**Progress and Trends in Integrating Industry 4.0 within Circular Economy: A Comprehensive Literature Review and Future Research Propositions**

**Abstract**

Society is facing many challenges, including, climate change, COVID, inequity and human population growth. Some researchers suggest that integration of Circular Economy (CE) and Industry 4.0 (I4.0) concepts and approaches can help us to make progress toward sustainable societies. Integrated implementation can help to improve the design of product-service systems focused on prevention and reduction of wastage of materials, energy, human health, and ecosystems. The CE practices enable consumers to return products after use and to reuse the products with more value. Will integrated adoption of CE and I4.0 practices help society to be more sustainable? What is known about the climate change benefits of integration of I4.0 and CEs to reduce energy and resource usage?’ The authors sought to answer these questions, via a systematic bibliometric literature review, and network analysis of literature on I4.0 and CE for logistics and supply chain applications. The review was performed by searching the SCOPUS database for literature about I4.0 and CE. A total of 165 articles was shortlisted for in-depth review. The literature review was complimented by bibliometric and network analyses. The review provided insights into the present and future trends in integration of I4.0 and related Artificial Intelligence (AI) tools in CE’s. Based on the findings, a framework for integrating I4.0 and CE, was developed to guide CE decision-making that will help researchers and industrialists, integrate I4.0 tools within CEs to improve logistics, resource efficiency, safety, product quality, and reduce fossil-carbon footprints.

***Keywords:*** Artificial Intelligence; Industry 4.0; Circular economy; Environmental policy; Bibliometric analysis; Resource efficiency; Sustainable societies.

1. **Introduction**

Biodiversity losses are a major concern in global societies. Many countries are working together to slow down and reverse biodiversity losses through integrated approaches to sustainable development and cleaner production (Wallace, 2020, Stefanelli, 2021). Many initiatives are being made to reduce climate changes through fossil fuel divestment and reinvestment in renewable energy-based system; Such divestments are especially prominent in the US and UK (Hestres and Hopke, 2020). But the divestment-reinvestment movement is spreading rapidly globally. Fossil fuel divestment is being done by dedicated, concerned stakeholders to divest from fossil fuel companies and to invest in renewable energy-based systems and energy and materials efficient Circular Economies (CE) and engaging in Cleaner Production (CP) (Plantinga and Scholtens, 2020). Industry 4.0 (I4.0) is a concept that can be used to enhance CE, CP and help societies to make progress toward indeed equitable, liveable, sustainable societies. The I4.0 is the fourth industrial revolution that utilizes Information Technology (IT) in the manufacturing sector to enable smart manufacturing (Tang and Veelenturf, 2019). The Internet of Things (IoT), big data analytics, Cyber-Physical System (CPS), Artificial Intelligence (AI), Augmented Reality/Virtual Reality (AR/VR), and Additive Manufacturing (AM) are some of the technologies of I4.0 (Yavas and Ozkan-Ozen, 2020; Vinodh and Wankhede, 2020). The I4.0 can be defined as “real-time, intelligent and digital networking of people, equipment and objects for the management of business processes and value-creating networks” (Dombrowski et al., 2017). Biomimicry is an approach that mimics nature’s processes to help to solve human problems by making technological innovations that mimic nature. (Blok and Gremmen, 2016).

Recent developments and industrial globalization are nearing planetary boundaries where small additional increases in carbon concentrations in the atmosphere will drastically increase global warming and exceed multiple planetary boundaries. (Zwier et al., 2018). Global warming has many environmental impacts such as land degradation, spreading deserts, biodiversity losses, degradation of freshwater, food insecurities and adverse human health challenges. According to Gartner’s survey of 528 supply chain experts in 2020, 51% of them are focused upon waste reduction and prudent resource consumption within the framework of CE, which is an essential aspect of sustainable production as it is built upon new product design so that they can be upgraded, repaired, remanufactured, and recycled, thereby, reducing the quantities of bio-based and geo-based resources that are needed to provide the goods and services society needs (Brown, 2020).

The CE approach is “*a strategy designed to help to reduce inputs of virgin materials and use previously used products or the materials of which there are made to close the economic and ecological loops of resource flows*” (Haas et al., 2015). The CE can provide Triple Bottom Line (TBL) environmental, social and economic benefits (de Sousa Jabbour et al., 2019; Ma et al., 2020; Agrawal et al., 2021). Linear economy business models have several weaknesses such as improper resource utilization, high costs, more wastes, more landfills, and increasing pollution (MacArthur, 2013; Riesener et al., 2019).

Electronic waste generation is increasing rapidly globally at a rate of 8% per year, and proper management of e-waste is a major challenge and opportunity (Tunali et al., 2020a). E-waste consists of valuable materials along with hazardous substances, therefore systematic recycling and repurposing of these materials. Remanufacturing is increasingly an essential element of CE, which makes high-quality products at good as new quality at low prices with reduced environmental impacts. Several authors suggested integrating CPS to IoT for smart product remanufacturing (Blömeke et al., 2020; Rocca et al., 2020; Vishal and Vinodh, 2021). For example, usage of robotics in disassembly can provide benefits in the disassembly process through efficient human-robot collaboration (Poschmann et al., 2020). Circular practices in logistics and supply chain management enable consumers to return products after use and replace them with remanufactured products. To obtain smooth CE practices, the deployment of I4.0 technologies is making positive contributions (Dev et al., 2020, Khan et al., 2021). Smart logistics and transportation promote sustainability, improve visibility throughout the product life cycle, improve system efficiency to reduce operational costs, and monitor sustainable performance across supply chain networks (Li, 2020; Pan et al., 2020).

Resource consumption is increasing globally, driven by the massive growth in the human population. The world’s population is increasing at the rate of 81,000,000 net increase per year. The global population is forecasted to reach 7.6 billion by 2025, which will increase food insecurities for millions and increase solid waste by 70% compared with the present quantities (Hoornweg and Bhada-Tata, 2012). A survey in the European region showed that 60% of the End of Life (EoL) materials are not reused and recycled. (Preston and Herron, 2011). The forecasts made by the UN on resource consumption showed that by 2030, the current resource demands would double due to population growth and increasing per capita resource consumption (Koh et al., 2016).

Increases in automation have supported the adoption of I4.0 and CE by many industries to enhance their efficiency, effectiveness, safety and improve customer satisfaction (Rajput and Singh, 2019; Yadav et al., 2020). Although, there are many studies about integrating I4.0 and CE practices, the authors of this paper mainly focused on integrating I4.0 technologies and CE practices for logistics and supply chain management (de Sousa Jabbour et al., 2018; Rosa et al., 2020; Ghobakhloo et al., 2021). Considering increasing resource conservation, smart and cleaner production, the authors analysed the significance of I4.0 and CE in the logistics and supply chain domain. There is increasing research in the field of I4.0 and CE, which was reviewed for this paper. The unique contribution of this paper is the development of a research framework for smart and circular supply chains for integrating I4.0 technologies and CE practices. This study was designed to answer the following research questions:

*RQ1.* What are the different approaches used in the field of I4.0 and CE?

*RQ2.* What are the current research trends in the field of I4.0 and CE?

*RQ3.* What new directions in research and applications are anticipated in the integration of I4.0 and CE?

The authors performed a systematic literature review and a bibliometric study of published articles, conference proceedings, and book chapters of content pertaining to the integration of I4.0 and CE. The SCOPUS database was used to search for and select relevant articles. The reason for selecting the SCOPUS database was, it is one of the largest and widely used databases containing many peer-reviewed articles from refereed journals (Sharma et al., 2020). The review was done based on the SLR methodology. The bibliometric study was performed to analyze the relevant contributions of the authors, institutes, countries, and journals.

Network analysis was performed to gain insights into the networks and collaborations of the researchers in the field of I4.0 and CE. The bibliometric study and network analyses were performed to review the evolution of the earlier research and project the research and development trends for the future of I4.0 and CE. Additionally, the authors proposed a research framework that can help researchers, Industrial practitioners and managers for successful adoption of CE practices through the integration of I4.0 technologies to help to ensure improved resource conservation and cleaner production for now and the future.

This paper is comprised of six sections: the introduction and the research questions in Section 1, Section 2 highlights the systematic literature review and review methodology Section 3 includes the results of the bibliometric study. Network analysis and emerging research themes of I4.0 and CE were highlighted and analyzed in section 4. Discussion and implications of the research are presented in Section 5. The conclusions, limitations, and future directions are presented in Section 6.

1. **The Systematic Literature Review**

A Systematic Literature Review (SLR) is a methodology used for performing a comprehensive study of past and present work on a research topic (Vinodh et al., 2021). The motive of SLR is to study the available work and to analyze the current trend on a specified topic. The SLR methodology helps the reviewers in identifying the gaps in the research and provides insights about potential future directions. Many authors have used the SLR methodology in different areas like; Cherrafi et al. (2017) identified barriers of lean green adoption using the SLR methodology, Kamble et al. (2018) reviewed frameworks for sustainable I4.0 through SLR, Sassanelli et al. (2019) used the SLR to review performance assessment models of CE, Moghdani et al. (2020) analyses transportation routing problem of a green vehicle using SLR, Sihag and Sangwan (2020) used SLR for energy consumption analysis of machine tools, and Sassanelli et al. (2020) presented a review on design approaches in the CE context using SLR.

The SLR methodology used by the authors of this paper is presented in Figure 1.

