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REVIEW PAPER

Clustering the Research at the Intersection of Industry 4.0 Technologies, Environmental Sustainability and Circular Economy: Evidence from Literature and Future Research Directions

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Abstract

Digital technologies may enable the adoption of Circular Economy models in production and consumption processes, thereby promoting environmental sustainability. Literature on these topics has grown exponentially over the last decades, focusing on the adoption of Industry 4.0 technologies and its implications for environmental sustainability or circularity. However, extant literature reviews failed to cover the vast amount of literature produced, since they either have a narrow scope or focus on a limited sample of articles. To fill this gap, a bibliometric literature review was carried out on a sample of 1002 scientific articles on Circular Economy, Industry 4.0 technologies, and environmental sustainability. Descriptive statistics are coupled with a cluster-based analysis to provide a comprehensive coverage of the broader subject matter. Eight research clusters have been identified, with two general clusters (linkages between Industry 4.0, Circular Economy, environmental sustainability) and six topic-specific clusters (Big Data analytics for supply chain circularity, circular and sustainable additive manufacturing, urban sustainability, sustainable circular and digital (re)manufacturing, blockchain and data integration for a sustainable Circular Economy, miscellaneous and sectorial applications). Clusters are discussed in terms of research themes, methodologies, technologies, and circular strategies. Finally, a research agenda is drafted, pointing out six cluster-specific and four more transversal research directions. Hence, this research offers a detailed and quantitative overview of the research landscape, helping researchers and managers in understanding past contributions, assessing current standings, and identifying future directions of the research at the intersection of Industry 4.0 technologies, environmental sustainability, and Circular Economy.

Keywords Bibliometric literature review · Circular economy · Digital technologies · Environmental Sustainability · Industry 4.0

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Introduction

To address the environmental challenges posed by the current production and consumption model, Circular Economy (CE) posits a new economic system wherein resources are reused, remanufactured, and recycled to create new products and services. In this context, Industry 4.0 (I4.0) technologies can facilitate the implementation of CE strategies and increase environmental sustainability. The amount of scientific literature on CE, I4.0 technologies and environmental sustainability has grown exponentially in recent years. Previous studies have linked I4.0 with the CE. For instance, a comprehensive theoretical and practical review has been conducted on the smart circular economy (CE) paradigm, explicitly linking the technical mechanisms of I4.0 technologies with CE operational strategies [1]. Further discussions have explored the design and implementation of circular manufacturing processes, emphasizing the integration of CE with I4.0 technologies [2, 3]. Previous literature has also investigated the linkages between I4.0 and sustainability, specifically focusing on sustainability performances, sustainability practices, and the influence of several moderating factors [4, 5]. Similarly, earlier literature studied the linkages between CE and sustainability, examining similarities and differences and their interrelationships at micro, meso, and macro levels [6, 7]. However, previous reviews in the field of CE, I4.0 and environmental sustainability have focused either on a limited number of papers or have a narrow scope, addressing specific aspects or technologies such as circular or sustainable business models, organizational barriers, and enablers for CE and sustainability implementation, without providing comprehensive coverage [8–10]. Therefore, the objective of this paper is to structure the vast amount of literature dealing with I4.0 technologies and CE or environmental sustainability, to identify how these knowledge streams have developed. The aim is to identify the main research themes and topics investigated, as well as to spot research gaps and define future research directions. Given the vast number of articles that have been written on these topics, a bibliometric review approach has been employed to achieve the research objective. Bibliometric literature reviews are a powerful tool for monitoring the evolutionary progress within a research field. This is achieved by analyzing the underlying structures and connections between different topics using the bibliographic coupling technique. This approach allowed to identify emerging thematic clusters within the field and determine a set of future research direction. The remainder of the paper is structured as follows. The next Section provides the background and explains the motivation of this study. Then, the methodology is outlined in the subsequent Section. Descriptive statistics are presented in the fourth Section, while bibliometric network and cluster analysis are reported in the fifth Section. Section 6 elaborates a list of future research directions. Lastly, the final Section concludes the review by summarizing key findings and their implications for the field.

Theoretical Background

Environmental Sustainability, Circular Economy, and Industry 4.0 Technologies

The concept of sustainability is defined by the Brundtland commission [11] as a "*development that meets the need of the present without compromising the ability of future generations to meet their own needs*". Within the broad domain of sustainability, the focus of this research has been narrowed down to environmental sustainability. This aspect emphasizes the importance of maintaining ecological balance and minimizing environmental impact by reducing resource consumption and waste generation across the entire supply chain [11]. In this context, CE is an economic model based on a restorative and regenerative approach, which aims to minimize resource input, waste generation, and energy leakage by slowing, closing, and narrowing material and energy loops, thereby replacing the end-of-life concept with the principles of reduce, reuse, and recycle [12–15]. It involves the reengineering of many aspects of production and consumption systems to separate ecological activity from resource depletion.

Scientific literature recognizes I4.0 technologies as enablers for the transition towards CE to achieve environmental sustainability. Broadly speaking, I4.0 can be seen as a paradigm shift that involves the digital transformation of industrial value chains, connecting different physical devices that continuously interact and exchange information not only between machines but also between humans. Several technologies are often included under the I4.0 umbrella, although their classification is challenging due to different perspectives adopted by scholars in various disciplines [16]. These technologies are transforming production and consumption systems, enabling companies to increase efficiency and reduce costs. One of the most mentioned I4.0 technologies is Internet of Things (IoT), a network of connected devices that communicate with each other and share data. IoT can be used to track and optimize resource usage, reduce waste, and enhance energy efficiency [17]. Big Data analytics, instead, refers to the storage, analysis, and interpretation of large and complex data sets. Big Data analytics provide insights into resource usage and product lifecycles, enabling companies to identify opportunities for resource optimization and circular practices development [18]. For example, the analysis of errors and failures during product usage can enhance green product development practices. Additive manufacturing based on 3D Printing allows for the creation of complex and customized products, reducing scraps and enabling local production [19]. This technology can also reduce the need for transportation and storage of goods, further enhancing environmental sustainability. It also supports the creation of closed-loop systems by allowing the use of recycled materials within manufacturing processes [20]. Blockchain is a secure and decentralized system for recording transactions. It can be used to track supply chain activities, improving traceability, ensuring product authenticity, and enhancing the transparency and security of goods [21]. Cyber-physical systems integrate physical and virtual components to monitor and control manufacturing processes. This technology can optimize resource usage and enable more efficient and precise manufacturing processes to minimize waste through the monitoring of physical processes [22]. Cloud Computing allows the storage and analysis of massive amounts of data on remote servers. This technology can reduce the need for on-premises infrastructure such as computer hardware and enable the creation of virtualized environments that can be easily duplicated and shared [23]. This technology also enables on-demand use of information required by manufacturing, which enhances the processing capability of information and thus improves production efficiency [24]. Augmented Reality enhances the real world with digital information through the combination of real and virtual worlds, resulting in new environments for visualizations where physical and digital objects coexist and interact in real time. This technology facilitates the provision of maintenance and repair activities, reducing downtime and improving workers' safety [25]. Lastly, industrial robotics encompasses the deployment of robots in industrial environments for the purpose of automating tasks, enhancing efficiency, productivity, flexibility, to facilitate interactions with other machines, and ensuring safe collaboration with humans [26]. It can help strengthen CE by increasing efficiency and precision in sorting and disassembling materials for remanufacturing and recycling, thus reducing unsorted waste and promoting resource conservation [27].

