# Unlocking Circular Supply Chain 4.0: Identifying Key Barriers through Bibliometrics and TISM-MICMAC

***Abstract***

**Purpose:** This paper examines the dynamic interplay between Circular Economy (CE) and Supply Chain (SC). Further, this paper develops a framework indicating the transition from conventional SC to SC 4.0. As it addresses the separate bodies of literature on CE and SC 4.0, the study attempts to bridge the gap by examining barriers to SC 4.0 adoption in CE.

**Design/methodology:** The article integrates bibliometric analysis with Total Interpretive Structural Modeling (TISM) and MICMAC analysis, thereby enriching the methodological rigour in investigating the barriers to SC 4.0 adoption within the CE context.

**Findings:** The paper provides insights into research trends, influential scholars, journals and prominent institutions through bibliometric analysis. Also, the findings identify four broad areas of driving, autonomous, linkage and dependent barriers to facilitate a comprehensive understanding of their impact and interdependencies.

**Research limitations/implications:** The findings imply that effective policy interventions, enhanced management practices, and the adoption of technological innovations are essential for overcoming barriers to SC 4.0. The research recommends that stakeholders focus on fostering collaborative networks, building competencies in line with CE requirements, and leveraging big data for strategic supply chain decision-making.

**Originality/ Value:** This work contributes to the advancement of the circular digital supply field by consolidating research streams, uncovering innovation prospects, and shaping a well-informed research agenda. The distinct contribution lies in its categorization of these barriers into driving, autonomous, linkage, and dependent barriers, offering a novel perspective on the structural dynamics impeding the integration of SC 4.0 in CE.

***Keywords***—Circular economy, bibliometric analysis, TISM-MICMAC Analysis, Digital Supply Chain, SC 4.0, Industry 4.0

## 1. Introduction

As the global economy continues its evolution, the radical paradigm shifts that are redefining industry and research have been ushered in by the demands for sustainable progress, which have led to profound changes in the ways of doing business. A seismic shift toward a future in which environmental stewardship and commercial efficiency are aligned is signalled by the merger of the Circular Economy (CE) and Industry 4.0 (I4.0), each of which is a beacon of innovation on their own (SuárezEiroa et al., 2019). The Circular Economy (CE) framework, as emphasized by Okorie et al. (2018), is built upon the principles of restoration, waste reduction, and the crucial move towards renewable energy. This model goes beyond mere compliance with environmental norms to uncover new business opportunities through innovation, operational efficiency enhancement, and profitability while ensuring systems are both resilient and capable of regeneration (Manninen et al., 2018). This transition to a regenerative economic model signifies a profound shift from conventional business approaches, signalling a redefinition of how value creation is perceived in the business world. At the core of CE are the principles of restoring ecosystems, minimizing waste, and adopting renewable resources. The primary goal is to leverage these principles to spur business opportunities, enhance efficiency, and secure profitability, thereby fostering an economy that is not only sustainable but also capable of regeneration. In the face of the need for optimal resource utilization, modern management practices are evolving to integrate stakeholder interests comprehensively and remain competitive in the market. With shifts in governmental policy and a rise in public awareness about environmental issues, companies are being driven to rethink their production strategies to sustainably meet growing consumer demands. This evolution has given rise to the Green Supply Chain (GSC) and the Sustainable Supply Chain (SSC) concepts, with GSC addressing the entire product life cycle and SSC applying the Triple Bottom Line principle to achieve resource optimization and waste reduction (Seuring and Müller, 2008). The journey towards environmental sustainability in supply chains is evolutionary, transitioning from traditional models to GSCs, then to SSCs, and eventually evolving into Supply Chain 4.0 (SC 4.0), which is aligned with the objectives of CE. Anticipating a further evolution into Supply Chain 5.0, this progression presents an opportunity to refine sustainability practices further.

Our investigation extends into the realm of digital technologies propelled by the advent of Industry 4.0, aiming to accelerate this evolutionary process. This study explores how sustainability is being incrementally integrated into supply chain operations, with a particular focus on the role of SC 4.0 in guiding enterprises towards sustainable practices. As we venture into discussions about Industry 5.0, with its emphasis on collaborative robotics and customization, our analysis remains grounded within the Industry 4.0 paradigm. This perspective highlights the significant role that digital transformation plays in advancing sustainable supply chain management, underlining the transformative potential of digital technologies in this context.

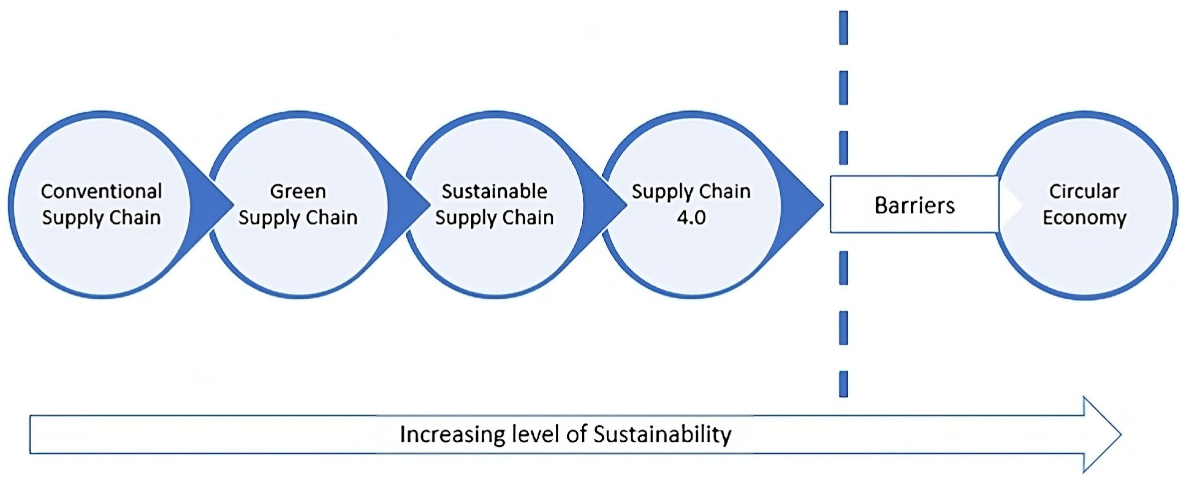


**Fig.1:** SC journey toward circular economy

Ever since its inception, Industry 4.0 has led a paradigm shift in the automated production, distribution, and procurement of goods through the utilization of decentralized decision-making, the Internet of Things (IoT), and Artificial Intelligence (AI). This digital transformation has resulted in the creation of Supply Chain 4.0 (SC 4.0), which is distinguished by the seamless automation of financial, informational, and material processes that are powered by Digital Disruptive Technologies (DDT). Although there is a significant amount of research on Circular Economy (CE) and SC 4.0 separately, their intersection has not been well investigated. The emergence of Industry 4.0 has served as a driving force behind a digital transformation, enabling the optimization of supply chain operations to improve financial performance and promote environmentally friendly manufacturing practices. The integration of digital practices within the supply chain, represented by SC 4.0, leverages advanced Information Technology (IT) capabilities to enhance the adaptability and effectiveness of supply chains. However, despite the progress made in this field, there is a knowledge gap about the differences between SC 4.0 and its conventional equivalent, as well as the obstacles that impede the smooth incorporation of SC 4.0 and Circular

Economy (CE) practices. This study seeks to close this divide by presenting a framework that demonstrates the progression of the supply chain towards SC 4.0 and assesses the obstacles to the adoption of CE. This framework will emphasize the significant impact of digitalization on the supply chain and highlight the challenges in incorporating circular economy techniques, particularly in terms of data management and operational efficiency.

Within the framework of contemporary supply chains, the amalgamation of Circular Economy (CE) concepts and Industry 4.0 technologies emerges as a ground for innovation and environmental sustainability. Yet, this promising conjunction remains somewhat enigmatic, with the extant literature pointing to several gaps that must be bridged to optimize the collaborative force of CE and Industry 4.0 in revolutionizing supply chain models. One notable void is the scarcity of holistic studies dissecting the principal themes and leading voices at the intersection of CE and Industry 4.0 within supply chains. This absence signals potential missed opportunities for gaining pivotal insights that could propel further academic inquiry and practical applications (Priyadarshini et al., 2022). Moreover, while the transition to Circular Digital Supply Chains (CDSC) is recognized as pivotal for sustainable growth, detailed insights into the specific facilitators or barriers of this evolution remain elusive. Unraveling these factors is essential for devising impactful strategies that encourage the uptake of CDSC methodologies (Mangla et al., 2018). Furthermore, although the hurdles in implementing Circular Supply Chain 4.0 (CSC 4.0) principles are well documented, the broader repercussions of these challenges for CE initiatives within supply chains have not been fully delineated. There exists an imperative demand for studies that not only catalogue these impediments but also delve into their influence on the practicality and success of CE approaches in supply chain management (Govindan and Hasanagic, 2018). To address these gaps, the paper focuses on assessing the alteration challenges from conventional SC to CSC 4.0 while addressing the following research question:

1. *RQ1: What are the dominant research themes and key contributors at the nexus of CE and Industry 4.0 within the context of supply chains?*
2. *RQ2: How do the principal mechanisms influencing the evolution from traditional supply chains to Circular Supply Chains (CSC) interrelate?*
3. *RQ3: What are the implications of identified barriers for the implementation of CSC 4.0 principles in the context of Circular Economy initiatives?*

The methodology chosen combines Bibliometric Analysis (BA), Total Interpretive Structural Modeling (TISM), and MICMAC analysis to provide complete and precise answers to the research questions. A thorough analysis of the academic landscape is conducted by BA to identify key research patterns and scholars. This analysis is crucial to answering Research Question 1 about emerging topics in CE and I4.0 within the SC domain. TISM's analytical approach allows for a thorough examination of the complex connections between factors that motivate the change to the supply chain, which directly affects RQ2. The MICMAC analysis aims to a better understanding of the different driving and dependence factors that affect the implementation of CDSC practices, hence addressing RQ3. By combining these three methods, we aim to offer a comprehensive analysis of circular digital supply chain research and reveal the main challenges faced.

This integrated approach ensures a strong and comprehensive analysis, which is crucial for revealing valuable insights into the merging of SC 4.0 and CE practices. Thus, this study will be organized as follows; Section 2 of the paper sheds light on the state of the art with a focus on SC and CE as well as barriers to circular SC. Section 3 entails the conceptual framework by describing the evolution of SC and the barriers. Section 4 describes the integrated research methodology and Section 5 analyses the barriers and relationship through TISM and MICMAC analysis. Having analyzed the implications of the results, research gaps and the prospective research agenda are presented in section 6, followed by the main findings summary and conclusion in the last section.

## 2. State of art

The concept of the CE encompasses the entirety of the SC, traversing from the initial stages of concept and manufacturing through to product use, disposal, and even innovation and technology aimed at transforming waste into valuable resources. Its importance lies in enabling businesses to enhance their resilience and competitiveness while concurrently achieving sustainability objectives for a positive environmental impact. By adopting CE principles, organizations can proficiently manage resources, diminish waste generation, and enhance environmental well-being while gaining market competitiveness (Merli et al., 2018). The interconnection between the SC and the CE mandates various adaptations within the SC to align with CE principles. In recent years, CE and I4.0 have been attracting attention for their ability to drive a systematic shift and aid in the attainment of Sustainable Development Goals (SDGs) (Dantas et al., 2021). Nevertheless, the widespread embracing of CE principles faces obstacles that can be surmounted through the deployment of disruptive technologies (Okorie et al., 2018). By integrating the digital tools into CE initiatives, a significant improvement in circularity performance can be achieved within SC, resulting in improvements in environmental ethnicity, human welfare, operational efficiency and effectiveness, technological innovations, customer loyalty and satisfaction (Agrawal et al., 2023). SC 4.0 presents a compelling approach to promoting sustainability by incorporating CE principles (Farooque et al., 2019). Yet, the literature has not thoroughly explored the factors influencing the implementation of disruptive technologies in tandem with CE practices within SCs (Agrawal et al., 2023).