[Figure 1 about here]

* 1. **Selection of Databases**

The first step in a literature review is the selection of articles from reliable databases. In this study, the SCOPUS database was selected to find relevant articles in I4.0 and CE domains. SCOPUS is one of the largest and most widely used databases containing millions of peer-reviewed articles from refereed journals (Nair et al., 2021). SCOPUS includes major publishers such as Emerald, Taylor and Francis, Elsevier, Springer, and IEEE. For this work, publications were selected from within the time interval of 2011-2020.

* Conclusions from study
* Practical and managerial implications
* Future direction for research work

Systematic review of shortlisted articles based on different perspective

Bibliometric analysis of collected articles using R package and VOSviewer

* Collection of articles pertaining to Industry 4.0 and CE based on database, inclusion and exclusion criteria and keywords
* Further shortlisting of articles based on relevance

**Selected keywords**

Industry 4.0 and “Circular Economy”, Smart manufacturing and “Circular Economy”, Digital manufacturing and “Circular Economy”, Internet manufacturing and “Circular Economy”, Intelligent manufacturing and “Circular Economy”, Cloud manufacturing and “Circular Economy”, Cyber physical system and “Circular Economy”, Smart factory and “Circular Economy”, Digital factory and “Circular Economy”, Internet factory and “Circular Economy”, Cyber manufacturing and “Circular Economy”, and “Circular Economy 4.0”

**Selected Database**

SCOPUS

(which includes major publishers like: Emerald, IEEE, Springer, Elsevier, and Taylor and Francis)

**Inclusion Criteria**

Refereed journals, conferences, and book chapters, English language

**Exclusion Criteria**

Magazine articles, Non- refereed journals and conferences

* To analyse literature on Industry 4.0 and CE;
* To identify and analyse research gaps from the selected literature
* To perform bibliometric analyses on Industry 4.0 and CE.
* To discuss future research directions
* Selection of database
* Selection of keywords
* Defining inclusion and exclusion criteria

**Figure 1:** SLR methodology Framework used in this study of I4.0 and CE

* 1. **Selection of Keywords**

One of the objectives of this study was to obtain insights on the integration of two emerging research topics (Industry 4.0 and Circular Economy) from the articles published in the 2011-2020 time interval. One of the major concerns was the selection of keywords/phrases to identify relevant articles. In this study, the following keywords were used for finding relevant articles in the field of I4.0 and CE:

Industry 4.0 and “Circular Economy”, Smart manufacturing and “Circular Economy”, Digital manufacturing and “Circular Economy”, Internet manufacturing and “Circular Economy”, Intelligent manufacturing and “Circular Economy”, Cloud manufacturing and “Circular Economy”, Cyber-physical system and “Circular Economy”, Smart factory and “Circular Economy”, Digital factory and “Circular Economy”, Internet factory and “Circular Economy”, Cyber manufacturing and “Circular Economy”, and “Circular Economy 4.0”.

* 1. **Defining Inclusion and Exclusion Criteria**

Inclusion criteria used in this study were peer-reviewed journals, refereed conferences and book chapters. Only articles written in the English language were considered in this study. Exclusion criteria used were: non-refereed journals, conference proceedings, and, magazine-type articles. You state that book chapters were included in the first sentence and that book chapters were excluded in the second sentence. Which way was it done? Please correct this.

* 1. **Collection of Articles on Industry 4.0 and Circular Economy**

Articles were collected from the SCOPUS database, searching for articles with selected keywords and inclusion and exclusion criteria in the field of I4.0 and CE. The total number of articles found in the searches included 267 articles. The numbers of articles pertaining to each keyword or keyword phrases are presented in Table 1.

**Table 1:** Search results of articles for the literature review on I4.0 and CE

|  |  |
| --- | --- |
| **Input keywords** | **Available papers** |
| Industry 4.0 and “Circular Economy” | 97 |
| Smart manufacturing and “Circular Economy” | 35 |
| Digital manufacturing and “Circular Economy” | 40 |
| Internet manufacturing and “Circular Economy” | 27 |
| Intelligent manufacturing and “Circular Economy” | 23 |
| Cloud manufacturing and “Circular Economy” | 12 |
| Cyber-physical system and “Circular Economy” | 12 |
| Smart factory and “Circular Economy” | 11 |
| Digital factory and “Circular Economy” | 8 |
| Internet factory and “Circular Economy” | 7 |
| Cyber manufacturing and “Circular Economy” | 5 |
| “Circular Economy 4.0” | 2 |
| **Total** | **267** |

* 1. **Narrowing Down the Number of Articles and Final Shortlisting of Selected Articles for In-depth Content Analyses**

For further narrowing the focus, articles were selected based on the relevance of their focus and scope. Duplicate articles were removed. Finally, 165 articles were selected for in-depth content analyses.

1. **The Bibliometric Analyses of the Articles Selected for this In-Depth Literature Review**

There were many articles based upon bibliometric analyses in different fields, which used an array of software packages. Some important packages for the performance of bibliometric analysis include HistCite, Publish and Perish, BibExcel, Gephi, R module, Pajek, and VOS viewer (Fahimnia et al., 2015; Sharma et al., 2020). Fahimnia et al. (2015) used Gephi and BibExcel for bibliometric analyses on the topic, ‘green supply chain management.’ The authors of this literature review highlighted the research in the field of the green supply chain and also highlighted research clusters and collaboration patterns among researchers in the field of the green supply chain.

Xu et al. (2018b) used BibExcel for bibliometric analyses of supply chain finance. They identified four research clusters: 1. The economic order quantity-based inventory model; 2. Inventory decisions under complex situations; 3. Relations between the replenishment model and the delay payment strategy; and 4. Roles of financing services in supply chain. The authors developed a roadmap for future directions in supply chain finance. Kamble et al. (2018) published a review on sustainable I4.0 using BibExcel, Gephi, and Pajek. The authors analyzed the research in I4.0, reviewed the frameworks for sustainable I4.0, and developed a sustainable framework for Industry 4.0 by considering three aspects: I4.0 technologies, process integration and sustainable outcomes. Sharma et al. (2020) used the R package, and the VOS viewer for their bibliometric study on sustainable manufacturing and I4.0 They evaluated relevant articles and provided a roadmap for future research directions in that evolving field.

Although HistCite, Publish and Perish, and BibExcel are widely used tools for bibliometric analysis, they all have limitations such as Publish and Perish only takes data from Microsoft academic research and Google Scholar. HistCite only builds upon data from the WOS, and BibExcel requires more time in performance of the analyses than required by some of the other methods. (Fahimnia et al., 2015; Sharma et al., 2020).

In this context, the authors of this article used the R-package for bibliometric analyses and the VOS viewer for network analyses. Based upon the selected articles, the number of selected articles published from 2001 to 2020 are presented in Figure 2.

**Figure 2:** Year-wise articles on I4.0 and CE selected for in-depth content analysis for this literature review.

From Figure 2, it is clear that increasing numbers of articles in this area were published from 2014 to 2019. In this paper, the bibliometric analyses were put into four groups, with several subgroups. The four groups were (1) document type, (2) authors, (3) countries of origin of the authors, and (4) word analysis.

**3.1 Document Study of Analysed Articles in the Field of I4.0 and CE**

A total of 165 documents were shortlisted for review and bibliometric analyses. A summary of the bibliometric analyses is presented in Table 2.

**Table 2:** Summary results from the bibliometric analyses of the 165 articles in the field of I4.0 and CE that were selected for this in-depth literature review

|  |  |
| --- | --- |
| **Description** | **Results** |
| **Main Information About Data** | |
| Timespan | 2011 through 2020 |
| Sources (Journals, Books, etc.) | 99 |
| Documents | 165 |
| Average years from publication | 1.45 |
| Average citations per document | 12.88 |
| Average citations per year per doc | 3.854 |
| Total References cited among the 165 articles selected for this literature review. | 9339 |
| **Document Types** | |
| Articles | 85 |
| Books | 1 |
| Book chapters | 6 |
| Conference papers | 48 |
| Conference reviews | 10 |
| Reviews | 13 |
| Short surveys | 2 |
| **Document Contents** | |
| Keywords Plus (ID) | 1111 |
| Author's Keywords (DE) | 532 |
| **Authors** | |
| Authors | 505 |
| Author Appearances | 614 |
| Authors of single-authored documents | 13 |
| Authors of multi-authored documents | 492 |
| **Authors Collaborations** | |
| Single-authored documents | 22 |
| Documents per Author | 0.327 |
| Authors per Document | 3.06 |
| Co-Authors per Document | 3.72 |
| Collaboration Index | 3.44 |

The data provide insights into the scope of the 165 articles published from 2011 to 2020 extracted from the SCOPUS database in the field of I4.0 and CE. From Table 2, it can be seen that a total of 165 articles about I4.0 and CE were selected and were published in 99 sources, including journals, conference proceedings, book chapters, reviews, and short surveys. The total keywords used were 1111. The number of unique authors of the 165 articles was 505, The number of articles with single authors was 22, and the remainder were authored by multiple authors. The top ten publishing sources of articles on I4.0 and CE are included in Table 3.