Research Gaps and Motivations for this Research

To establish the research context, a preliminary analysis of previous literature reviews on CE, I4.0 technologies, and environmental sustainability has been conducted. As shown in Table 1, many existing reviews have a narrow scope compared to the objectives of this research, since they limit their focus on specific CE or sustainability aspects. For instance, Ejsmont et al. [5] explored the relationship between sustainability and I4.0 without addressing CE. Similarly, Korner et al. [8] concentrated only on a specific technology (additive manufacturing). Montag [10] studied sustainability, supply chain management and CE without including I4.0 in the search strings, although the application of I4.0 technologies in circular supply was suggested by the authors for future research. Heittarachchi et al. [20] focused only on quantitative methods adopted for investigating sustainable supply chains, and Olivera Neto et al. [28] narrowed down their discussion to the implementation of eco-efficiency tools. Khan et al. [29] carried out a thorough content-based analysis, although specifically focusing only on sustainable business models. In other cases, CE or environmental sustainability have been treated only as side or marginal topics in the discussion of results [16, 30, 31].

Therefore, this research expands upon these existing studies in multiple aspects, attempting to fill their limitations on: (i.) the lack of a simultaneous integration of CE, environmental sustainability, and I4.0 perspectives; (ii.) the limited scope of research and the tendency to focus only on specialized investigations (such as specific technologies, specific methods, or specific aspects), rather than providing a comprehensive coverage of the broader subject matter; and (iii.) the relatively small number of articles analyzed (with the notable exceptions of [7, 16, 31]), which limits the breadth and depth of the research. This research, indeed, aims to analyze the vast amount of literature that touched the connections among Industry 4.0 technologies, CE and environmental sustainability and understand their linkages at the broader level, as well as their interrelation mechanisms and under investigated research areas.

Materials and Method

Bibliometric analysis is a well-established and widely recognized literature review method, allowing to analyze and summarize large sets of articles while encouraging the generation of novel research concepts. It uses mathematical and statistical techniques to evaluate large quantities of bibliographic information [34]. This technique measures the interaction of various bibliographic information using widely accepted academic indicators such as the total number of publications, the number of citations received, h-index, and so on [35]. This study adopted two distinct forms of bibliometric analysis. The first one (‘research performance assessment’), examines descriptive characteristics such as country, institutions, journals, and articles distributions within a specific research domain. The second one (‘science mapping assessment’) identifies the pattern of progression, intellectual structure, and dynamic evolution of research fields in a specific area [36, 37].

Table 1 Literature reviews related to circular economy, sustainability, and industry 4.0 technologies

Article	Objective, scope, and topics investigated	Search database	Articles and period coverage	Methodology	Literature analysis	Limitations
Nikolaou et al. [7]	To explore the interrelations, parallels, and variances of CE and Sustainability through investigation at micro, meso, and macro dimensions	Web of Science; Scopus; Google Scholar	Not specifically mentioned (around 4,500 articles); From 2011 to 2021	Bibliometric review	Descriptive analysis	The analysis does not consider I4.0 and discusses no technological solutions for implementing CE and sustainability
Montag [10]	To examine theoretical conceptualization of circular supply chain and sustainability	Web of Science; Scopus	127 articles; From 2010 to 2022	Bibliometric analysis	Descriptive and network analysis	I4.0, though crucial, lacked specific discussion. From a bibliometric perspective, only a few articles were considered, and a distinct delineation between sustainability and circularity was absent
Korner et al. [8]	To examine the barriers of additive manufacturing through the lens of business model innovation and sustainability	Web of Science; Scopus	78 articles From 2006 to 2020	Bibliometric review	Descriptive and content analysis	The article's scope is technologically limited to additive manufacturing, and it is further limited by insufficient coverage of future scope

Table 1 (continued)

Article	Objective, scope, and topics investigated	Search database	Articles and period coverage	Methodology	Literature analysis	Limitations
Hettiarachchi et al. [20]	To conduct a bibliometric analysis on the literature pertaining to I4.0-driven operations and supply chains in the context of the CE	Web of Science	414 articles From 2003 to 2020	Bibliometric review	Descriptive analysis	The scope is limited to the application of quantitative methods in sustainable supply chain management, and a small sample size of 22 was used for the cluster analysis
Ejsmont K. et al. [5]	To evaluate the relationship between sustainability and Industry 4.0	Scopus	162 articles From 2012 to 2017	Bibliometric review	Descriptive and network analysis	CE is treated as a side topic. Limited number of articles included in the bibliometric analysis
Neto et al. [28]	To evaluate the adoption of I4.0 in conjunction with CE and eco efficiency tools to accelerate sustainability	Web of Science; Scopus Emerald	122 articles From 2003 to 2019	Bibliometric review	Descriptive analysis	The objective is narrowed down to the use of eco-efficiency tools
Khan et al. [29]	To explore the implications of I4.0 by looking at three core topics: Triple Bottom Line, Sustainable Business Models and CE	Web of Science; Scopus IEEE explorer; ProQuest	81 articles From 2012 to 2020	Systematic literature review	Descriptive and content analysis	The analysis does not include bibliometric results

Table 1 (continued)

Article	Objective, scope, and topics investigated	Search database	Articles and period coverage	Methodology	Literature analysis	Limitations
Ghobakhloo et al. [16]	To examine the concept, scope, definition, and functionalities of Industry 4.0, along with its implications for sustainability	Web of Science; Scopus	745 articles From 2014 to 2020	Bibliometric review	Descriptive analysis	Sustainability and CE are not included in search criteria; rather they are only discussed as side topics during the analysis
Wu et al. [31]	To examine the role of AI, BC and IoT to advance sustainability in three specific contexts (Smart city, energy system, and supply chains)	Web of Science	960 publication From 1996 to 2020	Bibliometric review	Descriptive and thematic analysis	CE is not considered in this review. The article adopted a narrow perspective in terms of technology investigated (only Artificial intelligence, Blockchain, and IoT)
Tavares-Lehmann and Varum [30]	To understand the interrelationship between I4.0, Sustainability and CE to promote a shift towards green economy	Web of Science	393 articles From 2015 to 2021	Bibliometric review	Descriptive analysis	This article is an editorial piece that considers CE as a side and marginal topic, lacking a research agenda
Abideen et al. [32]	To investigate the advantages of I4.0technologies in influencing circular supply chains and circular business models	Web of Science	96 publication From 2010 to 2021	Bibliometric review	Descriptive analysis	Sustainability is overlooked in this analysis since the focus is only on circular supply chains and business models

Table 1 (continued)

Article	Objective, scope, and topics investigated	Search database	Articles and period coverage	Methodology	Literature analysis	Limitations
Hettiarachchi, Brandenburg et al. [33]	To conceptualize the integration of Additive Manufacturing and CE	Web of Science; Scopus	51 articles From 2012 to 2020	Systematic literature review	Content analysis	The technological perspective is limited to additive manufacturing. The analysis does not include bibliometric results

Literature Search, Identification, Screening, and Inclusion

The PRISMA framework is employed for the systematic identification, screening, eligibility assessment, and inclusion of relevant literature [38]. A comprehensive overview of the process utilizing the PRISMA approach is outlined in Fig. 1, depicting the number of articles identified at each successive step.