Circular Economy (CE) concepts are increasingly being adopted across diverse sectors and industries. A study focusing on the construction sector identified multiple challenges encountered in areas such as design, material selection, supply chain management, business model innovation, dealing with uncertainty and risk, fostering collaboration, acquiring knowledge, implementing supportive policies, integrating urban metabolism concepts, and methodologies for assessing CE effectiveness (Hossain et al., 2020). The study on barriers to smart waste management in China identified three primary causal barriers namely the absence of regulatory pressures, lack of environmental education and culture of environmental protection, and deficiency in market pressures and demands (Zhang et al., 2019). Ada et al. (2021) conducted a study on the obstacles to implementing Circular Economy (CE) principles within the food supply chain, identifying seven key barrier categories: cultural, business and financial, governmental and regulatory, technological, managerial, supply chain management, and knowledge and skills. Similarly, Ritzén and Sandström (2017) highlighted impediments to transitioning towards CE, pinpointing critical areas such as finance, organizational structure, operations, attitudes, and technology. The obstacles that prevent the widespread application of circular business models in practice have been gathered by Bianchini et al. (2019) and include issues with internal procedures, technology, the market, institutions, regulations, social issues, and financial and economic considerations. Data transparency, market competition, a lack of standardization, complex protocols, a lack of industry involvement, financial constraints, missing infrastructure, data transparency, and interoperability are the main obstacles that significantly affect the implementation of Blockchain Technology (BT) in the viable circular digital supply chains (VCDSCs). According to Chaouni Benabdellah et al. (2023), overcoming these constraints will be necessary to successfully integrate and utilize BT's potential within the VCDSC. A critical challenge in the successful implementation of Industry 4.0

technologies is poor leadership style. The world's senior management needs to take an inspiring and transformative leadership approach to harness the potential of these technologies, which can enhance a business's sustainability. However, transforming towards a Circular Supply Chain (CSC) and transitioning to Industry 4.0 (I4.0) can be hampered by several factors. The primary barrier for the CSC in the era of the I4.0 transition identified is the lack of knowledge about the fourth industrial revolution technologies and circular approaches. Shang et al. (2022) identified data security as a significant challenge in managing relationships within circular flows, highlighting a widespread lack of stakeholder understanding regarding data management. Additionally, there's a noted deficiency in recognizing the benefits of integrating autonomous systems in labour-intensive "End-of-Life (EOL)" activities within Circular Supply Chains (CSCs) as part of the transition to Industry 4.0. In a comprehensive study, Kondala and Nudurupati (2023) synthesized barriers to Circular Economy (CE) implementation reported across various studies. These barriers encompass a spectrum of issues, including insufficient awareness, financial limitations, a deficit in technical know-how, lack of institutional support, absence of effective performance metrics, inadequate policies, regulatory constraints, limited stakeholder engagement, challenges in technology and innovation, and a scarcity of authentic green suppliers. Further research by Nudurupati et al. (2022) focused on the hindrances faced by small and medium-sized enterprises (SMEs) in India in adopting CE principles, revealing obstacles such as financial restrictions, technological and expertise gaps, operational inefficiencies, consumer expectations, managerial commitment shortfalls, and resource-intensive scenarios.

Industry-specific studies have highlighted the sluggish progress organizations have made in adopting CE practices. These studies have also identified a range of difficulties impeding effective adoption (Farooque et al., 2019; Ozkan et al., 2020). Numerous studies have detailed barriers faced during the transition to CE. Economic, institutional, social, and technological challenges were identified (Liu et al., 2021). Meanwhile, 17 obstacles to utilizing big data analytics (BDA) for sustainable industrial activities were identified (Kumar et al., 2021) and identified 19 challenges associated with the maintenance field (Ingemarsdotter et al., 2021). Through a combination of systematic literature review (SLR) and multiple case studies involving 9 firms, the multifaceted nature of obstacles hindering progress towards a smart CE was explored (Trevisan et al., 2023). They identified magnitudes of barriers, each offering distinctive perceptions of the challenges posed by the transition. The practical implementation of CE in the industrial sector faces significant barriers due to the data accuracy deficiency about resources, products, and processes. Other barriers identified were substantial initial investment, low awareness, and lack of urgency as obstacles to CE employment (Masi et al., 2018). For industrial manufacturing firms, key hindrances to using disruptive technologies for circular strategies included issues with interface design, compatibility, interfacing, networking, technology updating, and integrating data analytics and IoT with existing technology (Rajput & Singh, 2019). Numerous challenges and barriers to CE adoption, such as insufficient consumer knowledge, limited understanding of CE, resistant corporate culture, inadequate waste management infrastructure, and others, can be effectively addressed through the adoption of disruptive technologies (Agrawal et al., 2023). Challenges and barriers to adopting SC4.0-enabled CE practices include a lack of awareness, absence of guidelines and best practices, and hindrances related to process, technology, economy, institution, regulation, structure, and culture. Notably, the most significant barriers impacting the integration of Blockchain Technology (BT) into SC4.0 for CE include data transparency, global fierce competition, complex protocols, high customization requirements, limited industry involvement, financial constraints, and interoperability (Chaouni et al., 2023).

In the current landscape, firms must align sustainability goals with long-term growth strategies alongside financial and operational priorities. For social, environmental, and economic objectives to be achieved through circular supply chain management, transparent strategic integration is necessary. This will enhance long-term efficiency performance (Carter and Rogers, 2008). The trajectory of industrial development is progressing toward I4.0, driven by advanced digitalization tools adoption (Papadopoulos et al., 2022). This advancement facilitates enhancements across industrial processes, from product design to smart factory construction, fostering adaptability to market changes and a competitive edge through dynamic capabilities (Kang et al., 2016). Using the literature and experts' consultations as a foundation, the main CE practices in conjunction with I4.0 technologies are depicted in (Table 1).

**Table 1:** List of barriers

| S. No | Barriers | Description | References |
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| 1 | Lack of operational efficiency | Both CE and I4.0 increase material flow, reduce life-cycle costs, improve tracking and tracing systems, and increase a firm's capabilities while promoting operational efficiency and lowering costs. Therefore, SC 4.0 can be hampered by a lack of produce design, process, production, and logistics. | Jabbour et al. (2018), Peng et al. (2018), Bag, Gupta, et al. (2021), Franco (2017); Bibi et al. (2017), Chari, et al. (2022), H. Lu et al. (2022) |
| 2 | Inadequacies in the management of data and knowledge | Among stakeholders, there is an absence of understanding of data management, I4.0 technology, and CE techniques. | Defee and Fugate (2010), Fatorachian and Kazemi (2018), Yang et al. (2018), Mukherjee et al. (2021), Shamsuzzoha et al. (2016), Yang et al. (2018), Jabbour et al. (2017), (Awan et al., (2021); Bag and Pretorius, (2020) |
| 3 | Lack of training and skill-competency | To manage the resources, managers adopting I4.0 technologies must possess innovative abilities, skills, and expertise. Businesses would be able to implement circular design products and be involved in reuse, refurbishing, and reprocessing if they had the necessary skills. | El-Kassar and Sigh (2018), Yang et al. (2018), Zhu and Geng, (2013); Lacy and Rutqvist, (2015) |
| 4 | Absence of risk control | High degrees of uncertainty exist for businesses embracing I4.0 and CE in terms of operational bottlenecks and data security. At the organizational level, the SC structure is extremely complicated. | Bag, Gupta, et al. (2021), Bag, Dhamija, et al. (2021), Sjodin et al. (2018), Fatorachian and, Kazemi (2018) |
| 5 | Lack of collaborative network/strategy | To overcome challenges, a call for cooperation across various stakeholders—public and private entities within and outside becomes essential. Better connectivity and intensive integration among partners can achieve shared goals with value creation with the use of cutting-edge technology and resources. | Jabbour et al. (2017), Despeisse et al. (2017), Kouhizadeh, Zhu, and Sarkis (2020), Yang et al. (2018) Mukherjee et al. (2021) Pan et al. (2018), Fatorachian and Kazemi (2018), Ramakrishna et al. (2020) |
| 6 | Lack of top management planning/support | Managing resources and technology effectively is essential for building circumstances for the best use of sustainable assets and techniques such as the 5Rs. The leadership should strive for resilience in the form of adaptability, agility, and strategies that look to the future and competitively advance sustainability. | Bag and Pretorius (2020); Shayganmehr et al., (2021); De Sousa et al., (2019); Díaz-Chao et al., (2021); Fabbe-Costes and Ziad, (2021); Shayganmehr et al., (2021); Shin and Park, 2020 |
| 7 | Policy regulations and standards challenges | Remanufactured product definitions and standards are lacking, which is problematic. A barrier to SC 4.0 is the lack of an environmental legislative framework for adopting circular supply models, as well as the absence of public authority incentives (through futile tax policies, import and excise duty, etc.). | (Yang et al. 2018), Mangla et al., (2015); Prendeville et al., (2016), Mangla et al., (2018),Tripathi et al., (2016), H. Lu et al, (2022) |
| 8 | Financing challenges | The ability to reduce costs is a requirement for circular enterprises to succeed. The move to circular practices is hampered by a lack of adequate finance mechanisms. Industries need financial encouragement to invest in green/circular concepts. The inadequate systems and procedures for managing end-of-life products and | (Sousa-Zomer et al., 2018), Mangla et al., (2015); Prendeville et al., (2016), Mangla et al., (2018), Venkatesh and Luthra (2016), |

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|---|---|---|---|
| | | reverse logistics. | Chari et al. (2022), Day and Godsell, (2017) |
| 9 | Challenges in customer awareness and participation | Customers' accountability and participation are essential for influencing their purchasing habits and promoting the adoption of more environmentally friendly goods and services. From an organizational perspective, ignorance of circular models sends a message of "lack of public perception and views," which might impede their adoption in the SC and, as a result, restrict the integration of technology for SC 4.0. | Masi et al. (2018), Chari et al. (2022), Mangla et al., (2018), Pan et al., (2015); Rizos et al., (2015); Ghisellini et al., (2016); Genovese et al., (2017) |
| 10 | Unsupportive systemic changes | Practices relating to green product and process design can be influenced by system design and system operations. A more holistic, integrated strategy that takes into consideration the numerous interlinkages within and between sectors, inside and across value chains, and between actors is necessary for the transition to a CE. Such a strategy would aid in accounting for the many incentives at play, the distribution of financial benefits, and the effects of actions along a value chain, spanning various industries and policy areas. | (Lopes de Sousa Jabbour et al. 2018), Mukherjee et al. 2021), (Kristoffersen et al. 2020; Wang and Zhang 2020) |
| 11 | Uncertainty about economic benefits and incentives | Uncertainty regarding the possible economic and environmental benefits of incentives and CE present a difficulty for SC 4.0. Businesses must comprehend how to create a revenue model that adds value along the entire value chain. An early internal barrier in any decision-making process results from inadequate internalization of externalities and effective resource pricing. | (Ellen MacArthur Foundation, 2012, 2013), Mangla et al., (2018), Park et al., (2010); Zhu and Geng, (2013) |
| 12 | Limited demand and acceptance by businesses | A method for implementing CSC initiatives is provided by highly developed technology and updating of facilities and equipment. However, the lack of demand for environmentally superior technologies leads to greater pollution, a shortage of energy, and decreasing financial gains. | Geng and Doberstein, (2008); Su et al., (2013), Mangla et al., (2018) |

The Circular Economy (CE) extends across the entire Supply Chain (SC), offering organizations the opportunity to bolster resilience and competitiveness while meeting sustainability targets. Embracing CE principles enhances market competitiveness through strategic resource management, waste minimization, and environmental responsibility. An organization's adaptability to changing environments is a crucial aspect of its dynamic capabilities, which are essential for this strategic orientation. These capabilities encompass the ability to integrate, build upon, and reconfigure both internal and external competencies. Integrating CE with Industry 4.0 (I4.0) enables firms to leverage these dynamic capabilities to evolve their supply chains towards Sustainable Development Goals (SDGs). The merger of I4.0 technologies with CE principles opens pathways for significant improvements in operational efficiency, human welfare, environmental integrity, and circular performance. However, transitioning to a CE-integrated SC faces hurdles like data accuracy issues, substantial initial investments, and a widespread lack of stakeholder urgency. Firms are prompted to adjust strategies and operations to navigate technological, economic, and societal barriers beyond the realm of dynamic capabilities.

In the era of the fourth industrial revolution, the importance of dynamic capabilities in enabling SCs to adapt and embrace CE concepts has become increasingly apparent. These capabilities allow businesses to manage and reshape their resource base to identify and address opportunities and threats, thus maintaining competitiveness. Dynamic capabilities thus play a pivotal role in facilitating the SC's integration of I4.0 technology with CE practices, ensuring that digital and physical systems are in sync to overcome the numerous challenges to CE adoption. These capabilities underpin the SC's capacity to exploit Industry 4.0 benefits and transform challenges into opportunities for innovation and sustainable growth. Dynamic capabilities, once considered solely firm-centric, are now acknowledged as essential for incorporating environmental and social responsibilities into the SC (Qiao et al., 2020).

This study explores the obstacles to combining CE and I4.0 and how they impact dynamic capabilities in the Sustainable Supply Chain Management (SSCM) framework. The conceptual framework, adapted from Lu et al. (2022) and grounded in the Dynamic Capabilities View (DCV), emphasizes the critical assessment of knowledge regarding resources held by SC stakeholders (Defee and Fugate 2010), the importance of selecting sustainable partners (Seuring and Müller 2008), the cultivation and reconnection of collaborative networks for accessing new resources (Pagell and Wu 2009), and resource management for enhancing firm resilience (Beske, Land, and Seuring 2014). The integration of CE principles with I4.0 technology presents an opportunity for organizations to not only elevate competitiveness and adaptability but also fulfil sustainability ambitions. Despite the presence of challenges, transformative Digital Disruptive Technologies (DDT) offer a means to surpass barriers to CE adoption within SCs. This alignment between circularity and technology can foster comprehensive improvements in environmental sustainability, waste management, and resource utilization.

Dynamic capabilities stand as a cornerstone in the SC's fusion of CE and I4.0, as visually represented in Figure 2. This conceptual framework illustrates the dynamic capabilities essential for CE practices implementation and I4.0 integration, highlighting the importance of knowledge resources, strategic partnerships, and high-level collaboration to navigate CE adoption challenges. These capabilities enable firms to surmount operational, technological, collaborative, and cultural hurdles, as delineated in the extensive literature review and expert interactions outlined in Figure 2.

