CE–I4.0 transition, including labor conditions, skill requirements, and social equity. Third, strengthened cross-country collaboration is needed, particularly between Asian and European research clusters, to identify contextual factors influencing CE–I4.0 implementation across different institutional settings. Fourth, deeper investigation of linkages among smart production, the circular economy, and sustainable performance is warranted, as smart manufacturing formed an independent cluster with limited connections to CE and SP concepts. Fifth, methodological advancement is required to examine causal relationships among I4.0 technologies, CE practices, and SP through empirical studies using quantitative methods.

In addition to its theoretical contributions, this study offers practical implications for managers. The peripheral position of themes such as resilience and reverse logistics suggests these areas remain underutilized despite their strategic importance. Managers should invest in capabilities strengthening supply chain resilience while advancing circular initiatives and recognize sustainability as a source of long-term competitive advantage through digitally enabled circular business models. Strategically aligning digital transformation with circular economy objectives may help organizations simultaneously enhance competitiveness and sustainability performance. While this study provides valuable insights, the findings should be interpreted in light of methodological limitations acknowledged in Section 6. The bibliometric approach is inherently descriptive, and research gap identification is based on indicators serving as signals rather than definitive evidence. Future research should employ complementary methods to validate and extend these findings.

Limitations and Future Research Directions

This study has several methodological limitations that should be acknowledged.

First, the analysis relies solely on Scopus-indexed articles. Including other databases like Web of Science could offer a more complete view of the field's intellectual landscape.

Second, restricting the search to English-language articles may have introduced linguistic bias. This is particularly relevant since leading countries in CE and I4.0—such as Germany, China, and Japan—may publish significant work in their native languages.

Third, the study focused on articles, reviews, and conference papers, excluding books and other scientific documents that can also shape research agendas and influence the direction of the field.

Fourth, the minimum threshold of five occurrences for keyword inclusion, while common in bibliometric studies, may have overlooked very recent but potentially impactful concepts that had not yet reached this frequency at the time of data collection.

Fifth, the 2026 data were extracted in February 2026, capturing only a portion of that year's publications. As more articles are indexed, both publication counts and citation patterns for 2026 are likely to change.

Sixth, the search strategy required at least one term from each thematic cluster, which may have influenced the centrality of core concepts. Future research could adopt more flexible search designs or validate findings using alternative databases and approaches.

Seventh, bibliometric indicators should be interpreted with care. Low frequency, density, or normalized citation scores may reflect factors like publication year or document type rather than genuine scholarly neglect. Complementary methods—such as systematic literature reviews, expert surveys, or case studies—are recommended to validate the research gaps identified here.

Despite these limitations, the systematic design of the search strategy and the use of four complementary criteria—frequency, total link strength, average publication year, and normalized citation—support the validity and reproducibility of our findings.

Despite these limitations, the robustness of our findings is supported by a systematic search design and four complementary bibliometric criteria, and future research can build on this by diversifying data sources, document types, keyword thresholds, and temporal validation.

Data Availability Statement

The *raw* bibliographic data were extracted from the Scopus database. Due to licensing restrictions, the raw data are not publicly available. The processed data and VOSviewer output files are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT for language editing, grammar checking, and improving readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendix A-E: Supplementary Tables

Supplementary material related to this article can be found online at https://cdn.imgurl.ir/uploads/w145576_Appendix_A-E.pdf