First, relevant studies are identified through Scopus. A Boolean search was conducted on 'title-abstract-keywords' based on two group of keywords. The first group focused on 'Industry 4.0 technologies' and 'Digital Technologies' and included terms such as 'Internet of things', 'Cyber physical system', 'Cloud computing', 'Industrial robotics', 'Data analytics', 'Big Data', 'Additive manufacturing', '3D printing', and 'Industry 4.0'. The second

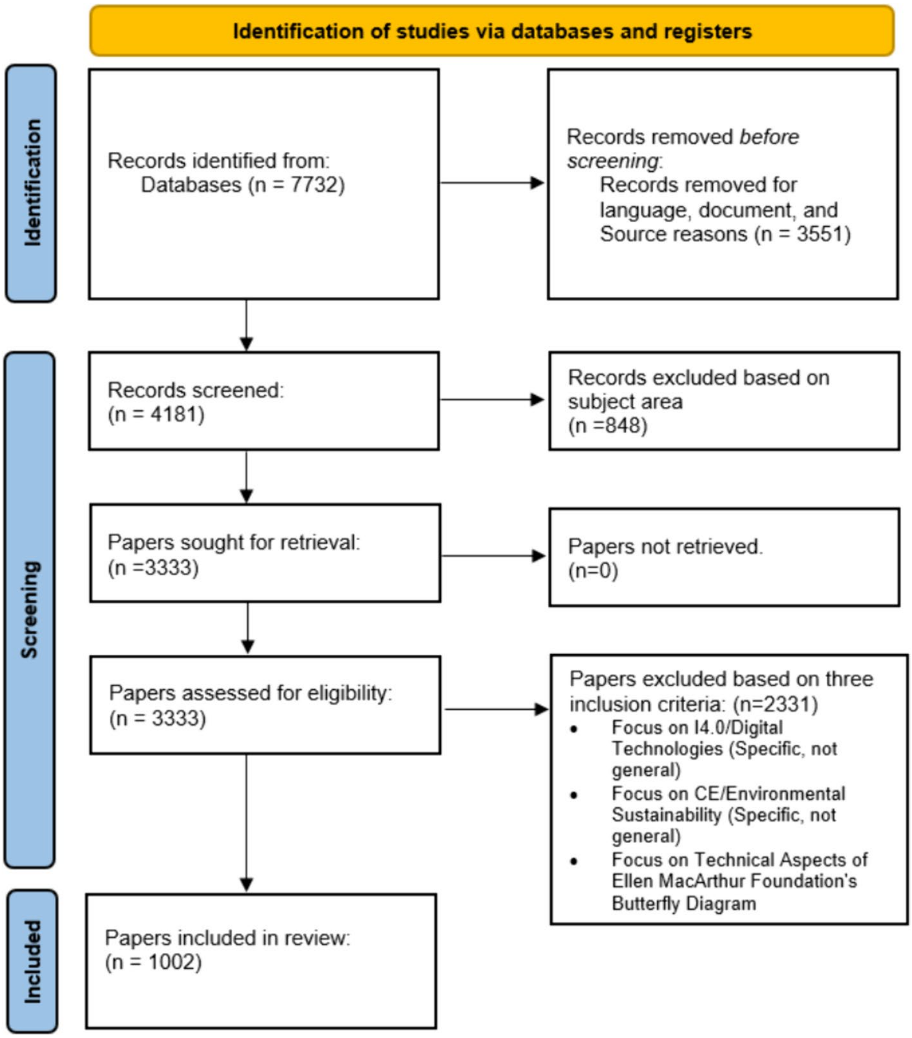


Fig. 1 Flow diagram for the selection of literature reviewed based on PRISMA

group of keywords was derived from 'Circular Economy' and 'Sustainability'. The search query led to extraction of 7732 records.

Then, a screening process was conducted to ensure the quality of the records. Authors excluded articles written in languages other than English. The results were further refined by focusing on scientific papers and restricting the selection to peer-reviewed journal articles and review papers, thus excluding books and conferences. Then, after narrowing down the subject area to engineering, business management, operations, services, manufacturing, decision science, interdisciplinary studies, and environmental science, a total of 3333 studies was selected.

Then, titles and abstracts were checked based on three inclusion criteria:

(i) The article must have a strict or specific focus on I4.0 technologies, digital technologies, or Industry 4.0, rather than discussing these topics in general terms.
(ii) The article must have a strict or specific focus on CE or environmental sustainability, rather than discussing these topics in general terms or merely acknowledging sustainability or CE as a relevant trend or theme.
(iii) The article must focus on the technical side of the Ellen MacArthur Foundation's Butterfly Diagram [12]. This side aims to retain the value of technical products, components, and materials at the highest value, encompassing processes such as reuse, repair, remanufacturing, and recycling.

The articles that matched all three of these criteria were chosen for further study. The final set includes 1002 articles.t

Descriptive, Bibliometric, and Thematic Analyses

The total of 1002 articles have been analyzed utilizing bibliometric analytic tools and techniques. All bibliographic information, including abstracts, keywords, citation details, funding information, and other relevant data, was recorded and exported in a.csv format. A MS Excel database was created to maintain and organize the data throughout the review process and facilitate quantitative evaluation of each article. The data was reviewed by two different authors for collaborative re-examination of the papers, aiming to track disagreements and verify the analysis. Biblioshiny, an R-based bibliometric software that accepts BibTeX or plain text format input from Scopus, was used for bibliometric analysis. This software offers statistical analysis and data visualization tools. To visualize and analyze the database, the authors employed VOS viewer [39], widely used in bibliometric analysis studies [16]. These tools are known for their reliability, replicability, and user-friendly nature, enabling the analysis to be reported accurately and consistently and yielding consistent results.

The fourth Section involves bibliometric analysis based on the descriptive statistical assessment of the database. The fifth Section, instead, discusses bibliometric networks and cluster analysis based on the bibliographic coupling method featured in VOS viewer. Bibliographic coupling is a science mapping methodology that analyses the similarities between two publications based on the number of shared references. This approach works on the idea that two publications that share references are also similar in content. This methodology is best applied within the same or a specific time-period and in the field of management [39], as it presents emerging literature and research fronts more accurately than co-citation analysis [36]. By analyzing the bibliographic coupling network of documents, underlying structures and connections between different topics or research areas can be revealed, thus creating thematic clusters [40]. The bibliographic information of 1002 articles were inputted into VOS viewer, and a bibliographic coupling analysis with documents was conducted using the fractional counting method. The minimum number of citations was kept to zero to give each publication the same weight regardless of the number of citations it has received. In fact, being very recent, many articles in the sample have few or no citations. Articles that had almost no bibliographic linkage with others have been removed [41]. As a result, the VOS viewer developed a network for 833 remaining documents, identifying eight clusters of connected articles where each paper has been assigned to only one cluster. Using thematic analysis, significant differences in the subject matter were identified among clusters. Title and keyword analysis identified all relevant papers within each cluster. Given the large number of articles, the top ten most influential articles in each cluster, based on total link strength and citation value, were chosen for a more in-depth thematic analysis. This approach has been followed several times in bibliometric literature reviews [42]. Various dimensions have been analyzed to delve deeper into the literature and extract meaningful information, such as articles' objectives, methodologies, CE strategies, and I4.0 technologies investigated [43]. The thematic analysis was also employed to define the research agenda. An analysis of the clusters revealed suggested research directions. From these, common and specific future research topics were identified.