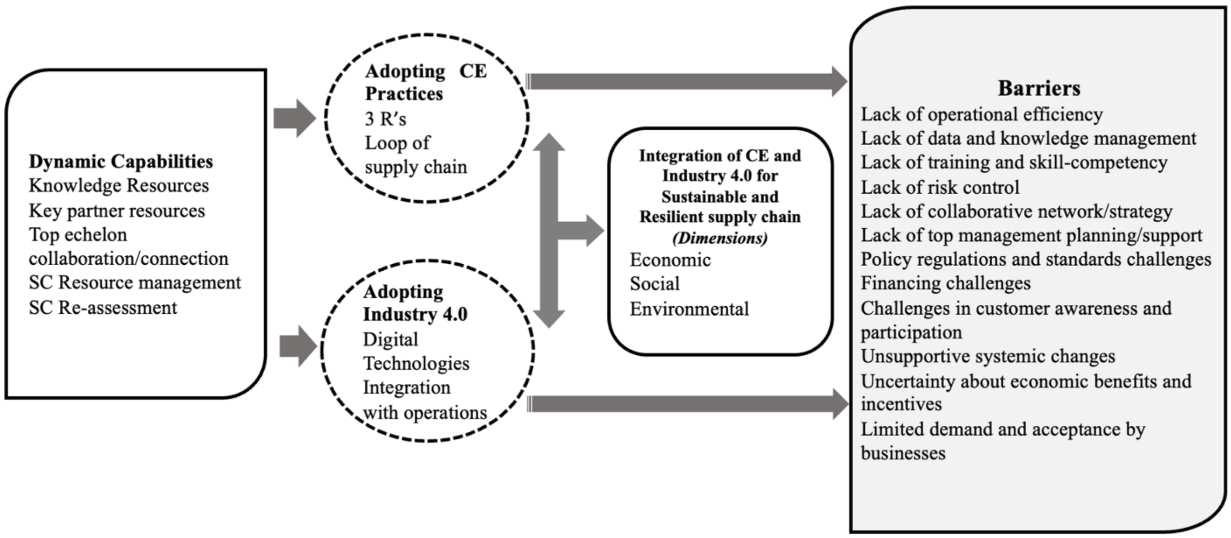


**Fig.2:** Conceptual Framework of SC 4.0 Barriers in CE

The conceptual model presented in Figure 2 underscores the critical role of an organization's dynamic capabilities in the journey towards sustainable practices, spotlighting the pivotal functions of harnessing knowledge resources, nurturing pivotal partner collaborations, and proficiently managing supply chain resources. These capabilities are the linchpins for embracing new paradigms as posited by Teece (2007). The model delineates, on one flank, the integration of Circular Economy (CE) practices within supply chains, emphasizing the commitment to material restoration, waste eradication, and strategies bolstering the transition towards renewable energy sources. These foundational CE elements are directed at catalyzing business opportunities through innovative value creation, an endeavour that not only augments environmental sustainability but also bolsters operational efficacy and profitability, thereby equipping businesses to thrive amidst resource limitations and escalating environmental directives (Okorie et al., 2018; Manninen et al., 2018). Simultaneously, the framework highlights the concurrent adoption of Industry 4.0 digital technologies within supply chains. The deployment of cutting-edge technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) is set to redefine supply chain dynamics, ushering in unparalleled automation, efficiency, and data-informed decision-making (Lasi et al.,

2014). This digital momentum is crucial for steering supply chains towards enhanced adaptability and efficiency, laying the groundwork for their successful fusion with CE principles.
At the heart of this framework lies the interconnection between CE and Industry 4.0, resulting in a supply chain that is resilient and sustainable across the triple bottom line of economic, social, and environmental measures (De Sousa Jabbour et al., 2018). Nonetheless, this integrated approach faces numerous barriers, identified on the right side of the framework, ranging from operational inefficiencies and data management challenges to skill shortages and resistance to change (Geissdoerfer et al., 2017). Hence, the framework articulates a comprehensive strategy for evolving supply chains, necessitating a thorough comprehension of the barriers and a unified initiative to surmount them.

## 3. Integrated Research Methodology

This article employs the bibliometric analysis (BA), to recognize the current research trends, influential scholars, and leading institutions involved in the CDSC domain (Donthu et al., 2021). This analysis goes beyond a surface-level examination and delves into the core barriers and challenges hindering progress in the field. In addition to bibliometric analysis, this study incorporates TISM and MICMAC analysis. These integrated combined methodologies provide further insights into the identified barriers by establishing hierarchical relationships among them and highlighting their interdependencies and impact (Priyadarshini et al., 2022). By categorizing the obstacles based on their driving power and dependence (Mathirathanan et al., 2021) researchers gain valuable guidance on which obstacles require immediate attention and intervention for effective decision-making. The methodology adopted in this study facilitates a systematic uncovering and structured classification of challenges facing the integration of Supply Chain 4.0 (SC4.0) within the Circular Economy (CE) framework. Through a bibliometric analysis that highlights prevailing research directions, key academic contributors, and significant publications, a solid foundation for the investigation is established (Ellegaard & Wallin, 2015; Mukherjee et al., 2022). The inquiry progresses with the application of TISM and MICMAC analyses, which highlight the mutual influences and implications of identified barriers (Sarkis et al., 2011; Touboulic & Walker, 2015).

This analytical approach deepens the understanding of the intricate challenges encountered. By integrating a thorough review of the academic landscape with a targeted analysis of specific hurdles, the chosen methodological framework effectively addresses the objectives of the research, thereby justifying its application. This comprehensive analysis not only maps out the field of study but also pinpoints and assesses the obstacles to implementing SC4.0 in the CE landscape, showcasing the effectiveness of this methodological blend in achieving the study's goals.

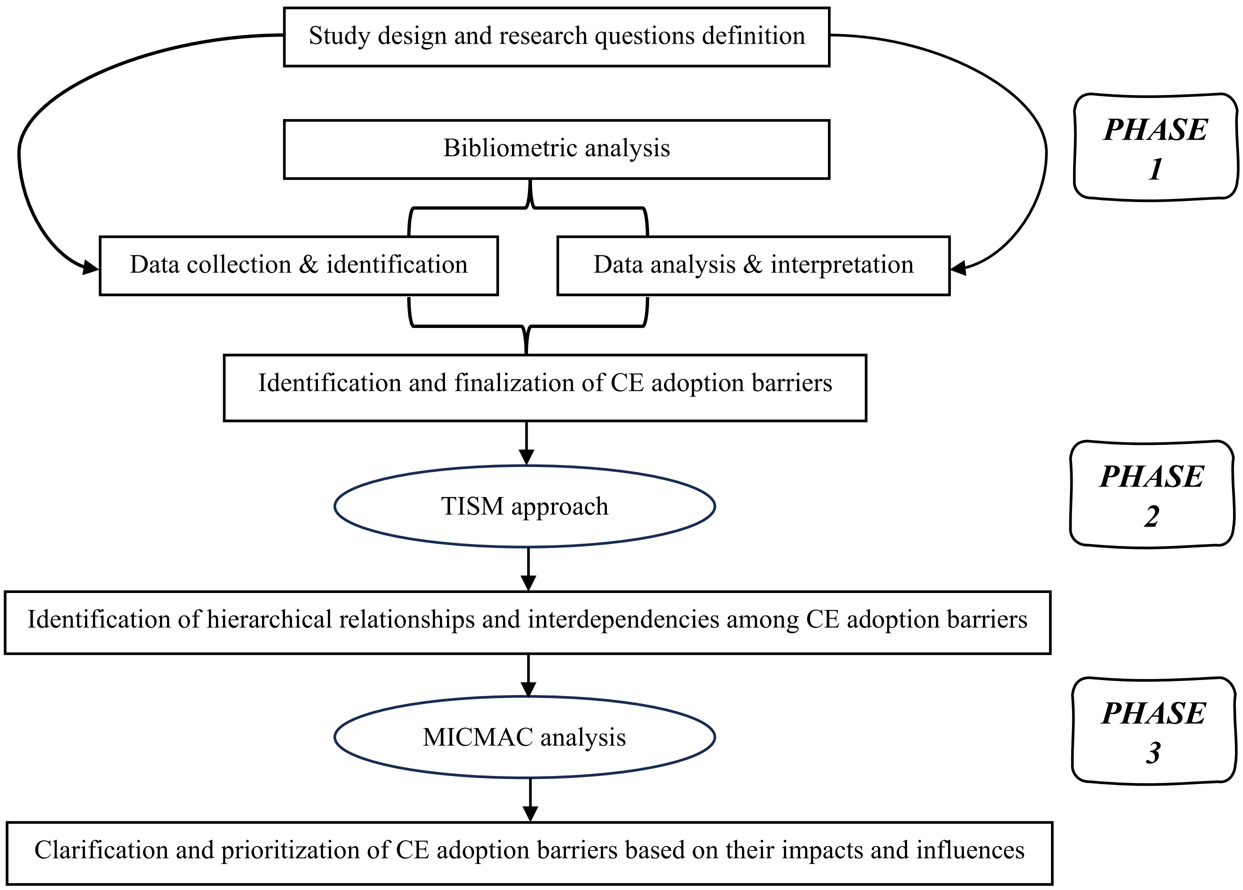


**Fig. 3:** Research Methodology

The initial step in conducting this review involves the collection of relevant literature from a comprehensive bibliographic database. To ensure a thorough exploration of the research topic, the Scopus platform was chosen for its wide-ranging coverage across diverse academic disciplines and the inclusion of reputable international publishers. Scopus provides access to an extensive collection of journals, offering not only abstracts but also citations, making it particularly well-suited for delving into the intricacies of the CDSC (Majumdar et al., 2022a). By leveraging the capabilities of Scopus, this review aims to encompass a broad spectrum of scholarly works, enabling a comprehensive analysis of the subject matter at hand. The decision to utilize Scopus was driven by its extensive coverage of scientific journals, including reputable publishers. Scopus encompasses an impressive collection of 39,237 journals (Majumdar et al., 2022a). Only those papers that focus on CE and DSC were included in this study. Boolean operators are used in the retrieval process to screen the publications using the following search query string. To determine the appropriate keywords for this study, a two-step process was followed. Initially, synonymous keywords associated with the four main aspects under investigation: SC, DDT, CE, and challenges, were identified by reviewing previous literature and similar studies (Kirchherr et al., 2017; Hettiarachchi et al., 2022; Agrawal et al., 2023). Subsequently, these identified keywords were subjected to discussion with an expert panel consisting of academicians and industry practitioners, during the Arab Green submit held in UAE (2023). This step aimed to obtain their confirmation and gather any additional commonly used keywords that may have been overlooked. Through this collaborative process, the final selection of keywords was refined and documented in Table 2.

**Table 2:** Query string keywords

| Category | Query String |
|---|---|
| SC | ("logistic*" or "supply chain" Or "SC management" or "Logistic" or "SCM") |
| CE | (“circular economy” OR “regenrat*” OR “sharing economy” OR “closed loop” OR “zero waste” OR “restorat*” OR “butterfly”) |
| Digital Disruptive Technology or I4.0 | (“digital technolog*” OR “smart technolog*” OR “I4.0 ″ OR ”disruptive technolog*“ OR ”I4.0″ OR “artificial intelligence” OR “machine learning” OR “big data” OR “big data analytics” OR “BDA” OR “cloud computing” OR “internet of thing” OR “IoT” OR “additive manufacturing” OR “augmented reality” OR “virtual reality” OR “digital twin” OR “cyber physical system” OR “CPS” OR “cyber security” OR “automation” OR “robotics” OR “blockchain” OR “3D printing”) |
| Barriers & Challenges | (“barrier*” OR “challenge*” OR “restriction*” OR “obstacle*” OR “hinder*” OR “issue*” OR “limitation*”) |

To ensure consistency and facilitate analysis, a set of inclusion and exclusion criteria were applied to identify papers relevant to our research questions, as outlined in Table 3. Initially, the search yielded a total of 544 articles, spanning from 2011 to 2023. By narrowing the focus to journal articles and reviews while eliminating redundancies through the removal of duplicate entries, a total of 370 unique articles were identified. Once the literature search was complete, the next step was to screen and select relevant publications. This involved reviewing the titles and abstracts of the retrieved articles to determine their relevance to the research question and scope. Articles that did not meet the inclusion criteria were also excluded. These additional filtering processes led to a final selection of 128 articles, which were utilized for the subsequent BA (Table 3). To ensure the preservation of essential information for analysis, the final search results were downloaded as a CSV file. This file encompassed crucial details such as author information, article titles, abstracts, keywords, affiliations, and references, providing a comprehensive dataset for further examination using selected bibliometric software tools.