**Table 3:** The top ten journals that published articles in the field of I4.0 and CE during the 2011- 20 timeframe, that were selected for in-depth content analyses for this literature review.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Year** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **Total** |
| Sustainability | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 7 | 2 | 12 |
| Resources, Conservation and Recycling | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 3 | 5 | 11 |
| Journal of Cleaner Production | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 2 | 5 | 9 |
| Procedia  Manufacturing | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 4 | 1 | 6 |
| Procedia CIRP | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 0 | 6 |
| Benchmarking: An International Journal | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 4 |
| Smart Innovation, Systems and Technologies | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 4 |
| Chemie-Ingenieur Technik | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 3 |
| Materials | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 2 | 3 |
| Energy Procedia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 3 |
| **Total** | **0** | **0** | **0** | **0** | **1** | **3** | **4** | **10** | **26** | **17** | **61** |

It can be seen that the journals: Sustainability, Resource Conservation and Recycling, and the Journal of Cleaner Production were among the most frequently used journals for publishing the selected review articles in the field of I4.0 and CE.

**3.2 Authors Statistics**

Author’s data were collected from the SCOPUS database and were fed into the R-package for analysis. The top ten contributing authors in the field of I4.0 and CE are presented in Table 4. It can be seen from Table 4 that Moreno M, Charnley F, and Tiwari A. were the top contributing authors. They have collaborated with many authors and published 8, 7, and 5 articles, respectively, in the field of I4.0 and CE.

**Table 4:** The top ten contributing authors in the field of I4.0 and CE during the 2011- 2020

|  |  |
| --- | --- |
| **Authors** | **Articles** |
| Moreno M | 8 |
| Charnley F | 7 |
| Tiwari A | 5 |
| Aguayo-Gonzlez F | 4 |
| Bag S | 4 |
| Tseng ML | 4 |
| Turner C | 4 |
| Hutabarat W | 3 |
| Pearce JM | 3 |
| Rosa P | 3 |

Authors Dominance Factor (DF) was calculated to evaluate the ranking of authors in their number of published articles in this joint field. The DF of any author is the ratio of the number of multi-authored articles in which the author’s position is first to the total number of multi-authored articles published by the author. The author’s DF can be calculated using the ratio given (Sharma et al., 2020).

The Authors DF is presented in Table 5.

DF=

Where *Nmf* is the number of the multi-authored document in which the author is in the first position. *Nmt* is the total number of a multi-authored document by that author.

**Table 5:** Contributing author’s dominance factor in the field of I4.0 and CE with regard to the articles selected for in-depth content analyses for this literature review.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Author** | **Dominance Factor** | **Tot Articles** | **Single-Authored** | **Multi-Authored** | **First- Authored** | **Rank by Articles** | **Rank by DF** |
| Bag S | 1 | 4 | 0 | 4 | 4 | 3 | 1 |
| Bressanell IG | 1 | 2 | 0 | 2 | 2 | 9 | 1 |
| Okorie O | 0.667 | 3 | 0 | 3 | 2 | 6 | 3 |
| Tseng ML | 0.5 | 4 | 0 | 4 | 2 | 3 | 4 |
| Byard DJ | 0.5 | 2 | 0 | 2 | 1 | 9 | 4 |
| Moreno M | 0.375 | 8 | 0 | 8 | 3 | 1 | 6 |
| Rosa P | 0.333 | 3 | 0 | 3 | 1 | 6 | 7 |
| Sassanell IC | 0.333 | 3 | 0 | 3 | 1 | 6 | 7 |
| Turner C | 0.25 | 4 | 0 | 4 | 1 | 3 | 9 |
| Charnle F | 0.143 | 7 | 0 | 7 | 1 | 2 | 10 |

**3.3 Institutional Statistics**

Institution’s data were taken from the SCOPUS database and were fed into the R-package for institutional statistics that were analysed based on the number of articles published. Institution’s statistics highlight op contributing institutes in the field. Table 6 presents the top ten contributing institutes in the field of I4.0 and CE. From the table, it is clear that the Cranfield University of the United Kingdom and Michigan Technological University of the United States were the top two contributing institutes with 10 and 8 articles respectively in the field of I4.0 and CE.

**Table 6:** Rank of the contributing organizations of articles in the field of I4.0 and CE that were articles selected for in-depth content analyses in this literature review.

|  |  |
| --- | --- |
| **Affiliations with Country** | **Articles** |
| Cranfield University, United Kingdom | 10 |
| Michigan Technological University, United States | 8 |
| Politecnico Di Milano, Italy | 6 |
| Asia University, Taiwan | 5 |
| Montpellier Business School, France | 5 |
| University of Nottingham, United Kingdom | 5 |
| University of Sheffield, United Kingdom | 5 |
| Aalto University, Finland | 4 |
| London South Bank University, United Kingdom | 4 |
| University of Johannesburg, South Africa | 4 |

**3.4 Country-Wise Statistics**

Data were extracted from the SCOPUS database for analysing country-wise statistics. Country-wise statistics were analysed based on the numbers of articles published, the Corresponding author’s country, and citations of articles. Table 7 presents the top contributing countries in the field of Industry 4,0 and CE.

**Table 7:** The top ten countries with authors publishing articles in the field of I4.0 and CE, that were selected for in-depth content analysis for this literature review.

|  |  |
| --- | --- |
| **Country** | **No. of Articles** |
| United Kingdom | 65 |
| Italy | 36 |
| China | 34 |
| United States | 28 |
| Germany | 20 |
| Spain | 20 |
| Brazil | 19 |
| India | 19 |
| Finland | 17 |
| France | 16 |

From Table 7, it can be seen that the UK, Italy, and China were the top contributing countries in the field of I4.0 and CE with 65, 36, and 34 published articles, respectively. Table 8 shows the corresponding author's countries, based on published articles and article frequency. While analysing country statistics, Single Country Publications (SCP) and Multi-Country Publications (MCP) were analysed.

**Table 8:** Corresponding authors countries of the articles selected for in-depth content analysis for this literature review in the field of I4.0 and CE.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Country** | **Articles** | **Frequency** | **SCP** | **MCP** | **MCP Ratio** |
| Italy | 10 | 0.1613 | 4 | 6 | 0.6 |
| China | 5 | 0.0806 | 3 | 2 | 0.4 |
| France | 5 | 0.0806 | 1 | 4 | 0.8 |
| Germany | 5 | 0.0806 | 5 | 0 | 0 |
| United Kingdom | 4 | 0.0645 | 4 | 0 | 0 |
| India | 3 | 0.0484 | 1 | 2 | 0.667 |
| Poland | 3 | 0.0484 | 3 | 0 | 0 |
| Singapore | 3 | 0.0484 | 3 | 0 | 0 |
| Spain | 3 | 0.0484 | 3 | 0 | 0 |
| USA | 3 | 0.0484 | 2 | 1 | 0.333 |

From Table 8, it can be seen that most of the corresponding authors were from Italy, followed by China, France, and Germany. The top countries with the highest citations and average citations per article are presented in Table 9.

**Table 9:** Ranking of the top ten country’s citations of the articles selected for in-depth content analysis for this literature review in the field of I4.0 and CE.

|  |  |  |
| --- | --- | --- |
| **Country** | **Total Citations** | **Average Article Citations** |
| Netherlands | 600 | 300.00 |
| Italy | 391 | 39.10 |
| France | 179 | 35.80 |
| USA | 55 | 18.33 |
| India | 46 | 15.33 |
| Poland | 44 | 14.67 |
| Spain | 38 | 12.67 |
| United Kingdom | 34 | 8.50 |
| Denmark | 28 | 14.00 |
| Singapore | 26 | 8.67 |

From Table 9, it is clear that authors from The Netherlands have the highest citation of 600 and 300 average citations per article, followed by authors from Italy and France with 391 and 179 citations respectively in the field of I4.0 and CE.

**3.5 Citation Statistics**

Citation data were collected from the SCOPUS database and were analysed for the citation statistics of the articles. Year-wise, citations in the field of I4.0 and CE are presented in Table 10.

**Table 10:** Year-wise article citations of the articles selected for in-depth content analyses in the field of I4.0 and CE.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Year** | **No. of Articles** | **Average total citation per article** | **Average total citation per year** | **Citable years** |
| 2011 | 0 | 0 | 0 | 9 |
| 2012 | 0 | 0 | 0 | 8 |
| 2013 | 1 | 0 | 0 | 7 |
| 2014 | 7 | 4.288 | 0.7143 | 6 |
| 2015 | 3 | 292.667 | 58.534 | 5 |
| 2016 | 7 | 14 | 3.5 | 4 |
| 2017 | 10 | 12 | 4 | 3 |
| 2018 | 28 | 21.5 | 10.75 | 2 |
| 2019 | 62 | 5.258 | 5.258 | 1 |
| 2020 | 47 | 1.532 |  | 0 |

From Table 10, it can be observed that articles published in 2015 have the highest average citations at 292, followed by articles published in 2018 with an average of 21.5 citations per article.

The main objective of citation statistics is to identify and analyse the most influential and highly cited articles. The top ten authors with the highest global citations are listed in Table 11.