Research Performance Assessment: Descriptive Results

This section presents the results of the research performance analysis, describing the temporal distribution of articles, the contributions of different countries, and leading journals. Figure 2 depicts the temporal distribution of the 1002 articles analysed, which spans between 2010 and 2022. The number of articles published have raised strongly over time,

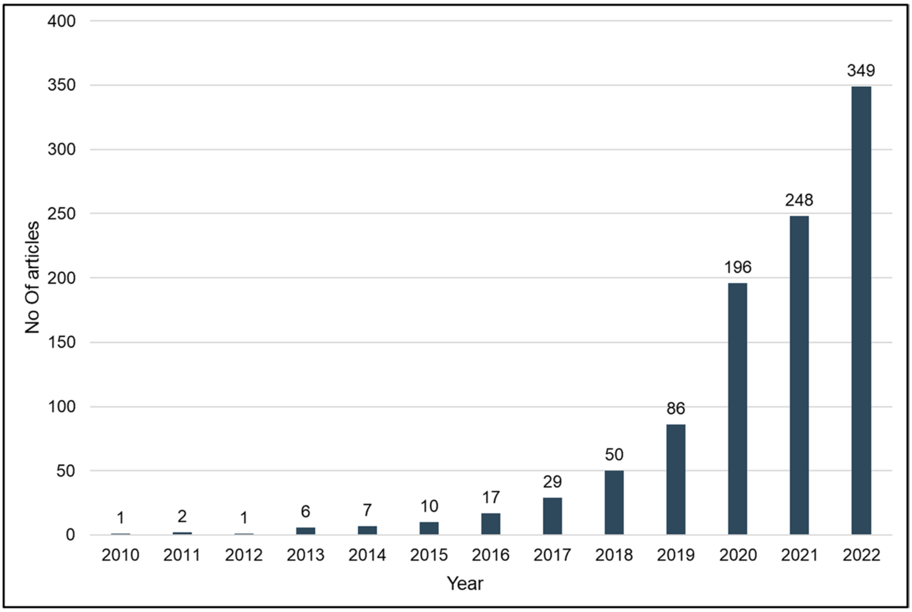


Fig. 2 Number of articles published by year

reaching 349 in 2022. This confirms that, over the last decade, there has been an exponentially growing interest in the research on CE, environmental sustainability and I4.0 technologies.

The geographic distribution of research is determined based on the corresponding author's affiliation. Since research articles are frequently co-authored by researchers from various countries, affiliation provides a more accurate representation of the research location compared to authors' nationality, as used in other literature reviews [44]. Table 2 shows the ten most active countries. The top ten countries account for more than the half of the papers in the sample (52%). China, being the most productive country, accounts for the 11% of the articles, followed by India and Italy (both close to 8%), UK, and USA. The geographical analysis of publications indicates that most active countries can be divided into two groups: western industrial economies (such as Italy, UK, USA, Germany, France, and Spain), and developing economies with large consumer societies (China, India, and Brazil). France has the highest average number of citations per publication (55.4), followed by China (48.2) and Germany (47.4). The Table shows the patterns of contributions and collaborations among countries through the Single Country Publications (SCP) and Multi-Country Publications (MCP) indexes. MCP indicates the number of articles that have at least one author who comes from a country different from the corresponding author, whereas SCP indicates the number of articles where all the authors are located in the same country. China leads also in the number of MCP (60), followed by UK (36), India (33) and Italy (24).

The 1002 studies have been published in 301 different academic journals. Among them, only eight journals published fifteen or more articles related to CE, environmental sustainability, and I4.0 technologies. They are Sustainability (223), Journal of Cleaner Production (107), Energies (21), Business Strategy and the Environment (20), International Journal of Advanced Manufacturing Technology (19), Resources, Conservation and Recycling (17), Production Planning and Control (16), and International Journal of Production Research (16). These journals cover altogether 43% of the total sample. Regarding total citations, the Journal of Cleaner Production achieved most citations (6176), followed by Sustainability (5080) and International Journal of Advanced Manufacturing Technology (2719). The latter, however, leads as the journal with the maximum average citations per article (143.1),

Table 2 Top 10 countries based on number of publications

Country	Articles	Single Country Publication (SCP)	Multiple Country Publication (MCP)	Citations	Average citations per publication
CHINA	112 (11%)	46%	54%	5401	48.22
INDIA	80 (8%)	59%	41%	1874	23.43
ITALY	79 (8%)	70%	30%	1929	24.42
UNITED KINGDOM	65 (6%)	45%	55%	2931	45.09
USA	50 (5%)	70%	30%	2185	43.7
SPAIN	41 (4%)	71%	29%	776	18.93
BRAZIL	31 (3%)	71%	29%	998	32.19
GERMANY	24 (2%)	63%	38%	1138	47.42
FRANCE	23 (2%)	35%	65%	1275	55.43
AUSTRALIA	21 (2%)	67%	33%	661	31.48

followed by International Journal of Production Research (94.6), Resources, Conservation and Recycling (74.0), International Journal of Production Economics (64.0), and Journal of Cleaner Production (57.7) (as shown in Table 3).

Science Mapping Assessment: Cluster Analysis

A cluster analysis based on the bibliographic coupling method was carried out using VOS viewer. Eight clusters were identified. Table 4 describes them, including their primary research topics and their dimension measured as the number of articles contained in each cluster. It also provides a visual representation of each cluster. Cluster 1 is the largest while Cluster 8 is the smallest. Cluster 7 covers the longest time span, with the earliest articles from 2011. The main topics, methodological aspects and research gaps of the clusters are briefly described hereafter. The supplementary material includes the categorization and allocation of the 1002 articles into clusters.

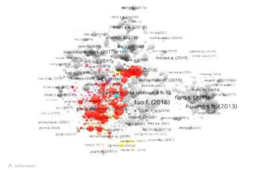
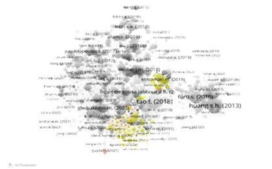
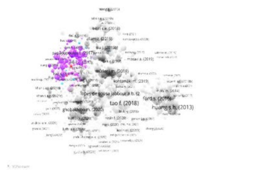
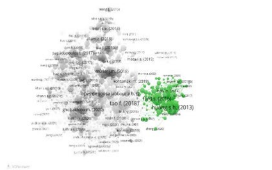
Cluster 1: General Linkages Between Sustainability and Industry 4.0 Topics

Cluster 1 is the largest (170 publications) and has a focus on general aspects about sustainability and I4.0. It discusses primarily the enabling role of I4.0 technologies for sustainability, their relationship to sustainable development, and their impact on environmental, economic, and social performances, but with no specific reference to CE. The papers in the cluster adopt various methodologies such as systematic literature reviews and framework conceptualization, often resorting to expert-based opinions. In fact, the articles in this cluster focused on exploratory research, mainly adopting qualitative approaches, and focusing on the development of conceptual frameworks. Expert based opinion methods are used to prioritize, categorize, ranks, and identify the relationship between different constructs [4, 9, 45]. For example, Ghobakhloo M. [27] found different functions of I4.0 technologies that contribute to sustainability and, through expert-based opinions, established contextual

Table 3 Top 10 journals

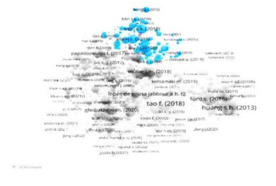
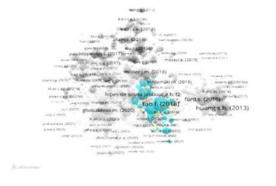
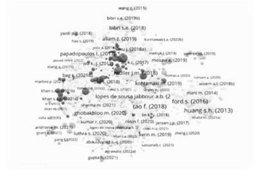
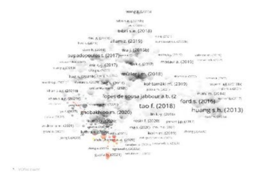
Journal	Number of publications	Total Citations	% of Publication on Total	Citation / Publication
Sustainability	223	5080	22.3	22.8
Journal of Cleaner Production	107	6176	10.7	57.7
Energies	21	434	2.1	20.7
Business Strategy and the Environment	20	414	2.0	20.7
International Journal of Advanced Manufacturing Technology	19	2719	1.9	143.1
Resources, Conservation and Recycling	17	1258	1.7	74.0
International Journal of Production Research	16	1514	1.6	94.6
Production Planning and Control	16	393	1.6	24.6
Journal of Enterprise Information Management	14	185	1.4	13.2
International Journal of Production Economics	12	768	1.2	64.0