**Table 3:** Screening process: criteria and results

| Criteria | Description | No. of documents |
|---|---|---|
| **Initial results** | | **544** |
| **Exclusion criteria** | | |
| Ex.C1: Source type | Only journal publications are exclusively focused on. | 381 |
| Ex.C2: Document type | Only journal articles and reviews are specifically chosen. | 370 |
| Ex.C3: Subject area | Emphasis is placed on the domains of industrial engineering, business management, computer science, environmental science and decision sciences, excluding other categories such as medical sciences, geography and architecture. | 142 |
| Ex.C4: Language | Only papers written in English are selected. | 142 |
| Ex.C5: Content | Abstracts and titles are read and analyzed. This study specifically included papers that centre around the topics of CE and digital SC. The full papers were meticulously examined by the three authors, and their findings were reviewed by the fourth author. | 128 |

Once the relevant publications have been identified, the subsequent step involves extracting data from these publications. This process entails collecting information on author names, affiliations, publication dates, journal titles, citation counts, and keywords. Referred to as the final step in the bibliometric review process and falling under the data analysis stage, it aims to identify the most influential authors, highly cited articles, and active research areas within the realm of CDSC. Notably, Maditati et al. (2018) have emphasized the significance of employing transparent and repeatable BA techniques to enhance reliability and minimize subjective bias in the LR analysis process. In alignment with this perspective, the present study utilizes both the VOSviewer software and Bibliometrix R-Tool for data analysis. These tools facilitate the mapping of publications, prediction of trends, and identification of critical points. Additionally, content analysis is performed to summarize literature trends and provide a comprehensive understanding of the reviewed documents, as highlighted by Gaur and Kumar (2018).

The data analysis in this study encompasses both quantitative and qualitative approaches to yield valuable insights into the CDSC. The most pertinent attributes investigated in this research are reviewed in Table 4 (Donthu et al., 2021). The analysis is carried out using two approaches:

a. Quantitative analysis (Descriptive features of SC 4.0 in CE literature): This is a bibliometric technique to quantitatively understand the research undertaken in CE and CDSC. In this approach publication trends are analyzed over a period along with identifying authors and institutions, determining citation counts, h-index, and co-citation analysis. Biblioshiny, a software developed in R, is utilized to provide metrics and visualization tools to conduct comprehensive bibliometric analyses.

b. Qualitative analysis (Science mapping): Qualitative analysis is conducted by using text mining techniques from the literature. This analysis is carried out by examining thematic areas, prominent keywords, and the geographical distribution of publications related to the CDSC. It helps in identifying emerging research patterns, knowledge gaps, and research themes. VOSviewer, a software application developed by Leiden University, enables the generation of bibliometric networks and maps to visualize the relationships between articles, scholars, journals, affiliations, and keywords.

**Table 4:** Literature review analysis categories and attributes

| Analysis approach | Scope /Focus | Analysis attributes |
|---|---|---|
| Qualitative analysis | Descriptive features of SC 4.0 barriers towards CE scientific publication | Distribution of papers by year of publication |
| | | Country-specific scientific contribution |
| | | Distribution of reviewed papers by journal |
| | | Distribution per subject area |
| | | Institutions/organizations influence. |
| | | H Index |
| Quantitative analysis | Science mapping and performance analysis | Analysis of citation metrics |
| | | Analysis of co-citation metrics |
| | | Analysis of the co-occurrence index |
| | | Challenges and barriers related to CE |

| | | |
|---|---|---|
| Analysis of the content | SC 4.0 barriers identification and analysis | Interrelationships analysis (TISM + MICMAC analysis)<br>Implications and Decision Actions Plans |

The findings and insights derived from the BA are subsequently compiled and reported to provide broad coverage of the digital CSC research domain in section 3.

By following these steps, researchers can conduct a comprehensive BA of the CDSC. This analysis facilitates the recognition of potential avenues for research, evaluates the significance of prior studies, and offers recommendations for forthcoming inquiries in this ever-evolving field.

## 4. Bibliometric analysis: results, analysis, and discussion

128 documents were collected for this study using the predefined keywords. Figure 4 presents data regarding articles obtained from Scopus, encompassing the period from 2014 to 2023, generated by Biblioshiny software. The figure reveals that a total of 128 publications were published across 68 journals, utilizing a cumulative count of 14,170 references and 452 author's keywords. Remarkably, the number of authors actively impacting this field reaches an impressive figure of 497, indicating significant involvement. Collaboration in the field of CSDG literature is pronounced, as evident from the collaboration index, equal to 3.87. Additionally, each article receives an average of 25.99 citations, and the articles per author ratio stands at 0.257, suggesting that, on average, nearly four authors have contributed to each document. The upward trend in collaboration among researchers signifies the growing complexity of interdisciplinary research and its positive impact on both the quantity and quality of published works. This trend is particularly evident in the field of SC 4.0 and CE research. As has been highlighted by the initial statistical results, SC 4.0 and CE is an interdisciplinary research area that requires collaboration among scholars' experts from diverse fields such as SC management, sustainability, DDT, environment sciences and CE practices. Through collaboration, researchers can collectively address the intricate challenges of SC 4.0 and CE, leading to comprehensive insights, and advancements in sustainable SC practices. The increased collaboration in SC 4.0 and CE research signifies the recognition of the importance of interdisciplinary cooperation in tackling complex issues at the intersection of circularity and digitalization.


**Fig. 4:** Descriptive statistical information about the selected papers

## 4.1 Descriptive analysis

### 4.1.1. Temporal analysis of academic publications

Figure 5 illustrates the annual publication trend. Initially, from 2011 to 2014, there was limited scientific contribution in the SC 4.0 in the CE domain, with fluctuating productivity and a minor peak of 12 publications in 2019. Subsequently, between 2019 and 2021, the publication trend remained steady, with an average of 15 publications per year. However, there was a significant surge in productivity between 2021 and 2022. The increase was an impressive 51.6%. Notably, 2022, particularly stood out with a remarkable rise in SC 4.0 in CE publications.

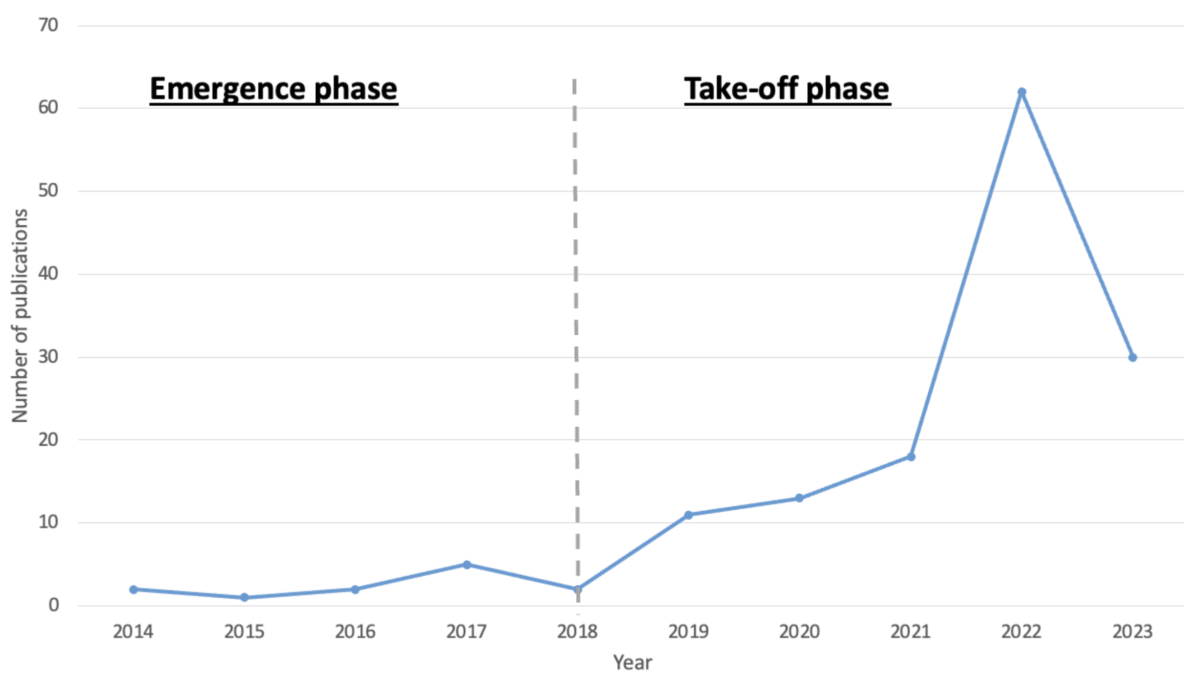


**Fig.5:** Temporal analysis of publication distribution over the last decade

Initially, from 1990 to the early 2000s, there was limited progress in comprehending the fundamental principles of the CE, despite some scientific research in the area. The CE gained scholarly attention after significant events such as China's economic crisis and the depletion of natural resources. In 2009, China changed its strategic direction and proposed the "China CE Promotion Law". Although this event has shifted the research focus of researchers towards studying CE, it remains an emerging field characterized by ambiguous concepts and principles (Jabbour et al., 2018). As a result, SC scholars have largely overlooked CE research, despite its growing prominence in Europe where the European Union emphasizes its potential to reduce costs and increase profits through CE research.

In 2015, the European Commission embraced its initial CE action plan, which aimed to smooth the transition to a CE in Europe. This comprehensive plan included measures addressing various stages of the life cycle. While there was a gradual increase in publications from European scholars and collaborators in this area, the scientific contributions remained limited. Until 2017, the number of articles remained low. However, the release of a comprehensive report by the European Commission in 2019 highlighted the progress made in implementing the CE action plan and reinforced the growing interest in DDT within the CE.

The COVID-19 pandemic highlighted the importance of CE practices for economic recovery and environmental challenges. It exposed the flaws of the linear economy, emphasizing its negative impact on the environment and SCs. The pandemic heightened awareness of inequality and climate risks, renewing focus on CE for climate mitigation and resilience. It also emphasized local manufacturing, consumer behaviour changes, and the role of public policy. Scholars explored technology's potential for environmental benefits. This led to a surge in digital CSC research in 2021-2022, shifting from pandemic concerns to environmental protection due to CE's recognized role in addressing global challenges.

#### 4.1.2. Country-specific scientific contribution

The analysis of the selected papers has provided insightful findings regarding the research on SC 4.0 in CE, which spans across 52 countries globally. In Figure 6, we observe a notable distribution pattern of papers, with more than 8 papers on average, reflecting the authors' geographical locations from 2014 to 2023. Notably, India emerges as the primary hub for SC 4.0 in CE research, with a remarkable count of 33 papers, signifying a substantial concentration of research activities in this field. Following India, the United Kingdom exhibits a strong presence with 28 papers, while China follows closely with 18 papers. These findings strongly indicate that the digital CE has garnered significant attention on a global scale.

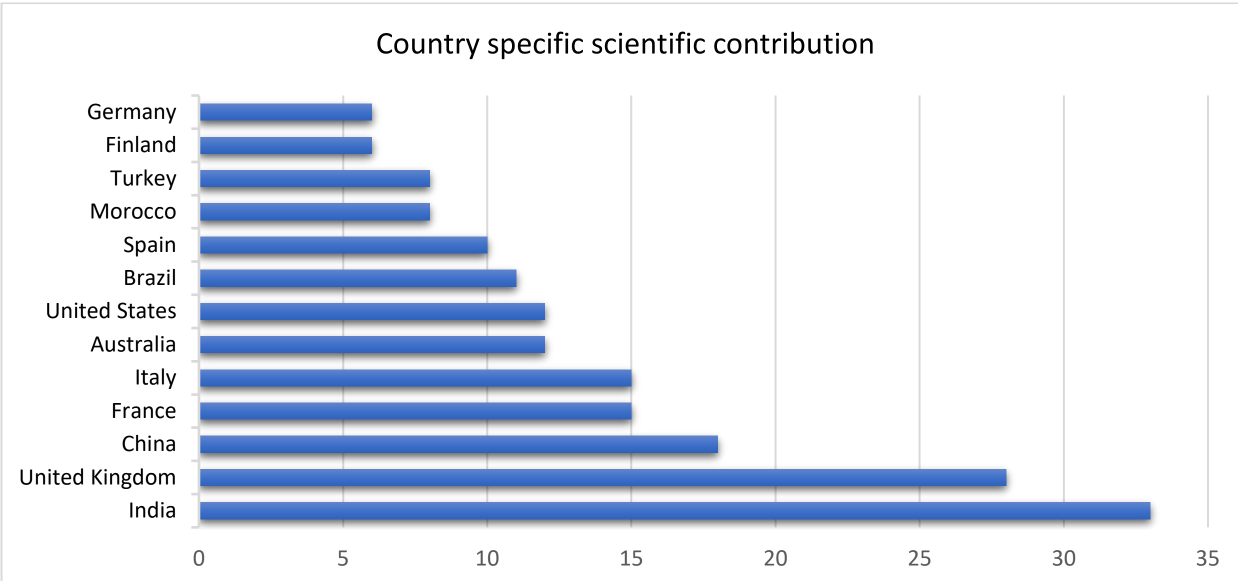


**Fig. 6**: Number of across the studied period

### 4.1.3. Distribution of reviewed papers by journal

In this section, the distribution results of research articles on CDSC across various academic journals are investigated.  A total of 128 selected articles were found to be published in 68 different journals. This wide coverage of journals indicates the expanding research landscape in the field of SC 4.0 in CE. Figure 7 presents the specific journals that have published articles related to CDSC with a minimum requirement of five papers for inclusion in the figure. To assess the scholarly impact of these journals, their rankings according to the SCIMAGO Ranking (SJR) platform were examined. All the journals listed in Figure 7 belong to the top Quartile 1 (Q1) group. From this observation, it can be concluded that SC 4.0 in CE research tends to be disseminated in highly specialized journals that focus on SC management, production, environment, and computer industries. Moreover, given the digital layer of the searched topic, it is fitting for publication in journals with a technological emphasis such as computers and industrial engineering, journal of manufacturing technology management, etc. This explains why CDSC publications have appeared in a wide range of journals.