**Table 11:** Top ten globally most highly cited documents based upon the articles selected for in-depth content analyses in the field of I4.0 and CE.

|  |  |  |
| --- | --- | --- |
| **Cited References** | **Total Citations** | **TC per year** |
| Tukker (2015) | 580 | 96.667 |
| Cucchiella et al. (2015) | 290 | 48.333 |
| de Sousa Jabbour et al. (2018) | 112 | 37.333 |
| Tseng et al. (2018) | 87 | 29 |
| Bressanelli et al. (2018a) | 64 | 21.333 |
| Fisher et al. (2018) | 61 | 20.333 |
| Jabbour et al. (2019) | 52 | 26 |
| Tolio et al. (2017) | 44 | 11 |
| Zhong and Pearce (2018) | 38 | 12.66 |
| Nascimento et al. (2019) | 38 | 8.6 |

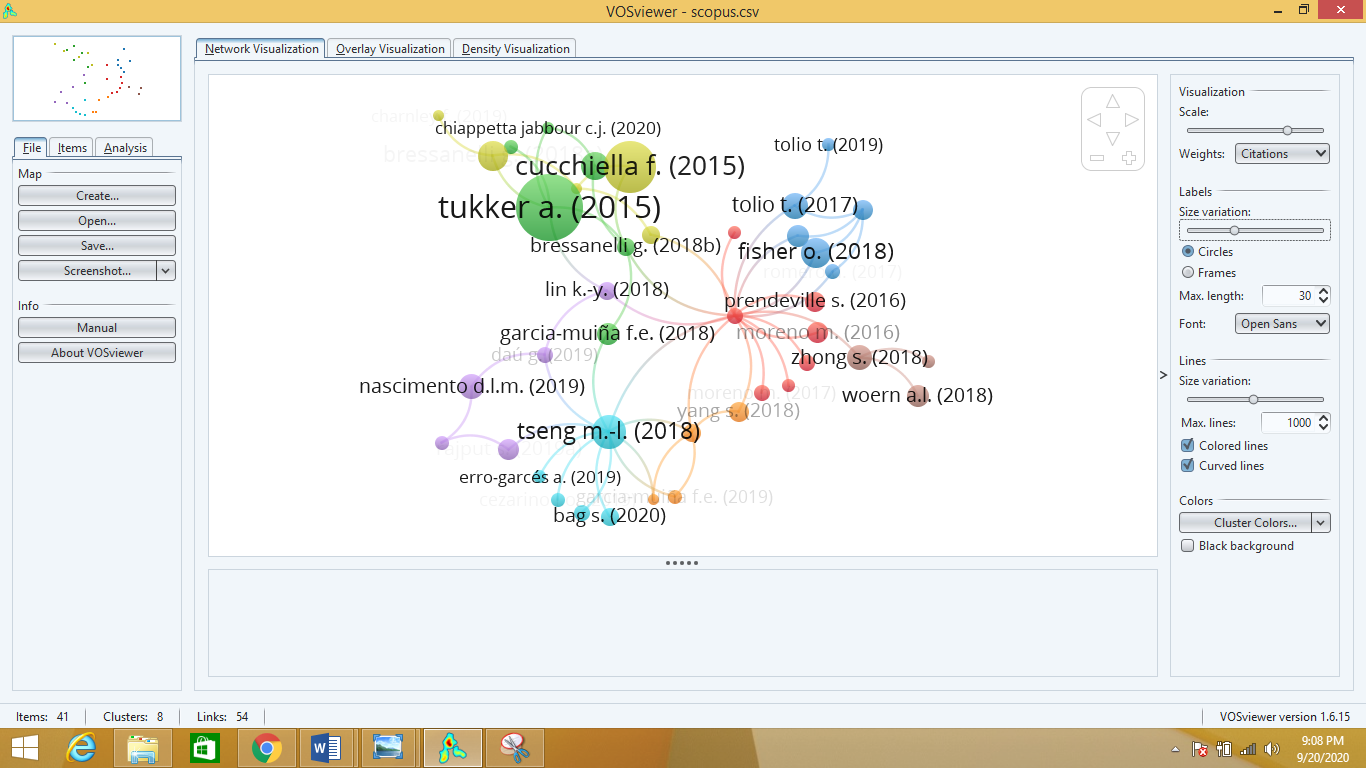
Local citations refer to the citations received by the selected articles (i.e., citation received from 169 selected articles). Global citations refer to the citations received by articles from the comprehensive SCOPUS database of articles. From Table 11, it is evident Tukker (2015) received the highest number of citations of 580, followed by Cucchiella et al. (2015) with 290 and by de Sousa Jabbour et al. (2018) with 112 global citations in the field of I4.0 and CE. Table 12 provides the top ten most local cited author teams in the area of I4.0 and CE

**Table 12:** The top ten most frequently cited documents based upon the articles selected for in-depth content analyses in the field of I4.0 and CE.

in the area of I4.0 and CE

| **Cited References** | **Citations** |
| --- | --- |
| Stock and Seliger (2016) | 17 |
| Kirchherr et al. (2017) | 10 |
| Ghisellini et al. (2016) | 8 |
| Lieder and Rashid (2016) | 8 |
| Pagoropoulos et al. (2017) | 8 |
| Abdi and Labib (2003) | 7 |
| Abdi and Labib (2004) | 7 |
| Antikainen et al. (2018) | 6 |
| Ghisellini et al. (2016) | 6 |
| Mehrabi et al. (2000) | 6 |

From Table 12, it is clear that the article by Stock and Seliger (2016) received the highest number of local citations of 17, followed by Kirchherr et al. (2017) and Ghisellini et al. (2016) with 10 and 8 local citations respectively in the field of I4.0 and CE. Figure 3 Contains a graphical representation of a global citation network.



**Figure 3:** Global citation network of the authors of the articles selected for in-depth analyses in the field of I4.0 and CE

**3.6 Keywords Statistics**

Keyword statistics designed to analyse the most frequently used keywords article titles and in the keyword’s section. Authors used different keywords in their studies in the field of I4.0 and CE. It is important to analyse different keywords used in the field of I4.0 and CE. From a list of 1111 keywords used by authors, the top twenty most frequently used keywords are presented in Table 13.

**Table 13:** Top twenty keywords used in the field of I4.0 and CE

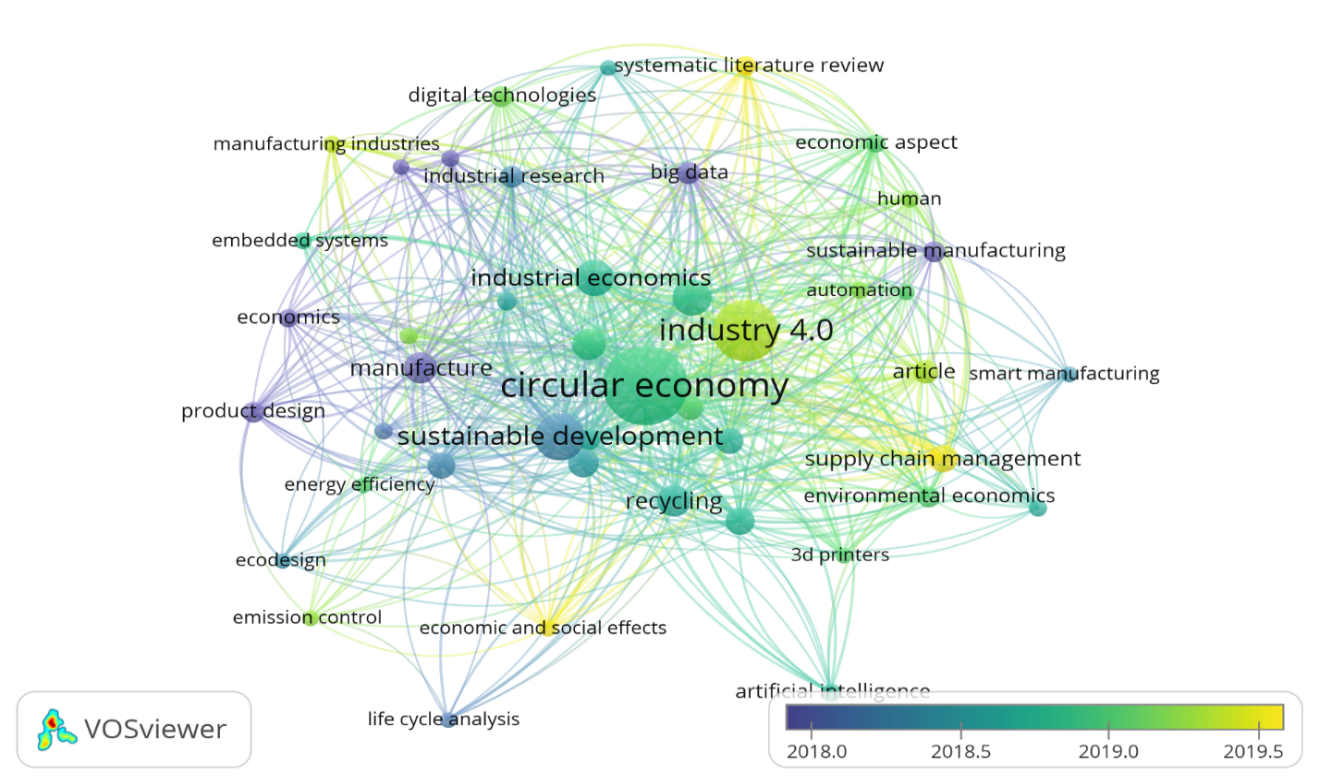
|  |  |  |  |
| --- | --- | --- | --- |
| **Words** | **Occurrences** | **Words** | **Occurrences** |
| Circular Economy | 58 | Internet of Things | 14 |
| Sustainable Development | 37 | Manufacturing | 14 |
| Industry 4 0 | 34 | Life Cycle | 13 |
| Industrial Economics | 24 | Article | 11 |
| Recycling | 21 | Environmental Impact | 11 |
| Manufacture | 19 | Sustainability | 11 |
| Waste Management | 18 | Big Data | 10 |
| Supply Chains | 16 | Industrial Research | 10 |
| Decision Making | 15 | Digital Technologies | 9 |
| Supply Chain Management | 15 | Environmental Economics | 9 |

A word cloud of the most frequently used keywords is developed using the R software and is presented in Figure 4.