Table 4 Research clusters based on bibliographic coupling

ID	Name of the cluster	Time range	No. of articles	Most frequent keywords	Visual representation
1	General linkages between sustainability and Industry 4.0 topics (Red)	2017-2022	N=170	Sustainable development, Industry 4 0, Sustainability	
2	General linkages between Circular Economy and Industry 4.0 topics (Yellow)	2016-2022	N=104	Circular economy, Industry 4.0, Digitalization, circular business model,	
3	Industry 4.0 and Big Data analytics for supply chain circularity and sustainability (Purple)	2014-2022	N=96	Supply chain management, Big Data, Sustainability, information management	
4	Additive Manufacturing for circularity and sustainability (Green)	2013-2022	N=140	3D Printers, Additive manufacturing, Life cycle	

relationships between pairs of factors. Similarly, Nara et al.[9] conducted a systematic literature to find different key performance indicators, grouped them based on experts' opinion, and validated them with a survey on 72 technical specialists and managers. At a more general level, the papers in this cluster highlight that I4.0 can significantly contribute to sustainable development through resource efficiency enhancement, waste reduction, and product design improvement. For example, Felsberger & Reine [46] investigated the effectiveness of I4.0 technologies such as smart factory technologies, data-driven technologies, and shop floor equipment technologies for different sustainability dimensions. El Baz j et al.[45] evaluated empirically the various sustainability drivers that influence the adoption of I4.0 technology and emphasised the importance of management support. Challenges related to the adoption of I4.0 technologies for achieving sustainability are also highlighted throughout the cluster. They include the high cost of implementing I4.0 technologies and the scarcity of expertise and skills needed for the implementation and management of these technologies. Additionally, challenges in the social dimension such as income and employment polarisation resulting from I4.0 have been highlighted [47]. Challenges about data privacy and security are also notable and requires an evaluation of the effectiveness of government policies [4]. Besides practical implementation challenges, several opportunities for future research arise from this cluster. From an organizational perspective, a promising future research direction involves investigating the application of I4.0

Table 4 (continued)

5	Urban Sustainability (Blue)	2012-2022	N=119	Smart city, Waste management, Big data	
6	Sustainable, Circular and Digital (Re)Manufacturing (Sky Blue)	2016-2022	N=87	Sustainable smart manufacturing, Remanufacturing, Life cycle	
7	Blockchain and Data Integration for sustainability and Circular Economy (Gray)	2011-2022	N=86	Blockchain, Internet of Things, Machine Learning, architectural design, Circular Economy	
8	Miscellaneous and sectorial applications (Brown)	2020-2022	N=31	Decision making, Circular supply chain, E-commerce	

technologies to improve personalized information and knowledge management [27, 46]. In addition, investigating how sustainability can drive the adoption of I4.0 technologies would be also highly relevant [4].

Cluster 2: General Linkages Between Circular Economy and Industry 4.0 Topics

Cluster 2 (104 publications) focuses on digitization in relation to CE and circular business models. The papers included in this cluster cover a vast range of topics, such as the role of digitalization in enhancing productive maintenance in manufacturing firms [48], circular business models [21], and circular supply chains [24, 49]. In general, research in this cluster develops frameworks to connect different constructs often based on systematic literature reviews. For instance, Gebhardt et al. [49] created a framework for the collaboration mechanisms enabled by I4.0 technology, focusing on IoT, Big Data analytics, and cloud computing as enablers of circularity in supply chains. Salvador et al. [21] investigated digital technologies to enable circular strategies such as design for circularity and their impact on business models. Liu et al.[50] investigated digital technologies to facilitate the integration of different Reduce, Reuse, Repair, Repurpose, Remanufacturing, Recycle, and Recover strategies [51]. Hence, I4.0 technologies such as IoT and cloud computing have been proven to be effective enablers of specific CE practices such as product life extension, reuse, and recycling. Some papers explored the challenges related to policy, technology, and behavioral change as well as the opportunities in implementing CE practices [52], while others aimed to develop conceptual frameworks or value chains designs to achieve circularity. Moreover, some of the articles highlighted the complexity behind a successful implementation of I4.0 technologies due to high cost and high financial risks. This, in turn, create a digital divide with some companies being able to adopt circular practices using expensive I4.0 technologies while others are left behind due to financial constraints and a lack of resources [53]. Overall, research articles in this cluster generally adopt a theoretical perspective. Therefore, more empirical studies are often suggested. Further investigation into the creation of collaborative platforms and systematic collaboration methods to connect different stakeholders involved in circular supply chains can be considered as a valuable future research direction in this cluster. Moreover, theories are needed to synthesize specific technologies and their interconnection in the context of CE [49, 54]. Lastly, studying various circular business model building blocks (such as consumer segments, value propositions, channels, consumer relationships, etc.) in specific manufacturing industries would be an intriguing area of research [21, 54].

Cluster 3: Industry 4.0 and Big Data Analytics for Supply Chain Circularity and Sustainability

Cluster 3 (96 publications) focuses on the relationship between I4.0 technologies and sustainable, circular supply chain initiatives. This cluster is therefore more specific than Clusters 1 and 2, focusing on supply chain management and emphasizing the role of Big Data analytics among the wide I4.0 technologies umbrella. The studies in this cluster shed light on the crucial role of digital technologies and advanced analytics in fostering sustainable supply chains, enhancing resilience, and enabling reverse logistics. They explore the intersection of supply chain management, I4.0 technologies (with particular to Big Data analytics), and CE strategies, drawing on diverse industries, geographical regions, and data sources. Interestingly, different papers in this cluster employ empirical methods, both quantitative and qualitative. Some of the research papers utilize surveys to test hypotheses in different geographical regions. For instance, Di Maria et al. [55] focus on the mediating role of supply chain integration in the correlation between I4.0 technologies and CE practices. Based on a survey of 1200 Italian firms, they found that supply chain integration plays a crucial role in realizing the potential benefits of I4.0 technologies in achieving circularity in supply chains. Akbari & Hopkins et al. [56] explored how digital technologies can enable supply chain sustainability in emerging economies by surveying 223 Vietnamese supply chain experts. Overall, the study emphasizes the importance of the interplay among sustainable supply chain management, CE practices and I4.0 technologies. The authors emphasize the importance of adopting a holistic and integrated approach to smart sustainable supply chain management that addresses supply chain disruption, supply chain capability development by enhancing flexibility and effectiveness, and resource recovery frameworks for low-cost material collection by improving environmental, social, and economic dimensions [57]. According to this cluster, reverse logistics is frequently neglected by manufacturing companies compared to forward supply chains due to operational challenges, knowledge gaps related to circular supply chains and smart technologies, low return on investment, a lack of support from top management and technological challenges [58, 59]. Therefore, it is suggested that future research should address these technological barriers such as data inadequacy, information structure due to different digital formats, a lack of industrial competency and expertise, and challenges in the implementation of innovative devices and information technology [57]. A focus should be placed on the government's role in assessing the effectiveness of implementing environmental taxation waiver schemes as well as developing regulations and policies to encourage firms to adopt waste disposal strategies within a circular supply chain network [60]. Researching data-driven approaches to measure and monitor supply chain sustainability performance, as well as evaluating sustainable outcomes, presents an intriguing area of study [20].