**Fig.7:** Top publishing journals in the field of SC 4.0 in CE

### 4.1.4. Distribution by subject area

The distribution of references in the field of CDSC research has been analyzed in this study by assigning source documents to journals and subject areas. The study focuses on five subject areas within the sciences: engineering (25%), business (28.7%), decision sciences (17.5%), computer sciences (16.8%), and environmental sciences (11.9%). By categorizing the references based on these subject areas, the researchers gain insights into the interdisciplinary nature of the field and identify the prominent domains contributing to the literature. The chosen subject areas for reference analysis highlight the diverse range of disciplines involved in CDSC research. This aligns with the definition provided by the Ellen MacArthur Foundation (2014, 2015) in the current discourse on CE. In alignment with their statements, the CE is a restorative and/or regenerative industrial system by intention and design, aiming to replace the "End of life" concept and shift to renewable energy, elimination of toxic chemicals, through superior design of materials, products and business models (Ekins et al., 2019; Kirchhenn et al., 2017).

With the integration of digital technology, the research in CDSC expands its focus to cover the five research fields under the umbrella of SC 4.0 in CE. However, the concept of CE has experienced some blurring due to its various interpretations (Gladek, 2018). Additionally, defining CE is multifaceted and transdisciplinary (Lieder et al., 2017; Sauvé et al., 2015). While the concept of CE is not new, with its origins dating back to the 1970s, the term gained renewed attention as it analyzed the linkages between the environment and economic activities (Ekins et al., 2019). The principles of "Reduce", "Reuse", and "Recycle" (the 3R principles) have been studied and highlighted in academic literature since the early 1950s. They are widely recognized, along with concepts such as "Remanufacture", "Reverse Logistics" and "Refurbishment" which gained traction in academic literature from 1984 onwards (Taddei et al., 2022). These concepts are frequently referred to as "Circular Approaches" in the context of CDSC research.

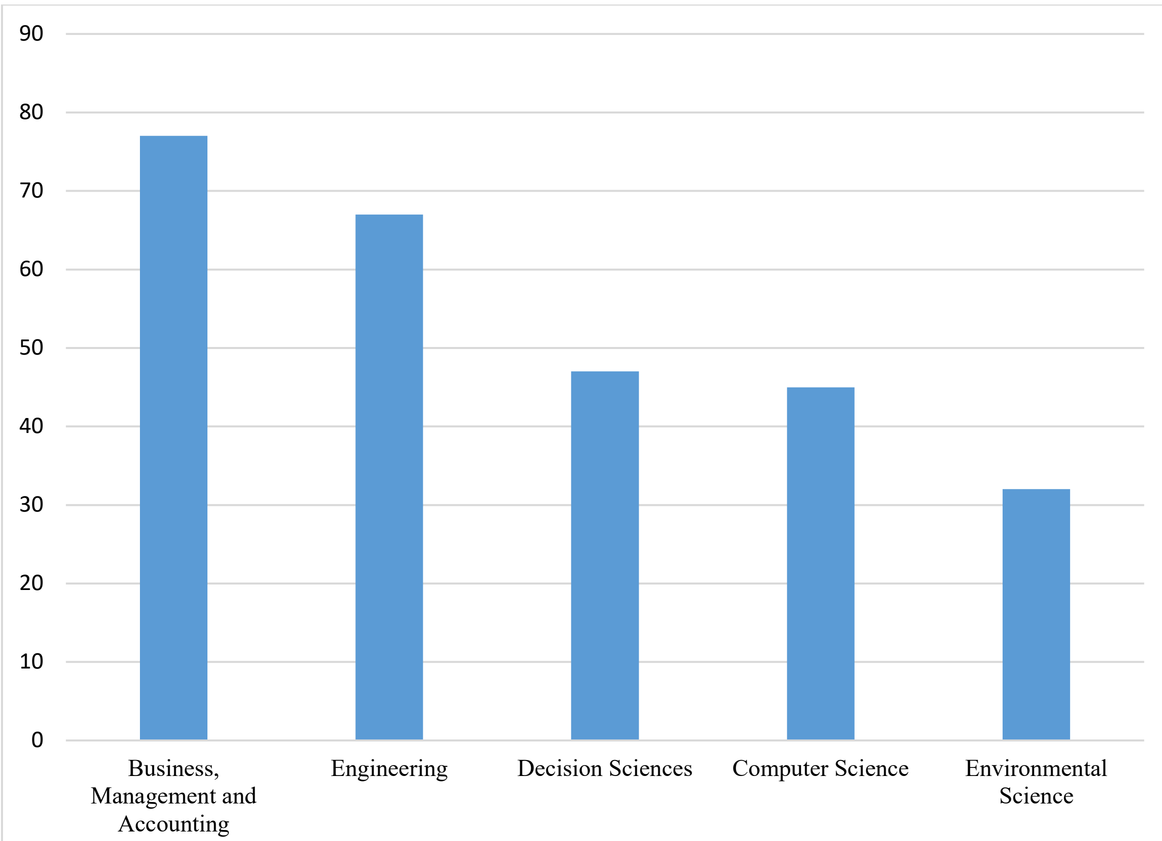


**Fig.8:** Distribution of documents by subject area

#### 4.1.5. Institutions/organizations influence.

The findings regarding the institutions' impact are consistent with the country distribution that was previously examined. The data presented in Figure 9 demonstrates that a significant number of the publications are written by writers from Europe, specifically from the United Kingdom and France. Among these, the Montpellier Business School in France has been identified as the most widely cited institution, followed by the University of Derby. Additionally, Indian authors have emerged as the most prolific contributors in terms of article output, with the National Institute of Industrial Engineering and O.P. Jindal Global University serving as notable institutions in this context.

Furthermore, universities from South Africa, Qatar, Morocco, and the United Arab Emirates have demonstrated a strong commitment to the research domain, revealing that SC 4.0 in CE are firmly on the agenda of numerous institutions worldwide.

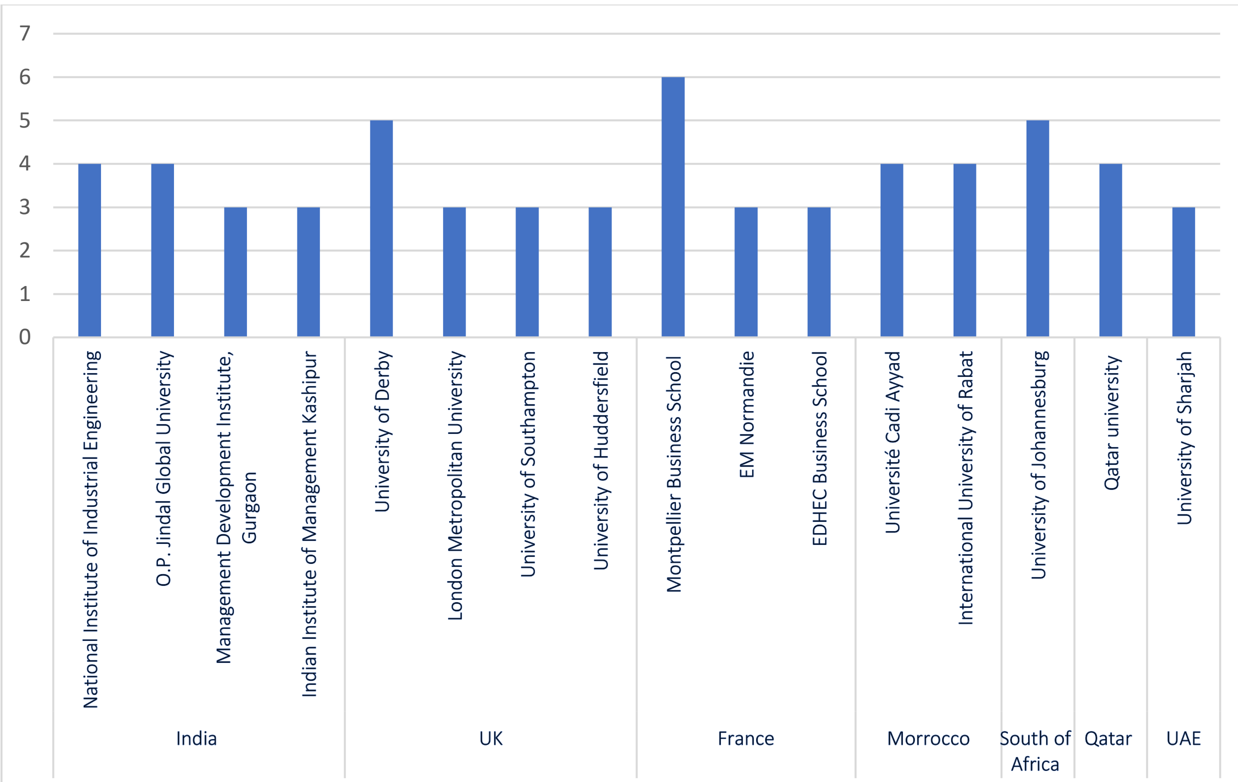


**Fig.9:** Documents by affiliation

### 4.1.6. Index value (yearly trend)

The documents included in the analysis are arranged in descending order based on their total citation count, represented on the vertical axis as positive integers. The 45-degree line on the graph signifies a 1:1 correlation between the number of documents and their corresponding total citation count. The h-index (Hirsch index), which measures the impact of published articles, is determined at the intersection point of the citation/document curve with the 45-degree line and is denoted by a star. For this research, the h-index was calculated based on the article collection obtained from the Scopus document search query. The h-index serves as a quantitative measure of productivity and influence. In this study, the article collection yielded an h-index value of 27, indicating that at least 27 publications out of the 128 analyzed had received 27 or more citations.

## 4.2 Quantitative analysis

The objective of this section is to uncover and analyze the connections between scholars' publications and the underlying structural elements, aiming to understand their relationships and influence on the scientific field (Donthu et al., 2021). To grasp the interrelatedness of the studied topics, occurrence and reference analysis were employed. The first step was constructed by considering citations and co-citation analysis (more than 50 citations to be considered in this study). Secondly, an analysis of the bibliographic coupling aims to link the past research (co-citation) with the current research (bibliographic coupling to forecast the potential agenda for future research in the field of SC 4.0 in CE. Step 3 focuses on the social network characteristics of our study by investigating the co-authorship network. Finally, co-occurrence (co-word) analysis is presented to be able to establish the different semantic relationships and build a conceptual structure of SC 4.0 in the CE domain based on the frequency of cited words and concepts, to construct similarity measures of the content and develop the semantic map.

### 4.2.1 Citation and co-citation analysis

Different methodologies have traditionally been employed to evaluate the significance of academic publications. Among these methodologies, citation analysis has emerged as the predominant approach, aiming to assess a publication's prominence by quantifying the frequency with which it is referenced by other works (Ferreira et al., 2016). The implementation of citation and co-citation analysis facilitates the identification of similarities between documents, aiding in the detection of shifts in research paradigms and thinking (Mukherjee et al., 2022). In this study, we conducted a citation analysis of the 128 papers. Table 5 highlights the top 11 papers within this set, based on their citation counts (more than 50 citations during 2014-2023). A brief overview of this list unveils the knowledge foundation of SC 4.0 in CE and provides preliminary insights into its topic structure, which will be further explored through co-citation analysis.

**Table 5:** Most Cited Documents in the field of SC 4.0 in CE

| Document Title | Authors | Total Citations |
|---|---|---|
| "Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations" | Jabbour et al., (2018) | 568 |
| "Exploring I4.0 technologies to enable CE practices in a manufacturing context: A business model proposal" | Nascimento et al (2019) | 407 |
| "Digitalisation and intelligent robotics in the value chain of CE oriented waste management – A review" | Sarc et al (2019) | 171 |

| | | |
|---|---|---|
| “Relationships between I4.0, sustainable manufacturing and circular economy: proposal of a research framework” | Bag and Pretorius (2022) | 114 |
| “Circular fashion SC through textile-to-textile recycling” | Sandvik and Stubbs (2019) | 110 |
| “Blockchain technology for bridging trust, traceability and transparency in the circular supply chain” | Centobelli et al (2022) | 97 |
| “Blockchain-enabled CSC management: A system architecture for fast fashion” | Wang et al (2020) | 96 |
| “Do blockchain and CE practices improve post-COVID-19 supply chains? A resource-based and resource dependence perspective” | Nandi et al (2021) | 92 |
| “An end-to-end Internet of Things solution for Reverse SC Management in I4.0 “ | Nandi et al (2019) | 85 |
| “Application of blockchain technology for sustainability development in the agricultural supply chain: justification framework” | Moktadir et al (2021) | 50 |

The most cited journal article by de Sousa et al. (2018) titled "Industry 4.0 and the CE: a proposed research agenda and original roadmap for sustainable operations" presents a roadmap for organizations to enhance the deployment of CE (CE) measures through I4.0 approaches. The article highlights the potential of I4.0 DDT in advancing both productivity and CE based on their intersection with the ReSOLVE model within SC operations. The authors propose a matrix that aligns different SC management decisions with six business models of the ReSOLVE framework, with the Internet of Things and Cloud computing being frequently dominant technologies. The roadmap suggests steps for organizations to transition towards CE, including determining suitable models, identifying viable I4.0 technologies, adapting sustainable operations management decisions, integrating SCs, and creating performance indicators. However, challenges such as coordination, cybersecurity concerns, and a lack of necessary talent are associated with implementing I4.0 technologies. While the paper provides a valuable research framework for circularity in SC, further studies are needed to explore additional research questions and expand the scope beyond the specific technologies and SC areas addressed in this paper. Afterwards, we noticed a new research orientation and focused on the SC 4.0 in the CE research field under 4 main clusters: General overview of the I4CE transition of SC business models (Nascimento et al., 2019; Bag et al., 2020), cluster 2 is the implementation of blockchain in the area of SC 4.0 in CE (Wang et al., 2020; Nandi et al., 2021; Moktadir et al., 2021; Centobelli et al., 2022) and cluster 3 and 4 are focusing on particular area of SC which are the waste management (Curtis et al., 2019) and the fashion industry (Sandis and stubbs, 2019). In the realm of understanding CSC, an influential and widely cited paper (More than 900 citations) by Govindan and Hasanagic (2018) titled "A systematic review on drivers, barriers, and practices towards CE: a SC perspective" provides valuable insights. While this paper specifically focuses on circular SCs, it does not incorporate the digital dimension, which is why it was not included in the analysis for this study.