**Figure 4:** The word cloud of the top keywords used in the selected articles of this literature review focused upon the field of I4.0 and CE

From Table 13 as well from Figure 4, it can be seen that the most frequently used words were Circular Economy, Sustainable Development, and I4.0 with the occurrence of 58, 37, and 34 times respectively in the field of I4.0 and CE. An overlay visualization of words was developed using the VOS Viewer, as shown in Figure 5.

******

**Figure 5:** Overlay visualisation of top keywords used in the articles selected for this literature review in the field of I4.0 and CE

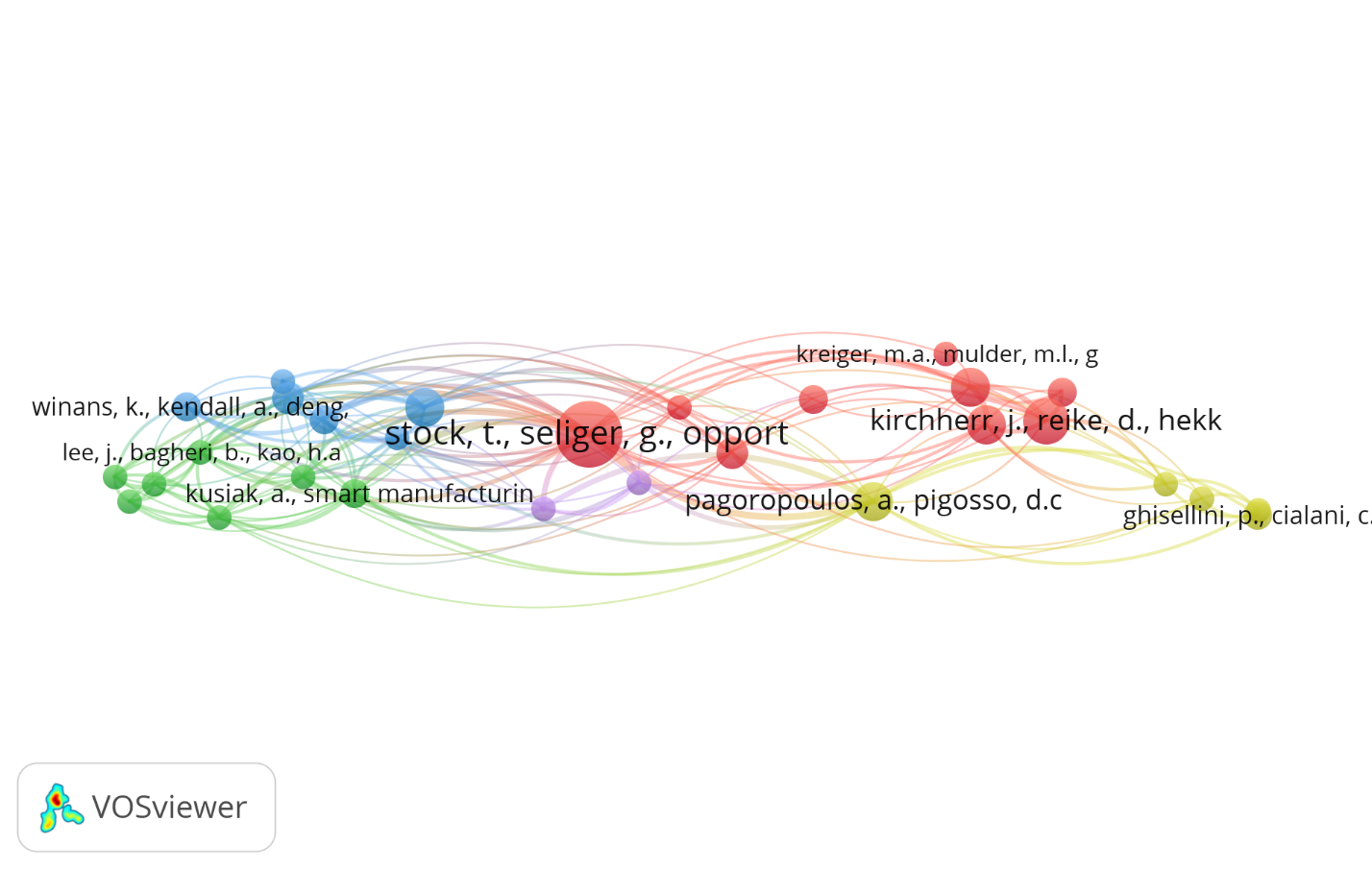
It shows connections and occurrence of keywords based on published articles in the field of I4.0 and CE.

1. **Network Analysis**

Network analysis was performed using the R-package, and the graphical visualization was done using VOS Viewer. The network analysis was done to analyse the network and collaborations of researchers. Network analysis includes studying global citation networks, co-citation analyses, and collaboration of researchers within different countries.

* 1. **Co-citation Analysis**

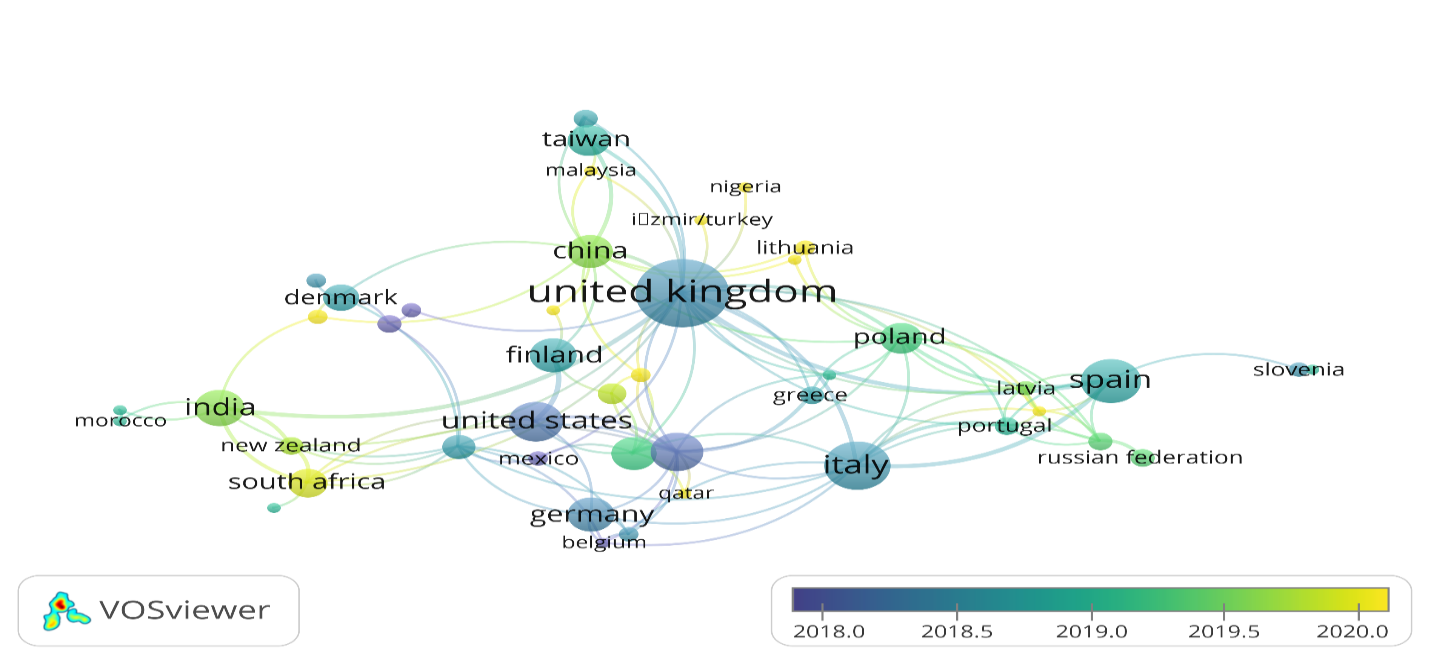
Co-citation of articles means the combined effect of articles. Co-citation between two articles occurs when other articles cite both articles. Co-citation analysis has been done in VOS Viewer with the help of SCOPUS data and is graphically represented in Figure 6. Nodes represent articles, and their co-citation occurrence is represented by links connecting nodes, as shown in Figure 6.



**Figure 6:** Co-citation analysis of articles selected for this literature review in the field of I4.0 and CE

* 1. **Country Collaboration**

Country collaboration is an essential aspect in network analysis to show collaborations of researchers with different countries researchers. The country collaboration network is presented in Figure 7. It can be seen that more collaborations are found from researchers belongs to the UK and Italy, as shown in Figure 7.



**Figure 7:** Country author collaboration in articles selected for this literature review in the field of I4.0 and CE

* 1. **Cluster Analysis**

Cluster analysis is an important aspect in the bibliometric study to analyse the network among authors, publications, and Co-citations. Cluster analysis is used to analyse the structure of a network based on published articles (Sharma et al., 2020). In this study, the top five research clusters have been formed in I4.0 and CE to show their research study. Table 14 presents lead articles under each cluster along with their links and Total Link Strength (TLS). The TLS indicates the total link strength of co-citation links of an article with other articles.