Cluster 4: Additive Manufacturing for Circularity and Sustainability

Cluster 4 (140 publications) focuses on additive manufacturing and 3D Printing as a technology allowing to minimize waste, optimize resource consumption, and promote circularity in the manufacturing industry. The articles in this cluster discuss the relationship between life cycle sustainability and additive manufacturing, providing frameworks for sustainability assessment and proposing strategies for optimizing the process for eco-effective production systems [61]. Topics addressed include the sustainability assessment of additive manufacturing, the design of distributed recycling via additive manufacturing [62], the integration of additive manufacturing and CE [33], and the impact of additive manufacturing on business models [63]. Several papers adopted a systematic literature review approach to condense and assess the current literature in the field. Interestingly, some papers in the cluster use analytical methods and statistical analyses to evaluate additive manufacturing parameters. For instance, Mele & Campana [64] proposed an adaptive slicing method for liquid crystal display 3D printing, which can reduce waste and energy consumption. Although several papers focus on reuse and recycling [61, 62], reduce is also a referenced CE strategy [64]. Articles highlight some of the potential benefits of additive manufacturing for circular product design [61], and sustainable business models [8], including operational and economic benefits related to reduced material waste, lower transportation costs [65], and the ability to offer consumer-centric customization [63]. A reduction in inventory is also possible through on-demand production. Additionally, another advantage of localized production is the potential to shorten the supply chain while improving environmental and social benefits [62]. However, there is a need to develop a reverse logistic framework to successfully implement additive manufacturing by connecting different supply chain actors. Furthermore, more empirical research is needed to understand how additive manufacturing initiatives are perceived at the social level. Both active participation and supportive policies of governments and policymakers need to be addressed to increase the adoption rate of additive manufacturing for sustainability and circularity purposes. A potential future direction is to investigate innovative additive manufacturing methods and strategies for preparing and using recycled materials as input feedstock, develop standardized indicators for assessing environmental impacts to produce additive manufacturing feedstock, and optimize energy and material-efficient production processes through methods like distributed recycling, polymerization, and laser cladding [62, 63].

Cluster 5: Urban Sustainability

Cluster 5 (119 publications) primarily revolves around the theme of urban sustainability, including the literature on data driven smart sustainable cities, ICT infrastructure for urban sustainability, and digital technologies in the context of smart cities. In the context of urban development, the integration of I4.0 technologies such as IoT, Big Data and cloud computing play a significant role in enhancing waste management and environmental sustainability. Wu et al. [31] focused on the collection and analysis of real-time data from digital instruments placed in urban environments. These enabling technologies contribute to the so-called data-driven smart cities [66], and their ICT infrastructures support data-driven decision-making to achieve urban sustainability and empower urban intelligence. Additionally, authors frequently discussed the potential risks, benefits, and ambidexterity capabilities (to achieve both innovation and efficiency) to fulfil the current business demand as well as future perspective. Challenges surrounding the adoption and implementation of digital technologies are also discussed. Some paper highlights the importance of citizen engagement and empowerment in the design and implementation of smart cities [67], while others emphasize the need for policies and regulations that balance innovation and sustainability [68]. However, the role of government in establishing political mechanisms and policy measures for smart cities still needs to be further explored. For instance, the prototype developed for the Stockholm Royal Seaport (SRC) uses a hybrid Smart Urban Metabolism approach to achieve sustainability through robust environmental policies, combining various methods and technologies to create a comprehensive solution for monitoring and analysing environmental sustainability aspects [67]. Additionally, greater attention should be given to social acceptability and the impact of adopting urban sustainability strategies. To create more efficient and sustainable cities, further research is needed on urban intelligence. This refers to a city's ability to harness real-time data and optimize interconnected systems like energy distribution, water distribution, waste collection, and communication networks. In addition to urban intelligence, research should explore resilient data-driven decision-making. This incorporates data acquisition from multiple sources, data stream management, and integration of diverse urban data to ensure effective decision making. This entails the development of frameworks, protocols, and methods for integrating sensor data into a standardized and structured format to facilitate more efficient analysis, while properly considering data privacy and security concerns.

Cluster 6: Sustainable, Circular and Digital (Re)Manufacturing

Cluster 6 (87 publications) focuses on the integration of sustainable principles, digital technologies and CE aspects in manufacturing and especially remanufacturing operations. Articles in this cluster investigate the role of digital technologies for achieving a sustainable and circular (re)manufacturing. Chau et al. [69] discussed the prospects for IoT-based technologies in remanufacturing process. Kerin & Pham [70] explored the use of I4.0 technologies in remanufacturing, particularly in smart remanufacturing environments. Chauhan et al. [71] proposed a framework for integrating I4.0 and CE principles to analyze and optimize resource consumption in the manufacturing industry. Lopes de Sousa Jabbour et al. [72] proposed a research agenda and roadmap for sustainable operations that incorporates I4.0 and CE principles for adopting sustainable operations management. According to this cluster, the efficiency and effectiveness of remanufacturing processes can be enhanced by digital technologies such as artificial intelligence, machine learning, and IoT, thus enabling real-time monitoring and optimization of energy consumption. Furthermore, significant resource savings and environmental benefits can be achieved through additive manufacturing. Investigating the role of governments in overcoming barriers and fostering new markets for remanufactured goods, along with the development of supportive infrastructure plans, presents an intriguing avenue for future research. From a knowledge perspective, studying data-driven frameworks that integrate smart circular strategies holds promise in providing extensive product and process information, underscoring the need for effective mechanisms for data quality control and data security. Future research could focus on identifying the barriers to the adoption of I4.0 technologies and exploring skill development, transfer, and trust-building strategies among employees to overcome them [72]. Additionally, further investigation should advance the understanding of the relationship between dynamic capabilities and the adoption of CE practices in response to changing environmental and market conditions [70].

Cluster 7: Blockchain and Data Integration for Sustainability and Circular Economy

Cluster 7 (86 publications) discusses Blockchain and data integration for sustainability and CE. The use of blockchain technology in CE practices is a key focus of this cluster, with some papers using empirical findings to develop hypotheses for understanding the impact on sustainable operations. For instance, Rajput and Singh [73] used a qualitative methodology to collect data through a literature review and case studies, examining the role of artificial intelligence, Big Data analytics, Blockchain, and IoT in CE strategies such as reducing waste and design for circularity. Zhang et al. [74] developed a framework for implementing blockchain-based life cycle assessments based on a systematic literature review. Other authors identified critical success factors for implementing a blockchain-based circular supply chain, including a shared vision among stakeholders and the ability to adapt to changing technological and regulatory environments [75]. Umar et al. [76] presented an empirical study on I4.0 technologies and green supply chain practices, using a quantitative approach with a survey questionnaire as the primary data collection tool. Similarly, the articles explored the potential of integrating blockchain with IoT and RFID to enhance sustainability in distribution and order management. Among these technologies, blockchain stands out due to its features such as immutability, transparency, reliability, and verifiability, making it an ideal solution for facilitating information flows among complex supply chain networks and stakeholders. Additionally, the papers highlight the importance of critical success factors for implementing blockchain-based circular supply chains, such as trust, transparency, and data privacy [73–75]. In line with other clusters, future research can expand the empirical studies by investigating the sustainability practices facilitated by blockchain-based solutions. There is a need for exploring the social impact of I4.0 on human resource management practices and examining the relationship between adoption rates and technical knowledge constraints. More attention needs to be given to the role of government policies and regulations in promoting the adoption of blockchain and I4.0 technologies. Another important aspect concerns enhancing data traceability, security, and integrity features of blockchain use for smart contracts. This improvement can contribute to building trust between partners and to fostering collaborative relationships [74, 75].