The second stage of citation analysis involves utilizing the co-citation method (Pilkinton and Meredith, 2009). This method operates on the assumption that the more frequently two documents are cited in conjunction, the stronger their relationship, indicating their inclusion within the same research field. The objective is to identify and demonstrate the knowledge of the interconnections and the clusters within the field of SC 4.0 in CE and the identification of the different structural knowledge groups. The results of the co-citations analysis are presented in Table 5. A total of 3 clusters have been identified (see Appendix 1). Cluster 1 comprises 16 papers that primarily focus on the phenomena of CE. The main objective of this cluster is to define and explain the constructs related to CE, with a particular emphasis on its environmental sustainability aspects. Most of the papers in this cluster adopt LR as their chosen methodology, which is commonly employed for emerging fields like CE. Through these LRs, there is a deliberate effort to clarify the distinctions between various terminologies closely associated with CE, such as sustainability and green reverse logistics.

Cluster 2 primarily focuses on addressing the challenges associated with implementing CE practices and I4.0 technologies. While some papers specifically examine these challenges within the manufacturing industry, others take a broader perspective encompassing various sectors. The papers within this cluster employ diverse methodologies, including LR, case studies, conceptual frameworks, and research propositions, to explore different aspects of CE and I4.0. Published in different journals and spanning across various years, these papers demonstrate the evolving nature of the field and contribute fresh insights and perspectives.

Cluster 3 represents a notable shift towards an integrated approach between I4.0 technology and the CE. These papers shed light on potential research gaps and areas that require investigation to enhance the implementation of circular practices within SCs using DDT. The focus is on leveraging the power of I4.0 to drive circularity and improve sustainability in SC operations.

Overall, these cluster papers, alongside the wider collection of articles, share a common objective of exploring topics related to CE, I4.0, and sustainable SC management. They collectively emphasize the integration of environmental sustainability with economic systems. Many of the papers offer comprehensive LRs, providing a thorough understanding of these concepts. These findings indicate that the field of CE and I4.0 is still in its early stages, and further research efforts are required to unlock its full potential.

### 4.2.2 Co-author analysis

In this section, we highlight the collaboration and social structure of SC 4.0 in CE. Figure 11, generated using Vosviewer for mapping and visualization, illustrates the relationships between documents based on their co-authorship. The size of the author labels corresponds to their weight, and colours represent the author clusters. The proximity of authors in the visualization indicates the strength of their co-citation links. Authors located closer to each other demonstrate stronger relatedness. The co-authorship network set a minimum of two publications for authors per document. Following Ajiferuke's framework (1988), the collaboration index was calculated to be 0.67, suggesting some disconnection among scholars in this field (Donthu et al., 2021). Additionally, many of the identified 31 authors in the network were not connected.

The prime connected group consists of 14 authors clustered into 3 groups. The Red cluster, comprising most authors (7 out of 14), focuses on the conceptual framework and theoretical understanding of CE and its potential intersection with I4.0. The green and blue groups tackle the primary challenges faced by industries in implementing CE practices within the SC and explore the contributions of DDT to address these issues. Due to the novelty of the subject, there is a poor relationship between the author clusters, which results in a discontinuity in the research spectra.

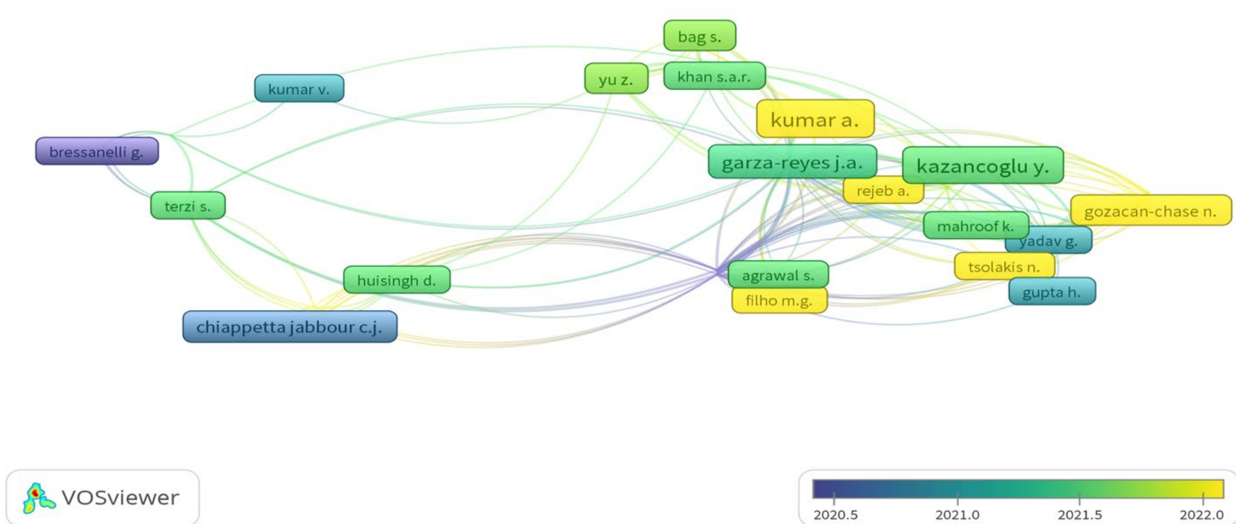


**Fig. 11:** The social structure of SC 4.0 in CE field based on co-authors analysis

### 4.2.3 Co-occurrence analysis

In this section, we conducted a co-occurrence analysis to establish relationships and construct a conceptual structure within the SC 4.0 in the CE research field. Based on the initial findings, we observed that the most used words in SC 4.0 in CE research titles were CE, sustainable development, and waste management (refer to Figure 12). A word cloud graphic was created to illustrate these findings, emphasizing the most frequent keywords by making them bigger and bolder in proportion to their occurrence.


**Fig.12:** Top- frequently occurring words in SC 4.0 in CE

Figure 12 presents the results of a keyword co-occurrence analysis focusing on journal articles. A more in-depth examination was conducted on the co-occurrence of 1,110 keywords that appeared at least 5 times in the collection, as depicted in Figure 13. Each node in the visualization represents a keyword or topic, and the thickness of the lines connecting nodes reflects the strength of their relationship based on their co-occurrence frequency in published papers.

The 41 most frequently occurring keywords were categorized into four distinct clusters, each represented by a different colour code.

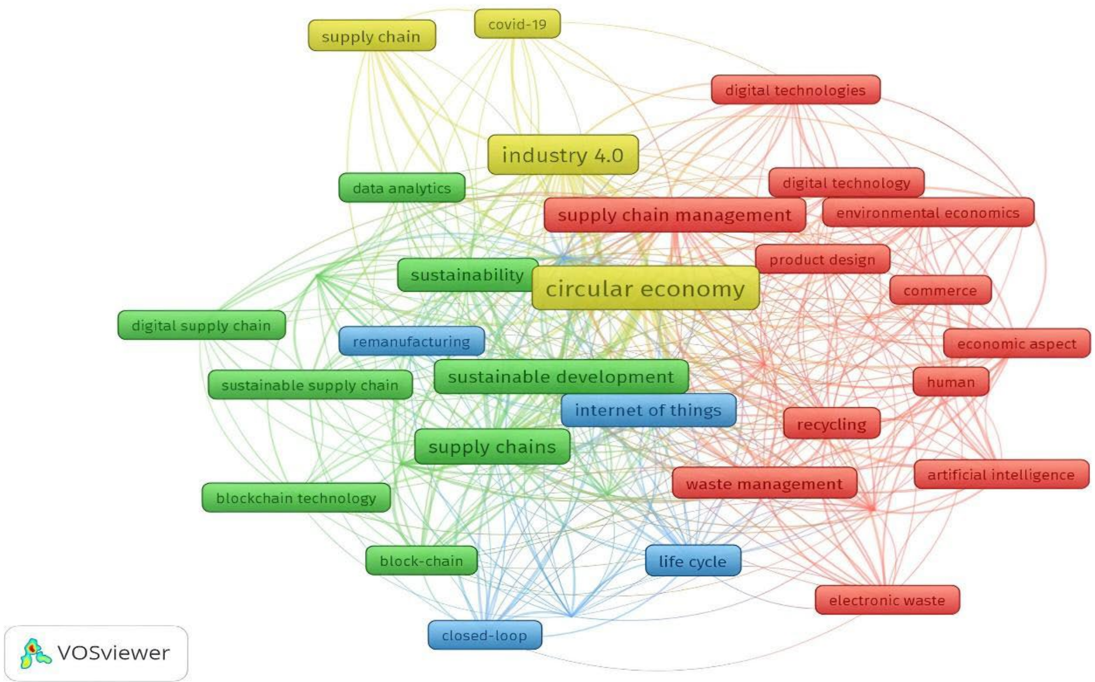


**Fig. 13:** Top- frequently occurring words in SC 4.0 in CE

In the green cluster (Figure 13), we can see a drive towards sustainable SC management. By implementing a CE, we can achieve this goal, using dynamic capability that enables SC organizations to innovate and develop sustainable practices that promote resource efficiency, waste reduction, and the reuse of materials. This shift has been particularly highlighted after the crisis of COVID-19 that forced SC managers to develop more resilient but at the same time more sustainable businesses. To achieve the right balance, the decision-making landscape needed to acquire a deeper understanding of the information to acquire more information, and that's where technology, specifically big data, came in. The shift to circular SCs, however, requires a transition from linear to circular economic models starting from raw materials and involving multiple stakeholders throughout the product's lifecycle. Therefore, a tool is needed that manages this complexity and keeps trust and transparency across the entire SC. For this reason, we see, the cluster yellow, the focus on blockchains and smart contracts, which are deemed the best technologies to address such a challenge in the SC.

The blue and red clusters represent areas of intensive research and scholarly work dedicated to implementing the principles of a CE. The red cluster, symbolizing the food industry, focuses on developing a generative model for a circular SC. Researchers are exploring various methods and technologies to recycle food effectively, aiming to generate economic value and reduce emissions. On the other hand, scholars in the blue cluster are concentrating on technical products, particularly electronics, which pose significant security challenges for businesses due to their waste. Their research involves analysing the life cycle of these products to improve design and minimize waste. Leveraging technologies like the Internet of Things, they track the product's life cycle and explore diverse closed-loop possibilities. Additionally, the research community has also shown considerable interest in the food industry, recognizing its significance in the context of CE implementation. Figure 14 illustrates the various topics that have been studied over time in the context of CE research. It is noteworthy that DDT has emerged as a central focus of research in the CE, albeit relatively recently, around the year 2020. This is understandable as both fields, CE, and DDT, are considered new research areas that are still maturing.