**Table 14:** Clusters of author teams of the articles selected for this literature review in the field of I4.0 and CE

|  |  |  |
| --- | --- | --- |
| **Cluster 1 articles** | **Link** | **Total Link strength** |
| Stock and Seliger (2016) | 25 | 62 |
| Antikainen et al. (2018) | 17 | 22 |
| Nobre and Tavares (2017) | 16 | 19 |
| Kirchherr et al. (2017) | 10 | 19 |
| Genovese et al. (2017) | 9 | 18 |
| Luthra and Mangla (2018) | 4 | 7 |
| Kreiger et al. (2014) | 2 | 2 |
| **Cluster 2 articles** | **Link** | **Total Link strength** |
| Kusiak (2018) | 17 | 30 |
| Lee et al. (2015) | 14 | 27 |
| Oesterreich and Teuteberg (2016) | 17 | 24 |
| Kamble et al. (2018) | 10 | 18 |
| Xu et al. (2018a) | 10 | 17 |
| Leitão et al. (2016) | 9 | 16 |
| Qin et al. (2016) | 8 | 13 |
| **Cluster 3 articles** | **Link** | **Total Link strength** |
| Su et al. (2013) | 15 | 29 |
| de Man and Strandhagen (2017) | 14 | 27 |
| Lieder and Rashid (2016) | 14 | 27 |
| Nasir et al. (2017) | 10 | 17 |
| Winans et al. (2017) | 9 | 15 |
| **Cluster 4 articles** | **Link** | **Total Link strength** |
| Pagoropoulos et al. (2017) | 17 | 34 |
| Murray et al. (2017) | 9 | 15 |
| Ghisellini et al. (2016) | 4 | 10 |
| **Cluster 5 articles** | **Link** | **Total Link strength** |
| Romero and Noran (2017) | 13 | 20 |
| Chang et al. (2017) | 9 | 19 |

* 1. **Emerging research themes**

***4.4.1 Cluster 1: Smart and circular supply chain***

The circular practices in logistics and supply chain management can help to enable consumers to return products after use and to reuse products with more value. To obtain a smoothly functioning circular supply chains, deployment of I4.0 technologies is essential. The literature about sustainable supply chains and smart logistics was reviewed. For example, the sustainable supply chain of a paper manufacturing company provided opportunities for transforming their linear chain to a CE chain by using 6R’s across the supply chain (Manavalan and Jayakrishna, 2019, Ozkan-Ozen et al., 2020).

***In cluster 1***, the top articles were authored by Stock and Seliger (2016) with a TLS of 62. They published reviews on the development of I4.0 practices, they highlighted the opportunities of using I4.0, and presented a case study example of retrofitting a machine tool for sustainable development in I4.0. Antikainen et al. (2018) have a TLS of 22. They recognized the difficulties associated with business adoption of 140 for improving data management, collection, collaboration, and competence requirements and providing solutions The study by Nobre and Tavares (2017) has a TLS of 19 and published a bibliometric study on IoT and Big Data in the CE context. Kirchherr et al. (2017) has a TLS of 19 and discussed the conceptualization of CE based on different definitions in the literature and provided insight into its relevance. The study by Genovese et al. (2017) has a TLS of 18: they compared the performance of the circular supply chain model with that of the linear supply chain through an life cycle assessment (LCA) integrated methodology. They found that circular supply chain model performs well in comparison to linear supply chain. The LCA integrated methodology reveal the information about the environmental impact facilitating Industry 4.0 in circular economy. Luthra and Mangla (2018) have a TLS of 7, and they identified potential challenges of adoption of I4.0 technologies in the sustainable supply chain in Indian manufacturing industries. The study found organization challenge as the most critical challenge in adopting I4.0 technologies for sustainable supply chain. The study recommended to focus on organizational challenges for smooth adoption of I4.0 technologies in sustainable supply chain. Kreiger et al. (2014), who have TLS of 2 in cluster 1, developed an LCA assessment on recycling filament used in 3D printing. They compared the centralized recycling system with that of the distributed recycling system and found that distributed recycling system consumes lesser energy in comparison with centralized recycling system. The study recommended to adopt distributed recycling system for filament used in 3D printing.

Implementation of smart manufacturing into the logistical system enhanced the remanufacturing capabilities of South African manufacturing firms (Bag et al., 2020a). The authors used an approach to integrate I4.0 technologies in smart logistics to improve their remanufacturing capabilities. Bag et al. (2020b) sought to improve the procurement process by adopting I4.0 technologies and CE principles. The authors surveyed South African manufacturing firms to assess the impact of I4.0 technologies in procurement optimization and CE performance. A structural equation modeling approach was used to analyse the survey results. The authors found that procurement 4.0 helps to improve the functionality of the business strategies, business performance, and CE performance. The authors used a simulation of business processes and demonstrated the potentials of Industry 4.0 technologies in the procurement process within a CE context.

Based upon the brief reviews of several articles as presented in the forgoing paragraphs. We propose the following propositions for future research in this identified theme:

***Proposition 1:*** Development and application of effective mathematical models is required to optimize industrial practices for minimizing resource consumption and waste generation.

***Proposition 2:*** To focus on adoption of big-data analytics in order to improve the efficiency and effectiveness of sustainability aspects of the entire industrial-customer system.

***Proposition 3:*** To analyse the risks and challenges of smart and sustainable supply chain concerning improvement in supply chain capabilities.

***Proposition 4:*** Examining the role of disruptive technologies of I4.0 in achieving the SDGs.

***4.4.2 Cluster 2: Business Models of Industry 4.0 and the Circular Economy***

The ‘*business models* used by companies help the management to evaluate and build upon the opportunities to provide quality products and services to their customers (Pizzi et al., 2021, Preghenella and Battistella, 2021). The models can help the companies to achieve competitive edges over their competitors (Rajput and Singh, 2019). Proper introduction and implementation of I4.0 technologies are needed to efficiently operate CE-based business models (Chauhan et al., 2018, Norris et al., 2021). In cluster 2, the article by Kusiak (2018) has a TLS of 30; their research investigated recent developments in manufacturing and discussed various technologies of smart manufacturing. They recommend adopting the data-driven model for a smooth transformation to smart manufacturing. Lee et al. (2015) have a TLS of 27, and they presented a CPS architecture for implementation in manufacturing systems. They found that the developed architecture can provide practical guidelines for manufacturing organization to adopt the CPS. In this way the product quality would enhance, and system reliability becomes more intelligent along with flexible manufacturing equipment.

The study by Oesterreich and Teuteberg (2016), who have a TLS of 24, reviewed the deployment of I4.0 technologies in construction industries and documented the beneficial implications on TBL aspects of sustainability. Kamble et al. (2018) have a TLS of 18, they analyzed the current research in I4.0, and reviewed frameworks for sustainable I4.0. The authors analyzed the research in I4.0, reviewed the frameworks for sustainable I4.0, and developed a sustainable framework for Industry 4.0 by considering three aspects: I4.0 technologies, process integration and sustainable outcomes. Xu et al. (2018a) have TLS of 17 and, they reviewed I4.0 technologies and their adoption in China. They found that lack of powerful tools still exist as a major hurdle in completely utilizing the potential of I4.0. They recommended to identify unique challenges that are crucial for exploiting the I4.0 technologies in CE.

The study by Leitão et al. (2016) has a TLS of 16; they investigated various aspects of CPS and reviewed the challenges of adopting CPS. They found that application and understanding of industrial automation pertaining to CPS technologies recognized as the key challenge in adoption of CPS. They recommended to raise present technology readiness level leading to broad use of CPS based system in industrial automation systems. Further Qin et al. (2016) have a TLS of 13; they discussed the concepts of I4.0 and identified the gaps between current manufacturing scenarios and I4.0. They recommended a multi-layer framework for implementation of I4.0 and the recommended framework enables the practitioners to understand the requirement of I4.0. Nascimento et al. (2018) established a business model for reuse and recycling of the material waste with the help of I4.0 and CE integration. They investigated these aspects and identified of CE implementation success factors and difficulties through a literature review. They developed a conceptual framework for integration and validation of the framework by conducting interviews with top-level managers. The findings of the study underscored the importance of using a circular model to facilitate the recycling of electronic devices via the smooth implementation of CE practices.

An IOT based decision-support system for a CE business model that can facilitate monitoring and tracking of products in real-time was implemented by Mboli et al. (2020). The authors integrated an ontological model with IoT-based decision support system (DSS) to support the CE model. The DSS and ontological model were implemented in real-time to test validate its application.

Therefore, to research more deeply on this theme, we propose the following propositions for future research:

***Proposition 5:*** Todevelop a hierarchical model and prioritization using suitable decision-making methods.

***Proposition 6:*** Identification of industrial strategies for smooth adoption of CE practices can be a potential future research direction.

***Proposition 7:*** To conduct performance assessment of adopted CE practices by developing a smart business model.

***Proposition 8:*** Development of a smart decision support system is essential to facilitate integration of I4.0 and CE.

***4.4.3 Cluster 3: Sustainable practices and Circular Economy***

In cluster 3, the study by Su et al. (2013) has a TLS of 29, and they reviewed practices of CE practices adoption in China and recommended that the government support promotes adoption of CE practices. Further, de Man and Strandhagen (2017) have a TLS of 27 in cluster 3. They developed a sustainable business scenario and identified opportunities for implementing I4.0 technologies. The study proposes the business strategy on how I4.0 can be adopted to enable business model more sustainable.

Lieder and Rashid (2016) also have a TLS of 27. They reviewed concepts of CE and presented a conceptual framework for the implementation of CE practices. The study recommended that the complete support from stakeholders is important for successful adoption of CE practices. Nasir et al. (2017) have a TLS 17 as they integrate CE principles in the sustainable supply chain domain for the construction industry. Winans et al. (2017) have a TLS of 10. It was based upon their review of the history and recent trends in CE development and its adoption.