Cluster 8: Miscellaneous and Sectorial Applications

This cluster (31 publications) delves into industry-specific applications and other miscellaneous topics related to CE and sustainability. It includes 32 papers, making it the smallest cluster. The papers investigate various facets of I4.0 and CE implementation in different industrial contexts. For instance, Abdul-Hamid et al. [77] scrutinized the drivers of I4.0 in the palm oil industry in Malaysia, while Piyathanavong et al. [77] examined the role of project management in sustainable supply chain development in the Thai metals industry. Other papers focus on specific industrial applications of CE and I4.0 technologies. Vimal et al. [78] analyzed the drivers for the adoption of I4.0 technologies in a circular sharing network for paper, cement, and sugar. This cluster emphasizes the importance of empirical research to explore and assess the impact of I4.0 technologies on CE strategies, including the identification of key factors that facilitate successful implementation. For instance, integrated data management systems can significantly enhance collaboration for optimized procurement and production across industries. Additionally, exploring the impact of management systems in mitigating employee resistance to change is suggested as an intriguing avenue for further investigation.

Research Agenda

The influential articles identified through bibliographic coupling analysis and the gaps they point out have been considered as the basis for the development of a research agenda, consisting of ten main research directions. Table 5 connects each identified research direction to the clusters in which it emerged. Research directions are then described in the following. The first four research directions are highly transversal, appearing in at least five clusters, so they are described with more details. Three research directions are common to two clusters, while three have been suggested by one single cluster.

First, an important gap highlighted by the literature concerns the need to move beyond conceptual papers and embrace empirical investigations to gain a deeper understanding and move towards theory-testing research of the relationship between I4.0, environmental sustainability, and CE at both conceptual and practical levels. Furthermore, empirical studies are necessary to address the development and configuration of effective business models and digital manufacturing ecosystems that foster sustainability [54]. Hence, six clusters emphasised the need for empirical research to investigate and quantify the impact on sustainability and CE as well as to develop indicators assessing economic, environmental, and social impacts [4]. Empirical evidence would help to fully understand the positive and negative effects of I4.0 adoption for CE and sustainability such as rebound effects.

Research direction #1 To carry out empirical and quantitative research at the intersection of Industry 4.0, environmental sustainability, and Circular Economy.

Seven out of eight research clusters emphasized the importance of addressing the social implications of I4.0 adoption in the context of CE and environmental sustainability. There is a lack of comprehensive investigations into the changes occurring in the current social platform setting, such as education and skills and wealth disparities in consumer markets, which strongly motivates future research. One key aspect emphasized is the effect of automation on low- to middle-skilled jobs [63]. On the other hand, the creation of new opportunities in technology and engineering fields also deserves further investigation [53] The importance of addressing income and employment polarization should also be mentioned [27]. It is vital to ensure social inclusion, citizen participation, and equitable access to sustainable urban development. Atif et al. [79] suggest exploring the social acceptability of CE products and services as an area for investigation. Additionally, the social aspect of sustainability in supply chain management requires increased attention, with the adoption of reliable social performance measurement models like the social return on investment (S-ROI) [73, 80]. Policymakers have a pivotal role to play in promoting the adoption of emerging technologies and fostering

Table 5 A Research Agenda for the research on Circular Economy, environmental sustainability, and Industry 4.0 technologies

Research direction	Cluster 1 – General linkages between Sustainability and Industry 4.0	Cluster 2 – General linkages between Circular economy and Industry 4.0	Cluster 3—Industry 4.0 and Big Data Analytics for supply chain circularity and sustainability	Cluster 4—Additive Manufacturing for Circularity and Sustainability	Cluster 5—Urban Sustainability	Cluster 6—Sustainable, Circular and Digital (Re) Manufacturing	Cluster 7—Blockchain and Data Integration for Sustainability and Circular Economy	Cluster 8—Miscellaneous and Sectorial Applications
1. Carrying out Empirical Research at the intersection of I4.0, environmental sustainability, and CE	*X*	*X*	*X*	*X*		*X*	*X*	*X*
2. Investigating the social impact of Industry 4.0 technologies used for CE and sustainability	*X*	*X*	*X*	*X*	*X*	*X*	*X*	
3. Investigating the role of government regulations and policies	*X*	*X*	*X*	*X*	*X*	*X*	*X*	*X*

Table 5 (continued)

Research direction	Cluster 1 – General linkages between Sustainability and Industry 4.0	Cluster 2 – General linkages between Circular economy and Industry 4.0	Cluster 3—Industry 4.0 and Big Data Analytics for supply chain circularity and sustainability	Cluster 4—Additive Manufacturing for Circularity and Sustainability	Cluster 5—Urban Sustainability	Cluster 6—Sustainable, Circular and Digital (Re) Manufacturing	Cluster 7—Blockchain and Data Integration for Sustainability and Circular Economy	Cluster 8—Miscellaneous and Sectorial Applications
4. Developing Data Management and Data Integration frameworks and Platforms for Sustainability and Circular Economy for companies and smart cities			*X*		*X*	*X*	*X*	*X*
5. Addressing Data and Cyber Security issues in the context of I4.0, CE, and Environmental Sustainability	*X*				*X*			
6. Exploring the influence of specific I4.0 technologies on CE and environmental sustainability		*X*				*X*		

Table 5 (continued)

Research direction	Cluster 1 – General linkages between Sustainability and Industry 4.0	Cluster 2 – General linkages between Circular economy and Industry 4.0	Cluster 3—Industry 4.0 and Big Data Analytics for supply chain circularity and sustainability	Cluster 4—Additive Manufacturing for Circularity and Sustainability	Cluster 5—Urban Sustainability	Cluster 6—Sustainable, Circular and Digital (Re) Manufacturing	Cluster 7—Blockchain and Data Integration for Sustainability and Circular Economy	Cluster 8—Miscellaneous and Sectorial Applications
7. Exploring Novel Business Models for advancing CE, environmental sustainability and I4.0		*X*			*X*			
8. Investigating Sustainability as a driver for Industry 4.0 adoption	*X*							
9. Developing Sustainable Additive Manufacturing materials, technologies, and supply chains				*X*				

Table 5 (continued)

Research direction	Cluster 1 – General linkages between Sustainability and Industry 4.0	Cluster 2 – General linkages between Circular economy and Industry 4.0	Cluster 3—Industry 4.0 and Big Data Analytics for supply chain circularity and sustainability	Cluster 4—Additive Manufacturing for Circularity and Sustainability	Cluster 5—Urban Sustainability	Cluster 6—Sustainable, Circular and Digital (Re) Manufacturing	Cluster 7—Blockchain and Data Integration for Sustainability and Circular Economy	Cluster 8—Miscellaneous and Sectorial Applications
10. Exploring the Role of Dynamic Capabilities in the Adoption of CE Practices for Sustainable, Circular, and Digital (Re) Manufacturing						*X*		

skill development [74]. Research should finally delve into the role of social media in influencing consumer behavior and improving sustainable supply chains.

Research direction #2 To Investigate the social impact of Industry 4.0 technologies adopted for Circular Economy and sustainability.

Government regulations and policies play an important role in enhancing sustainability and CE, as well as the adoption of I4.0 technologies. Government policies and initiatives directly influence several industry aspects, such as market creation, production and logistics as well as engaging different stakeholders at the micro, meso, and macro levels [69]. It is important to investigate the effectiveness of policy interventions such as subsidies and energy saving regulations that promote sustainable practices, also to minimize socio-economic inequality in reference to I4.0 technologies [71]. Another aspect to be addressed concerns the environmental impact of the implementation of I4.0. Additionally, given the heavy reliance of I4.0 on data-driven technologies, policies need to address concerns related to data privacy, security, and governance, e.g., safeguarding data, protecting intellectual property rights, and developing regulations for data sharing [24]. Furthermore, governments have a critical role to play in promoting sustainability among consumers in urban areas: future research should focus on investigating innovative policy measures, monitoring policy effectiveness, and understanding the involvement of stakeholders in the development and implementation of urban sustainability policies [81]. Moreover, to promote CE practices, policymakers can incentivize the adoption of circular supply networks and green products and provide support to remanufacturing industries [76]. Finally, cross-national studies can provide valuable insights into different policy-making approaches, enabling policymakers to enhance their strategies and create new markets for sustainable products.