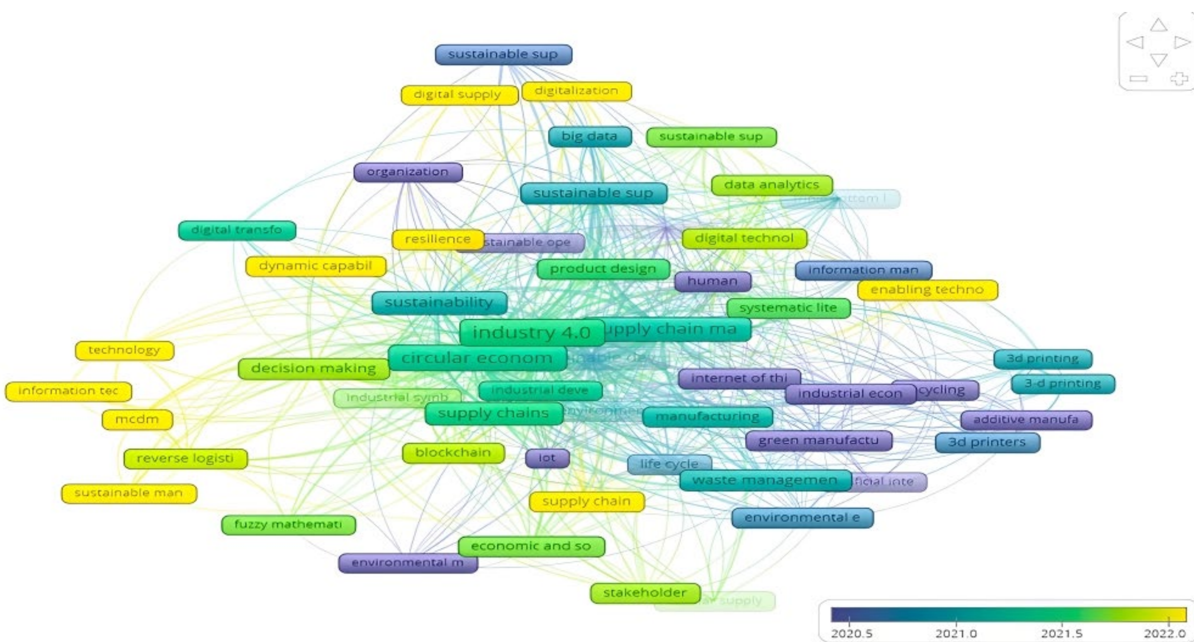


**Fig.14:** Evolution of the themes and concepts over time in SC 4.0 in the CE research field

Scholars have been exploring different research questions independently in these domains. However, more recently, there has been an increased interest in investigating the interactions and impact of CE and SC 4.0.

## 5. Analysis of SC 4.0 in CE barriers and relationships: TISM and MICMAC Analysis

The article adopts the TISM approach to establish a relationship-based model. The TISM model is further supplemented by the application of MICMAC analysis to classify the barriers. The next section provides the steps involved in constructing the TISM model. After that MICMAC analysis identifies the interdependencies between the elements in the system, distinguishing between dependent and independent barriers.

### 5.1 Conducting Modified-TISM Analysis

With the finalization of 12 critical barriers, the next step is to establish a contextual relationship among them as various barriers hinder firms from fully capitalizing on enhanced dynamic capabilities through the implementation of CE and I4.0 practices. In this paper, we followed Mathiyazhagan et al (2013) and Sharma et al (2021) methodology for m-TISM implementation (Details provided in Appendix 2). The m-TISM approach represents an advancement over the traditional TISM model. TISM elucidates the hierarchy of factors or enablers by examining their interrelationships. Like the traditional ISM model, m-TISM employs reachability matrices and partition elements. However, it merges steps for pairwise comparisons and transitivity checks, reducing the need for expert-based comparisons. Through an iterative process, each identified factor or variable is systematically interpreted alongside others and represented in a digraph (Sushil, 2012). Thus, a pairwise comparison matrix (SSIM) for the 12 barriers is developed with the help of an extensive literature review (whether one key barrier i influences/affects factor j – Y/N and so on) (is presented in Table 6). The contextual relationship is known as "leads to", indicating that one barrier precedes another is chosen as this relationship type allows one to delve into the obstacles more comprehensively. By establishing contextual or pairwise comparisons, we can uncover the directional nature of connections between these barriers.

To achieve this, the contextual relationships among the barriers employ a set of four symbols (i and j):

- V: Barrier i leads to j, but not the other way around.
- A: Barrier j leads to i, but not vice versa.
- X: Both barriers i and j lead to each other.
- O: There is no discernible relationship between barriers i and j.

The subsequent step involves creating a reachability matrix by replacing V, A, X, and O with (1, 0) and integrating transitivity criteria. The ultimate goal is to formulate the final reachability matrix while adhering to specific rules, as outlined below:

• If the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix becomes 1, while the (j, i) entry becomes 0.

• If the (i, j) entry in the SSIM is A, then the (i, j) entry in the reachability matrix becomes 0, and the (j, i) entry becomes 1.

• If the (i, j) entry in the SSIM is X, then both the (i, j) and (j, i) entries in the reachability matrix become 1.

• If the (i, j) entry in the SSIM is O, then both the (i, j) and (j, i) entries in the reachability matrix become 0.

This matrix serves as a crucial tool in our analysis process.

**Table 6:** Structural Self-Interaction Matrix for barriers to adoption of CE

| **Notation** | **Barriers** | **B1** | **B2** | **B3** | **B4** | **B5** | **B6** | **B7** | **B8** | **B9** | **B10** | **B11** | **B12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **B1** | Lack of operational efficiency | X | X | X | X | V | A | X | A | A | X | X | X |
| **B2** | Lack of data and knowledge management | | X | A | X | X | X | X | V | V | X | V | V |
| **B3** | Lack of training and skill-competency | | | X | V | V | A | O | A | O | A | V | V |
| **B4** | Lack of risk control | | | | X | A | A | X | A | O | X | V | V |
| **B5** | Lack of collaborative network/strategy | | | | | X | A | A | A | O | A | A | V |
| **B6** | Lack of top management planning/support | | | | | | X | X | V | V | V | V | V |
| **B7** | Policy regulations and standards challenges | | | | | | | X | V | O | V | V | V |
| **B8** | Financing challenges | | | | | | | | X | O | V | V | O |
| **B9** | Challenges in customer awareness and participation | | | | | | | | | X | X | O | O |
| **B10** | Unsupportive systemic changes | | | | | | | | | | X | X | V |
| **B11** | Uncertainty about economic benefits and incentives | | | | | | | | | | | X | O |
| **B12** | Limited demand and acceptance by businesses | | | | | | | | | | | | X |

The reachability matrix, shown in Table 7, is a product of the SSIM analysis and the application of the rules. This matrix provides insights into the interrelationships between capability drivers. Additionally, the driving and dependent powers of each variable are also illustrated in this table. The driving power of a variable signifies the total number of variables, including itself, that it can contribute to achieving. Conversely, dependence power represents the total number of variables, including itself, that can aid in its attainment. These powers aid in categorizing variables into distinct groups, including autonomous, dependent, linkage, and driver variables.

**Table 7:** Final Reachability Matrix (FRM) for barriers to adoption of CE

| **Notation** | **Barriers** | B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 | B9 | B10 | B11 | B12 | **Driving Power** | **Rank** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B1 | Lack of operational efficiency | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | **11** | 2 |
| B2 | Lack of data and knowledge management | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **12** | 1 |
| B3 | Lack of training and skill-competency | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | **7** | 5 |
| B4 | Lack of risk control | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | **9** | 4 |
| B5 | Lack of collaborative network/strategy | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | **4** | 6 |
| B6 | Lack of top management planning/support | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **12** | 1 |
| B7 | Policy regulations and standards challenges | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | **10** | 2 |
| B8 | Financing challenges | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | **7** | 5 |
| B9 | Challenges in customer awareness and participation | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | **3** | 8 |
| B10 | Unsupportive systemic changes | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | **9** | 3 |
| B11 | Uncertainty about economic benefits and incentives | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | **4** | 7 |
| B12 | Limited demand and acceptance by businesses | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | **2** | 9 |
| **Dependence Power** | | **11** | **8** | **7** | **9** | **10** | **3** | **5** | **5** | **5** | **9** | **9** | **9** | **90** | |
| Rank | | 1 | 3 | 4 | 2 | 2 | 7 | 5 | 5 | 6 | 2 | 2 | 2 | | |

Next, the barriers are categorized into multiple levels, facilitating the assessment of their significance within the barrier hierarchy. At the uppermost level of the hierarchy, a factor is placed if the overlap between the reachability set and the antecedent set matches the reachability set itself. Subsequently, for the determination of levels for all other factors, we iteratively eliminate the element that ultimately ascends to the topmost position in the hierarchy. These identified levels are used in constructing the directed graph (digraph) and the ultimate model, which are both illustrated in Table 8 for reference.

**Table 8:** Final levels of the barriers after 6 iterations

| Notation | Barriers | Level |
|---|---|---|
| B1 | Lack of operational efficiency | IV |
| B2 | Lack of data and knowledge management | VI |
| B3 | Lack of training and skill-competency | III |
| B4 | Lack of risk control | IV |
| B5 | Lack of collaborative network/strategy | I |
| B6 | Lack of top management planning/support | VI |
| B7 | Policy regulations and standards challenges | VI |
| B8 | Financing challenges | V |
| B9 | Challenges in customer awareness and participation | I |
| B10 | Unsupportive systemic changes | IV |
| B11 | Uncertainty about economic benefits and incentives | II |
| B12 | Limited demand and acceptance by businesses | I |

### 5.2 Investigating Barrier Relationships

Upon establishing the levels of each barrier, we proceed to conduct a MICMAC analysis. This analytical step assesses the driving and dependency powers of each barrier through FRM, which involves the summation of rows and columns. Specifically, the driving power and the dependence power for each barrier are calculated by summing the respective rows and columns (as illustrated in Figure 15). The MICMAC analysis is employed to delve deeper into the causes and consequences associated with the complex challenges of extending circular models within industrial SCs. By subjecting the barriers to the MICMAC analysis, we gain valuable insights into the intricate interplay between these barriers, shedding light on their effects and underlying factors.


**Fig.15**: MICMAC analysis

The 12 identified barriers have been classified into four distinct categories, as illustrated in Figure 16:

- **Autonomous Barriers**: These barriers are relatively detached from the system and exhibit weak driving and dependency power, as depicted in the bottom-left quadrant. An example is the challenges in customer awareness and participation (B9), indicating higher reliance power. Addressing this barrier could potentially enhance consumer acceptance of sustainable SCs by gradually eliminating other obstacles.
- **Dependent Barriers:** Barriers in this category possess weak driving power but strong dependence power, as shown in the lower-right quadrant. Positioned at the top of the hierarchical model based on TISM) three barriers fall under this category: uncertainty about economic benefits and incentives (B11), lack of collaborative network/strategy (B5), and limited demand and acceptance by businesses (B12). These barriers are pivotal as their strong dependence implies that their resolution necessitates the removal of all other barriers for the effective adoption of SSC concepts.
- **Linkage Barriers:** Positioned in the upper-right quadrant, these barriers exhibit strong driving power as well as strong dependence power. This category occupies the middle ground in the TISM-based hierarchical model and contains the highest number of barriers. Depending on their significance, these variables can either amplify or hinder the impact of driving barriers. Due to their strategic nature, these barriers play a crucial role. The barriers within this quadrant include

lack of data and knowledge management (B2), lack of operational efficiency (B1), lack of risk control (B4), and unsupportive systemic changes (B10).

- **Driver Barriers:** Positioned in the upper-left quadrant, these barriers demonstrate strong driving power but weak dependence power. Placed at the bottom of the TISM-based hierarchical model, this category encompasses three barriers: lack of top management planning/support (B6), policy regulations and standards challenges (B7), and financing challenges (B8). These barriers possess the potential to drive the transformational process, even though they are less influenced by other barriers.

Given their potential to be the underlying causes of other barriers, firms should prioritize these obstacles. These barriers can address and potentially eliminate other barriers situated within the central and upper tiers of the TISM-based hierarchical framework. As certain dependent barriers are influenced by high-driving power barriers, addressing the latter becomes crucial, as they exert a direct influence on the former.

Leveraging the outcomes of the MICMAC analysis, we proceeded to construct the TISM model and the corresponding directed graph (digraph). The structured TISM model, utilizing FRM, was developed using nodes (vertices) and edges (lines). The digraph visually portrays the structural model of interconnections among barriers, based on the levels identified through iterative cycles. This transformation involved removing transitivity links and replacing their nodes with designated barriers. The hierarchical TISM-based model for the barriers was thus formulated, as depicted in Figure 16. This model encapsulates the intricate relationships and relative significance of the barriers in question.