Thus, we propose the following propositions for future research under this identified theme:

***Proposition 9:*** To classify existing challenges in I4.0 and CE by developing a hierarchical model and prioritization using suitable decision-making methods.

***Proposition 10:*** Development of CE framework for effective transition from linear business model to the circular business model. To develop a comprehensive CE framework with integration of I4.0 to better interpret an effective transition from linear business model to the circular business model.

***Proposition 11:*** Analysing the sustainable practices for smooth adoption of circular economy in a manufacturing organization.

***Proposition 12:*** Analysing the relationship between I4.0 and circular economy to enhance sustainable practices using structural modeling techniques.

***4.4.4 Cluster 4: Digital Circular Economy***

The connections between CE and data science’s generic process model were reviewed via a literature review and a case study by Kristoffersen et al. (2019). The authors developed a model based upon the “Cross Industry Standard Process for Data Mining” (CRISP-DM) along with data validation and analytic profiles. In cluster 4, Pagoropoulos et al. (2017) have a TLS of 34, and their research assessed the impacts of I4.0 technologies in the transition towards CE. Their study concluded that I4.0 technologies support the transition towards CE by enabling the reverse flows of materials and optimizing forward flows of materials. Murray et al. (2017) have a TLS of 15, and they analysed challenges and limitations in the adoption of CE. Ghisellini et al. (2016) have a TLS of 10 and discussed CE principles and their adoption at micro and macro levels. Thus, we propose the following propositions for future research for this identified theme:

***Proposition 13:*** To utilise smart Industry 4.0 techniques for real-time data analysis of energy usage in remanufacturing process.

***Proposition 14:*** Adopting smart AI technologies to differentiate different materials with the help of the image recognition approach can be a potential future research work.

***Proposition 15:*** Development of digital-driven CE framework enabling smart circular strategies for manufacturing organizations.

***Proposition 16:*** To examine the role of digitalization in achieving sustainability through the concept of CE.

***4.4.5 Cluster 5: Smart Disassembly***

Adopting ICT-based tools is important for increasing the value of remanufacturing of products and creates opportunities for business collaboration in the supply chains of returned/used products (Glöser-Chahoud et al., 2021, Chiarini, 2021). Several authors (Charnley et al., 2019; Kerin and Pham, 2019; Blömeke et al., 2020) suggested integrating CPS (Cyber-physical system) to IoT for smart remanufacturing. Remanufacturing produces high-quality products that are as good as new products but sell at lower prices and have reduced environmental impacts because there is a dramatic decrease in materials and embedded energy wastage. The application of robotics in disassembly processes can provide benefits and enhanced human-robot collaboration. The robots and other automated systems require enhanced skill-based work, which can motivate management to provide relevant training to enhance worker’s knowledge and skills for effective integration of I4.0.

Additionally, such skilled workers will often contribute to research and innovation to improve the remanufacturing system. In cluster 5, the papery by Romero and Noran (2017) with a TLS of 20, developed a conceptual model of GSVEs and their essential applications. Their model was tested for various life cycle scenarios of GSVEs such as operation, creation, evolution, and dissolution. Chang et al. (2017) have a TLS of 19, and they worked to adopt disassembly methods across several phases of product life cycles to enhance sustainable product development. Thus, we propose the following propositions for future research for this identified theme:

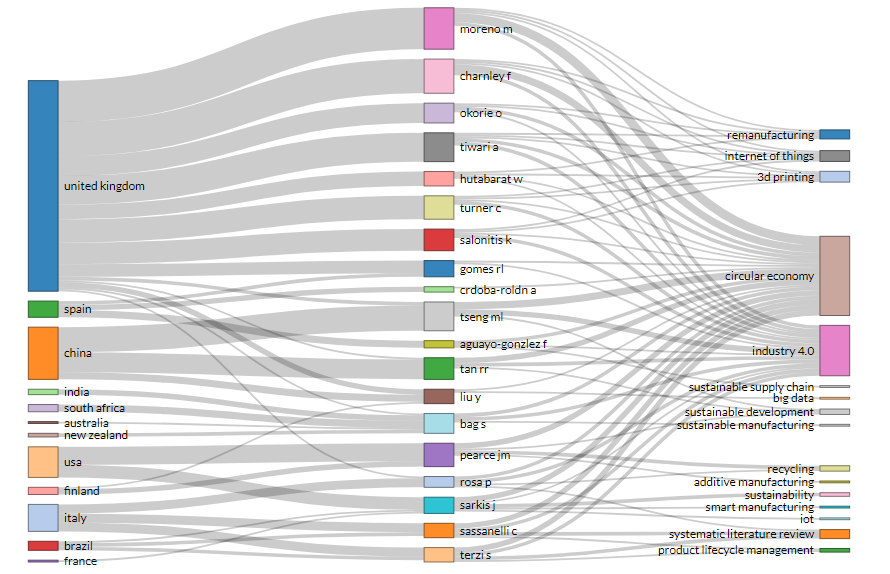
***Proposition 17:*** To enhance the CE practices in I4.0 driven industries by assessing design for smart disassembly.

***Proposition 18:*** To examine the significance of Industry 4.0 technologies in remanufacturing of products enabling smart disassembly.

***Proposition 19:*** Examining the workforce attributes related to I4.0 and CE integration to improve the research and innovation of remanufacturing systems.

***Proposition 20:*** Analysing the significance of robotics technology in enhancing the disassembly process facilitating the reduced environmental impacts.

Finally, three field diagrams were developed based on the bibliometric study, as presented in Figure 8. Three-level field analysis is the graphical representation to linked countries with top contributing authors and used keywords.



**Figure 8:** Three field diagrams from articles selected for in-depth analysis in this literature review in the field of I4.0 and CE

1. **Discussion of Findings**

The authors of this literature review summarised the contents of 165 articles on the integration of I4.0 and CE into supply chain management. In this regard, SLR and bibliometric analyses of I4.0 and CE research were conducted. To proceed with the SLR, articles, conference proceedings, and book chapters published by major publishers like Emerald, IEEE, Springer, Elsevier, and Taylor and Francis were considered. The systematic review of the shortlisted articles considering different criteria such as digital redistributed manufacturing, data analysis in CE, smart disassembly and remanufacturing, smart waste management, digital CE, smart and circular supply chain, business models, challenges, strategies and principles of I4.0 and CE, and framework integrating CE and I4.0.

Additionally, to extract useful information on this integration research, a bibliometric analysis was conducted. In this study, the bibliometric analysis considered four major groups, i.e., document type, authors, countries, and word analysis. Using bibliometric analysis, top journals, influential organizations, leading authors and countries, and significant research trending were identified. Top journals such as Sustainability (Switzerland), Resources, Conservation and Recycling, and Journal of Cleaner Production published articles from I4.0 and CE integration (Table 3). Among the top trending articles, Stock and Seliger (2016), Kirchherr et al. (2017), Ghisellini et al. (2016), Lieder and Rashid (2016), and Pagoropoulos et al. (2017) were identified via co-citation analysis. The top institutions with faculty publishing on I4.0 and CE integration are Cranfield University, United Kingdom, Michigan Technological University in the United States, and Politecnico Di Milano, Italy. Cluster analyses were performed to gain insight into the research networks among the authors. Figure 9 describes the future strategy in the form of a conceptual framework to clarify the benefits of I4.0 technologies for CE. Future research directions are also described.

Smart factory

Customer

DSS integrating IoT and Machine Learning

Disposal

Reuse

Smart Disassembly

DSS integrating IoT and Machine Learning

Upgrade, Reuse, Refurbish, Remanufacture, Recycle, Repurpose & Recover

Smart Management

Feedback

Use

**Figure 9:** The research framework for I4.0 and CE make this and all figure and table legends into compete sentences.

From the systematic literature analysis, missing dimensions such as ethical, ecological, philosophical, and technological concerning CE and I4.0 integration were documented. Currently, CE concentrates on manufacturing redesign, which can contribute to reducing negative environmental impacts. There are ethical aspects such as intra- and inter-generational equity, religious equity, gender, racial equality, financial equality, and social equality, which need to be explored from the CE and I4.0 integration perspectives.

Moreover, reductions in negative ecological impacts from production and consumption are essential because of the finite resources on planet earth. If the annual net increase of 83,000,000 humans on the earth continues, there will be inadequate bio and geo resources to achieve and maintain genuinely ‘Sustainable Societies’. These two dimensions evolve from the social pillar of sustainability, focusing on human stakeholders and human rights. A dimension that must be addressed in future research pertains to the philosophical aspects of CE and I4.0. The idea of circularity has deep philosophical, ethical, and historical roots. In relation to the CE, being responsible for conserving the world’s resources provides the philosophical background of CE, and I4.0 integration that needs to be addressed by researchers to help to achieve equitable, sustainable societies in the context of climate changes, pandemics, food insecurity, water insecurity, cyber insecurity and insecurity due to wars.

Another aspect that was missing in previous studies was the technological dimension. As per the supply chain dive reports, 51% of supply chain practitioners expect an increase their focus on CE strategies in the next two years. Also, reverse logistics concepts are being introduced to make circular systems more effective. These aspects open new avenues for researchers to investigate new ways of helping company leaders to integrate sustainable supply chain concepts that are built upon CE, I4.0 and other evolving digital approaches.