Research direction #3 To investigate the role of government regulations and policies in improving the effectiveness of I4.0 adoption for CE and Sustainability.

Addressing gaps and challenges in data management and integration should be a priority for future research. For instance, the integration of new technologies and the resolution of compatibility issues within existing systems in circular procurement and supply chain management should be addressed. Additionally, ensuring data accuracy, timeliness, and completeness hold significant importance in developing data-driven circular strategies in manufacturing. Research should address challenges associated with developing blockchain-based data management systems, including data manipulation, integration, scalability, and transmission [20, 59]. It is essential to enhance data traceability, security, and integrity in blockchain utilization to foster trust and collaborative relationships. Researchers can also concentrate on developing data-driven frameworks that promote semantic interoperability between machines, designing efficient interfaces and data networks to encourage stakeholder collaboration Moreover, fostering knowledge management by enhancing the collection, storage, and sharing of information generated through I4.0 technologies within an organization could significantly contribute to digital supply chain network. In the realm of urban sustainability, there is a requirement to integrate data sources and technologies for effective decision-making in smart cities. This involves developing frameworks, protocols, and applications for the collection and analysis of sensor data, optimizing ICT infrastructure, and for the exploitation of the potential of Big Data and cloud computing [68].

Research direction #4 To develop frameworks and methods for Data Management and Data Integration for sustainability and Circular Economy purpose.

Moreover, further attention needs to be given to data and cyber security due to the involvement of large data transactions and sharing in I4.0. This is crucial because cyber threats from anonymous user can be challenging to identify, yet they can significantly impact operations and pose challenges [16]. Additionally, there are opportunities for a more transparent and traceable option using encrypted digital records in the context of manufacturing sustainability. Future research should focus on leveraging digitization to respond to security and privacy concerns in the smart city and manufacturing environments, addressing security threats across different layers of data technologies, and investigating the security and safety of digital infrastructure for citizens, vendors, and stakeholders [73].

Research direction #5 To address data and Cyber Security issues in the context of Industry 4.0, Circular Economy, and environmental sustainability.

The role of specific I4.0 technologies in decision-making solutions that support planning, control, execution, business model innovation, corporate competitiveness, and on-the-job training capabilities, within the CE paradigm for environmental sustainability has not been thoroughly investigated. While some specific technologies such as IoT and Big Data have been extensively explored, the specific contribution of other I4.0 technologies has been neglected. Given that CE implementation is relatively new, it is crucial to explore the interconnection between different technologies and their role in establishing a CE paradigm [57]. Additionally, classification frameworks or theories could point out the roles of specific technologies, also acting as prescriptive conceptual tools to support practitioners within the CE context.

Research direction #6 To delve deep into the impact of specific Industry 4.0 technologies on Circular Economy and environmental sustainability.

Clusters 2 and 5 found that future research should explore the development of novel business models and value propositions and the redesign of current business models to prioritize environmental sustainability, in urban settings as well as for different types of manufacturing industries [54]. As an example, investigations into new business models for streamlining waste management, recycling, and collaboration among local actors in the urban environment are needed [82]. Additionally, studies should focus on developing new business models for data collection and processing of urban data and solid waste materials management, potentially utilizing emerging technologies such as blockchain or Big Data analytics [66, 68, 81]. Finally, future research should explore how digital technologies enable the transformation of business models in inbound, outbound, and reverse logistics.

Research direction #7 To explore novel Business Models frameworks for advancing Circular Economy, environmental sustainability, and Industry 4.0.

In cluster 1 it is highlighted that numerous studies have examined I4.0 as an enabler of environmental sustainability and discussed the sustainability impacts of the adoption of I4.0 technologies. However, both researchers and industries have been focusing on how the adoption of I4.0 technologies can drive sustainability. On the other hand, there has been relatively little research on how environmental sustainability can strategically drive the adoption of I4.0 technologies, and the digitalization process of companies and supply chains alike, understanding how a strategic path towards increasing circularity and achieving, e.g., “Net zero” could be undertaken by incorporating investment in digital technologies. This represents a crucial area for future research area [4].

Research direction #8 To investigate environmental sustainability as a driver for Industry 4.0 adoption.

As promising research directions for sustainable additive manufacturing, Cluster 2 emphasized the combined development of eco-friendly and recycled materials with a technological advancement of 3D printing processes. This involves evaluating different recycling and manufacturing methods, as well as assessing the environmental footprint of the materials used [65]. Some potential areas of investigation involve designing and developing systems to save resources, reduce energy consumption, and optimize labor and material costs. Future research should address how to use secondary raw materials as additive manufacturing powders and design reverse supply chains to collect them and connect various stakeholders [63, 65].

Research direction #9 To develop Sustainable Additive Manufacturing materials, technologies, processes, and supply chains.

Future research should advance the understanding of the relationships between dynamic capabilities and the adoption of CE practices, as mentioned in Cluster 6. More specifically, research should address how firms can develop, acquire, and improve dynamic capabilities and resilience using I4.0 technologies in manufacturing supply chains to adapt to changes and environmental uncertainties. Further investigation is needed to overcome the challenge of developing dynamic capabilities in isolation and identify the roles of different stakeholders in supporting CE transition for enhanced resilience [83].

Research direction #10 To explore the role of Dynamic Capabilities in the adoption of Circular Economy practices for Sustainable, Circular, and Digital (Re)Manufacturing.

Conclusion

Despite the significant research interest in the role of I4.0 technologies for environmental sustainability and CE, the literature on this topic remains sparse and fragmented. This study provided a systematic understanding of all these three dimensions. By analyzing a vast amount of literature, this bibliometric review pointed out the most active countries and influential journals within these areas of study. Additionally, a network-based analysis has led to the identification of eight major clusters that shed light on key research areas and themes. A large amount of literature has adopted a high-level conceptual approach (in particular Cluster 1 addressing the linkage between ‘General Sustainability and Industry 4.0’; Cluster 2 discussing the impacts of ‘General Circular economy and Industry 4.0’) while other studies have a more specific focus on one or few technologies on a more narrow domain (Cluster 3 focusing on the role of Big Data analytics in supply chains; Cluster 4 on ‘additive manufacturing’ in R&D and production process, Cluster 7 on Blockchain).

Finally, some clusters have a stronger focus on the application domain (Cluster 5 on 'urban sustainability'; Cluster 6 on manufacturing and remanufacturing; Cluster 8 discussing several sectorial applications). In conclusion, a structured and comprehensive research agenda is identified. This agenda includes ten promising research directions for scholars in this field. These directions encompass development at the technological level (data integration, security), material level (additive manufacturing), social dimensions, general policy dimensions, and managerial dimensions. The research agenda lays a solid foundation for future investigations in this field.

From a managerial point of view, this bibliometric literature review offers a valuable resource for practitioners and policymakers, enabling them to leverage the insights gained from prior research to raise and support awareness. By exploring our clustering of the research, stakeholders can acquire a comprehensive understanding of the topics and themes investigated and use the findings in their operative environments.

Like other bibliometric literature reviews, our findings are subject to some limitations. The review exclusively focused on peer-reviewed journal papers indexed in Elsevier's Scopus database. To enhance the comprehensiveness of this review, it would be beneficial to include additional data sources and databases, and in particular the grey literature, that can provide valuable knowledge on the practical advancements in these domains. Lastly, and considering the speed with which literature on these topics increase over time, the authors advise future research to repeat such bibliometric analysis in the next years and compare the updated findings with our clusters and research agenda.

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Declarations

Competing Interests The author declares no competing interests.

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