* 1. **Implications of this Study**
     1. ***Implications for industrial practitioners***

In principle, CEs will not only help to save resources but will also monetize and create value across supply chains. However, industrial practitioners and key stakeholders need to accelerate the transformation of their linear models to CE models. To achieve this, digital solutions can support the operation of CE business models. The authors of this review documented the advantages of I4.0 in CE, including the implementation of digital technologies such as IoT and AI for improving manufacturing and product usage analysis. Some of the advantages include smart and circular supply chain which enable consumers to reuse the products with more value. Further, integrating I4.0 technologies into logistics enhances their remanufacturing capabilities.

The re-distributed manufacturing (RdM) business model i.e., redistributed manufacturing business model integrated with 3D printing can help producers of consumer goods enhance sustainable consumption of resources (Turner et al., 2019). The RdM business model can help practitioners to reduce their transportation costs and improve circularity in their processes (Soroka et al., 2017; Turner et al., 2019). The I4.0 technology, big data analytics can help small and medium enterprise (SME) enterprises in a smooth transition towards CE (Sawe et al., 2021). Digital intelligence can help to control and optimize manufacturing assets by integrating CE approaches into their business models. In addition to RdM and I4.0 advantages to CE, documented by (Pagoropoulos et al., 2017; Tseng et al., 2018; Lin et al., 2019) documented the importance of big data for supporting the smooth transition towards CE by creating a reverse flow of materials and enhancing process efficiency and effectivity.

However, practitioners will need to implement AI-based machine learning techniques to take advantage of big data manufacturing processes. The industry practitioners could deploy sensors in machines which can help in collection of critical process parameters. The big data collected through these sensors will help in addressing the process parameter related aspects in turn contributes to manufacturing process improvements. Smart disassembly and remanufacturing will help practitioners to enhance their CE performance through process optimization and effectiveness. But, to ensure the smart disassembly of products, the products must be designed to be upgradeable, repairable, remanufacturable, reusable, recyclable. Also, practitioners will have to develop robotic infrastructure within their industries. Findings from many authors contributed towards smart waste management, digital CE, smart product design, circular supply chains, business models, and frameworks integrating CE and I4.0.

The information based on the I4.0 and CE will help practitioners to work with the challenges and drivers related to CE and utilize the I4.0 solutions to overcome them. Several author teams have proposed frameworks for enhancing workforce skills about I4.0 to ensure smooth CE implementation (Bressanelli et al., 2018; Rosa et al., 2020). Despite the advantages of CE and I4.0 integration, the practitioners will also have to address the technical difficulties associated. The technical difficulties that need to be addressed by the practitioners include sensor technologies, CPS standards, digital up-gradation, semantic interoperability, lack of automation, lack of process design, and expensive infrastructural investments. And the products not being designed to be integrated into these advanced AI facilitated approaches.

* + 1. ***Implications for managers***

The literature review uncovered interesting linkages between I4.0 and CE, such as RdM, smart disassembly, strategies for implementation, smart product design, sustainable supply chain, etc. The critical insights developed from the review can help managers to understand the transformation process of linear economy business models into circular models by realizing the relationships between I4.0 and CEs.

This review can help managers build upon the beneficial synergies between CEs and I4.0 drivers .and their influence in distributing CE concepts among businesses. This will help them to improve their economic and ecological efficiency. Based on the literature review, the authors developed a conceptual framework for applying I4.0 technologies within evolving CEs. That framework can help managers support the implementation of a sustainable culture in manufacturing company’s CE scenarios. However, governmental support and motivation are crucial in encouraging the use of I4.0 technologies for reducing resource consumption and expanding cleaner production. Additionally, the governmental leaders should provide subsidies for developing technological infrastructure for implementing and maintaining CE business structures in the manufacturing sector.

Despite the cost involved in implementing I4.0, managers or critical decision-makers should consider this as a strategic move to improve their economic efficiency, reduce resource consumption, improve worker health and safety, improve consumer safety, promote recycling. Also, considering plastic pollution, a significant global problem that threatens marine and terrestrial ecosystems throughout the world, annually, about eight million tons of plastic are released into water bodies (Tunali et al., 2020b). Hopefully, this review will help decision-makers to address these concerns by integrating CEs and I4.0 The globally increasing biodiversity losses should be used as an additional motivation for company leaders to integrate advanced digital technologies within their evolving CE business models and cleaner production practices (Wallace, 2020). The environmental burden reduction through investment in renewable energies instead of fossil fuel energies will help practitioners reduce their fossil carbon footprints and help them contribute to reducing climate change. (Plantinga and Scholtens, 2020).

* + 1. ***Implications for researchers***

From the analysis of the selected articles for this literature review, the following future research directions are suggested for researchers:

* Although, previous research established various frameworks regarding I4.0 and CE, there still is an urgent need to develop a guideline framework for integration of I4.0 technologies within various stages of CE implementation.
* Previous authors documented strategies, challenges, and principles of I4.0 and CE, which helped to draw the roadmap towards CE and I4.0 implementation. However, it is essential to prioritize the challenges related to I4.0 and CE integration using single or hybrid MCDM techniques to understand how to involve industrialists effectively and efficiently in integration of I4.0 and CE throughout their business models and throughout their entire system. Also, design principles or strategies should be analysed to build upon the digital benefits of I4.0 for achieving CE-enabled solutions.
* More studies that contribute to the application of I4.0 technologies in CE are needed.
* Establishing mathematical models are needed to help to optimize practices related to resource consumption, waste prevention and material’s reusage by using big data tools to make progress toward CE and more sustainable societies.
* Analysing supply chain challenges and finding ways to solve them pertaining to the integration of I4.0 technologies within evolving CEs is urgently needed.
* Using LCAs of AM products to address the long-term CE benefits of additive manufacturing.
* Future research should be focused on developing strategic plans for using IoT-based tools for reducing energy consumption and improving material’s recovery/reuse in the recycling of wastes within CEs.
* The linkage between RdM, I4.0, and CE should be researched to develop a more precise structural model of how they should be improved to become more synergistic to catalyse widespread implementation.
* Regarding the energy industry, incorporating IoT into energy meters will help collect real-time data and analyse power consumption patterns. This will provide insights on how to help customers optimize their energy usage and thereby, help utility grid managers even out their supply and demand fluctuations.
* Missing dimensions such as ethical, ecological, philosophical, and technological regarding CE and I4.0 integration need to be addressed.
* The adoption of information technologies needs to be enhanced in manufacturing sectors to reduce fossil carbon emissions. Besides shifting to renewable energy-based systems, more research needs to be done on Carbon Capture and Storage.

sedbackal. (2019)8) exploreds.

* 1. **Unique Contributions of this Literature Review Article**

The unique contribution of this article is the development of a research framework (as shown in Figure 9) for smart and circular supply chains by integrating I4.0 technologies and CE practices. This study is one of the first efforts to examine the literature of I4.0 and CE integration from manufacturing supply chain perspectives combined with bibliometric analysis. The authors prepared a comprehensive, systematic literature review of I4.0 and CE to identify progress made, trends in implementation, and research gaps that should be addressed via future research. The literature review was focussed on ten different perspectives, i.e., digital RdM, data analysis in CE, smart disassembly and remanufacturing, smart waste management, digital CE, smart and circular supply chain, business models, challenges, strategies, and principles of I4.0 and CE and framework integrating CE and I4.0. The bibliometric analysis was performed using R programming software and the VOS viewer tool for evaluating four major groups, i.e., document types, authors, countries, and word analyses. Using bibliometric analysis, top journals, influential organizations, leading authors, and countries and significant research trends were documented. The authors also performed a cluster analysis to analyse the networks among the authors, publications, and Co-citations.

1. **Conclusions and Recommendations**

The authors performed a systematic literature review and bibliometric analysis of I4.0 and CE. They selected 165 articles from the Scopus database for in-depth analyses. Using bibliometric tools such as R programming software and VOS viewer, leading authors, leading articles, influential institutions, author co-citation analysis, and cluster analysis were performed. The systematic review of articles focussed upon different parameters such as digital RdM, data analysis in CE, smart disassembly and remanufacturing, smart waste management, digital CE, smart and circular supply chain, business models, challenges, strategies and principles of I4.0 and CE, and framework integrating CE and I4.0 The review documented significant contributions in the development of smart circular supply chains for overcoming associated challenges. Digital RdM was documented to facilitate automated monitoring, optimization, and control of manufacturing resources and accelerating the entry of CE concepts into evolving business models.

Another set of aspects that need to be addressed is how can the Seventeen Sustainable Development Goals (SDGs) be implemented within CEs to help improve the quality of all species upon the planet. Balanced ecological regeneration and sustainable economic growth are essential for sustainable development and truly sustainable, equitable societies. The fourth industrial revolution technologies can play significant roles in helping societies achieve the SDGs by improving the effectiveness and efficiency of sustainable development methods. Industry 4.0 can help deliver SDG solutions by augmenting the quality of life through the production and usage of sustainable products and services within CEs.

The authors concluded that the research on I4.0 and CE for circular supply chain practices has enormous potential for helping to solve some problems of supply chain management. For example, the transformation of raw materials, products, and energy should be incorporated with the I4.0 technologies within CEs. It will enable designing product-service systems, producing goods and services, upgrading them, repairing them, remanufacturing them, and recycling them. The present study possesses some limitations as it considers only published articles from journals, conference proceedings, and book chapters related to I4.0 and CE. However, considering the growing aspect of I4.0 and CE, significant information may be gathered from other sources such as white papers, magazines, industry reports, etc. Further, this article highlights the understanding of I4.0 and CE related to its progress and trends from limited clusters. In the future, more clusters could be identified to broaden the knowledge on I4.0 and CE integration.

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