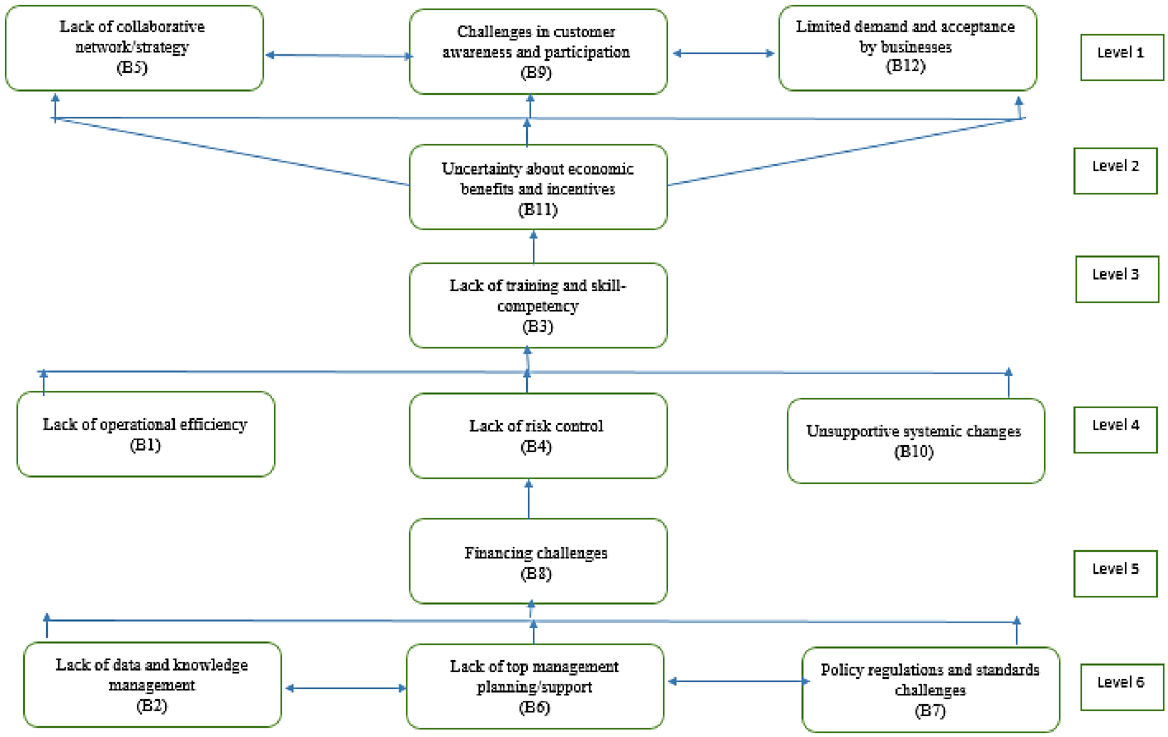


**Fig.16:** TISM model of barriers to SSCM (Diagraph illustration)

Companies that effectively incorporate CE (CE) and I4.0 can enhance their dynamic capabilities. However, those struggling with these changes will face challenges in establishing a sustainable SC. Scholarly sources (Bocken and Geradts, 2020; Shayganmehr et al., 2021) highlight that "dynamic capabilities" play a crucial role in transitioning to CE. In addressing sustainability and CE challenges, organizations need to adapt to changing environmental demands and build eco-capabilities like resilience (Souza et al., 2017).

The barriers at level 6, such as 'lack of data and knowledge management (B2)', 'lack of top management planning support (B6)', and 'policy regulations and standards challenges (B7)', form the foundation of the SSCM model's hierarchy. These barriers, influenced by DCV, emphasize the importance of enhancing knowledge resources, acquiring, and utilizing techniques, and advocating for resources to achieve policy and regulation standardization in the market.

At level 5, the obstacle of 'financing challenges (B8)' hinders the shift towards circular practices (Chari et al., 2022), and when combined with barriers at level 6, they emerge as significant catalysts for other obstacles. Particularly for Small and Medium-sized Enterprises (SMEs), finding appropriate funding for the necessary innovations in the CE (CE) transition is exceptionally challenging (Geng et al., 2010; De Jesus and Mendonça, 2018). Moreover, Ranta et al. (2017) emphasize that due to the substantial costs associated with CE innovations and initiatives, financial support becomes imperative for a successful CE transition (Rizos et al., 2015). Financial injections are essential to render CE efforts economically viable. Governments can contribute to alleviating this financial barrier by extending financial assistance to companies adopting CE practices and by establishing robust, transparent policy frameworks that encourage investment and experimentation (Preston, 2012; Kirchherr et al., 2017).

At level 4, barriers such as 'lack of operational efficiency (B1)', 'lack of risk control (B4)', and 'unsupportive systemic changes (B10)' are pivotal for maintaining resilience. CE demands the integration of SC sustainability throughout operational processes, encompassing product design, processes, production, and logistics (Lopes de Sousa Jabbour et al., 2018). I4.0 significantly enhances operational, financial, and sustainable SC performance by facilitating decision-making, optimizing material flow, and reducing life cycle impacts, thereby strengthening organizational capacities (Peng et al., 2018). By systematically eliminating material waste across operations through transparent flow, businesses can considerably enhance their material efficiency (Despeisse et al., 2017). While the systemic approach promotes an integrated stance towards sustainable practices, it also presents the challenge of constructing the essential dynamic system (H. Lu et al., 2022). A responsive SC necessitates a real-time exchange of accurate information, placing high demands on flexibility and agility for the dynamic creation of temporary processes and transparent SC networks (Verdouw et al., 2018).

At level 3, the barrier of 'lack of training and skill-competency (B3)' closely relates to operational inefficiency and the growth of employee skills and capabilities (El-Kassar and Sigh, 2018; Liboni et al., 2018). Workforce expertise and relevant skills are paramount for real-world sustainability practices. Diverse aspects, including knowledge dissemination, design specification and information exchange, reuse and repair, historical tracking of returned items, and employee retention, to a certain extent, constrain life cycle design.

Research conducted by Mangla et al. (2014) highlights that embracing environmentally friendly and sustainable practices is a strategic decision that often yields financial advantages on a strategic level. Therefore, the uncertainty surrounding short-term economic benefits stands as a noteworthy barrier, contingent upon the elimination of other obstacles. Market barriers to reaping economic benefits (level 2) arise from significant issues, including high initial costs, absence of reverse logistics/reverse SC, and restricted funding for circular business models (Kirchherr et al., 2018).

Finally, at level 1, the barriers 'lack of collaborative network/strategy (B5)', 'limited demand and acceptance by businesses (B12)', and 'challenges in customer awareness and participation (B9)' are highly interdependent. Businesses adopting CE (CE) face challenges in motivating collaboration within the value network. Establishing a "green SC" is intricate, given the potential costs suppliers might bear (Rizos et al., 2015), compounded by SC partners' conservative stance (Kirchherr et al., 2018). This barrier is further compounded by other obstacles like operational efficiency, top management directives, or unsupportive systemic changes. Deficiencies in consumer awareness and interest hinge on standards, certifications, or labelling systems such as those for energy and carbon (Preston, 2012). Employing digital technology can enhance traceability and transparency, maximizing awareness of CE practices and associated benefits. By adopting sustainable SC management practices—an integral CE component (Bai et al., 2019; Genovese et al., 2017)—organizations can achieve sustainability (de Sousa Jabbour et al., 2019). Therefore, a comprehensive end-to-end SC perspective must consider sustainability holistically to avert negative outcomes such as burden-shifting.

## 6. Results implications and future research agenda

### 6.1 Main findings

This research explores the integration of Circular Economy (CE) principles with Industry 4.0 (I4.0) technologies in the context of Supply Chain 4.0 (SC 4.0), marking a critical area of academic inquiry especially noted post-2019. The study employs bibliometric analysis, revealing a notable scholarly engagement with an average citation count highlighting the pertinence of this research within the academic community (Mukherjee et al., 2022). It scrutinizes new insights, identifies research gaps, and assesses the potential impact of advanced technological integration within supply chains, contributing significantly to the evolution of thought in this field (Ellegaard and Wallin, 2015).

Addressing the research questions proposed, this paper identifies a lack of comprehensive analysis in the literature regarding the sequential evolution of supply chains from their traditional forms to the integration of SC 4.0 and CE principles. It bridges this gap by offering a novel framework that not only traces the transition journey but also meticulously evaluates barriers to the adoption of CE practices within this paradigm shift. The study underlines digitization as a critical facilitator in this transition, while also identifying and categorizing 12 distinct challenges, with data management and operational efficiency being paramount.

The research further highlights the importance of top management's support in navigating the CE transition effectively. It also identifies specific barriers across different stages of the supply chain, including skill and training deficiencies, risk management, policy regulations, financial constraints, and the need for greater market demand and acceptance. These findings point to the necessity of adaptive strategies, customer education, and stakeholder collaboration to foster a circular and technologically advanced supply chain environment.

The study identifies three primary research themes that are important in the discourse of integrating CE with Industry 4.0 within supply chains in line with research question 1. These themes include the foundational principles of CE, the integration of CE with Industry 4.0 technologies across various industry sectors, and a comprehensive approach that combines technological innovation with sustainability goals. This delineation of themes signifies a progressive academic narrative that transitions from theoretical foundations to practical applications, illustrating a robust multidisciplinary engagement in sustainable supply chain management. The emphasis on advanced technologies such as big data, blockchain, and smart contracts further highlights the strategic pivot towards resilient and technologically empowered supply chains (Mukherjee et al., 2022).

Concerning research question 2, the paper identifies digitization as a crucial enabler in the evolution from traditional supply chains to SC 4.0. Despite extensive research on individual stages or comparisons between them, a comprehensive analysis tracing the entire transition journey has been scarce. This study fills this gap by offering a framework that not only traces the transition from traditional to SC 4.0 but also critically assesses the barriers to adopting CE practices. It highlights the essential role of top management support, skill and training enhancement, and overcoming regulatory and financial challenges as key mechanisms that influence this evolution. The findings suggest that digitization catalyzes the shift towards more sustainable and technologically integrated supply chains.

Further, research question 3, assesses the complex hierarchy of barriers hampering CSC 4.0 principle implementation within CE initiatives. These barriers range from foundational issues like data management deficits and executive support gaps to practical obstacles such as financial constraints and limited market demand. Through the employment of TISM and MICMAC analyses, the research not only categorizes these barriers but also highlights their interdependence, providing actionable insights for organizations aiming to navigate the transition towards sustainable and technologically integrated supply chains effectively. This comprehensive evaluation points towards the necessity for adaptive strategies, emphasizing the critical need for continuous skill development, stakeholder collaboration, and regulatory adaptability to foster a circular and technologically advanced supply chain environment.

Thus, the paper advances the understanding of how Circular Economy (CE) principles can be integrated with Industry 4.0 (I4.0) technologies within the sphere of supply chain management. The investigation into dominant themes, critical mechanisms, and barrier implications not only clarifies the current academic and practical landscape but also charts a clear path forward for harnessing the synergistic power of CE and I4.0 (Sarkis et al., 2011; Touboulic and Walker, 2015; Mukherjee et al., 2022; Ellegaard and Wallin, 2015). This research highlights the complexities of transitioning to Circular Digital Supply Chains (CDSC), despite existing barriers. It highlights the importance of digital innovation as a catalyst for sustainable transformation and stresses the potential of collaborative ventures between academia and industry in creating supply chains that are not only efficient and adaptable but also sustainable (Mukherjee et al., 2022; Ellegaard and Wallin, 2015). By mapping out a strategic course for overcoming identified challenges, this paper contributes significantly to the field of sustainable supply chain management (Sarkis et al., 2011; Touboulic and Walker, 2015).

The outcomes of this comprehensive analysis hold significant implications. The identification of ongoing research trends, influential scholars, and prominent institutions nurtures a collaborative atmosphere, promoting the exchange of knowledge and cross-fertilization of ideas. The acknowledgement and prioritization of barriers and challenges empower stakeholders to formulate effective strategies, interventions, and policy recommendations. Moreover, the holistic comprehension attained through this analysis aids in consolidating disjointed research streams, resulting in a cohesive framework for future investigations. The meticulous review and assessment of the literature catalyze the advancement of the digital CSC field. By bridging research gaps, uncovering fresh innovation prospects, and shaping a well-informed research agenda, this exhaustive analysis lays the foundation for transformative progress. Researchers and practitioners are equipped to make informed choices, devise targeted interventions, and propel positive change in the pursuit of sustainable and efficient SC practices.

The paper is an attempt towards developing a roadmap to overcome barriers in SC 4.0 for the adoption of CE which has not been explored in previous literature. The outcomes of this paper can be adopted by scholars for conducting research based on organizational theories and ideas in the area of sustainability (Sarkis et al., 2011; Touboulic and Walker, 2015). Infrastructural plans can be developed by policymakers and sustainability plans by the government based on the barriers identified in this paper. On the other hand, managers can implement SC 4.0 in the adoption of CE for each industry thus holistically advancing them. In future, the outcomes of research can be applied to exploring the qualitative side of SC 4.0 and CE as well as developing the framework of CE across nations and cultures by overcoming barriers.

### 6.2 Implications

The present analysis underscores the substantial influence that SC 4.0 and CE have when aligned. The integration of CE principles with the operational efficiency enabled by I4.0 can lead to a transformative SC that is not only efficient and adaptive but also inherently sustainable.

#### 6.2.1 Policy Implications:

The integration of CE principles and Industry 4.0 technologies into supply chains presents a complex challenge that requires strategic policy interventions and robust government initiatives. To address the barriers such as lack of top management planning/support, policy regulations and standards challenges, and financing challenges, there is an urgent need for enhanced support through targeted policy interventions. Governments and regulatory bodies are called upon to establish supportive frameworks that incentivize the adoption of these practices. The European Commission's action plan for the Circular Economy exemplifies such an effort, aiming to boost competitiveness, stimulate sustainable economic growth, and create new job opportunities. This comprehensive plan encompasses measures that span the entire product life cycle, from production and consumption to waste management and the secondary raw materials market.

Furthermore, the importance of fostering collaboration through public-private partnerships is highlighted as a critical step towards overcoming barriers like the lack of a collaborative strategy. Such partnerships can significantly facilitate knowledge sharing, resource allocation, and the dissemination of best practices, thereby enhancing the resilience and sustainability of supply chains. The Horizon 2020 program, funded by the European Union, stands out as a notable initiative that supports research and innovation projects across various domains, including CE and SC 4.0, promoting cross-sectoral and transnational collaboration.

To overcome financing challenges, policymakers are urged to provide financial incentives and green financing solutions. These could include subsidies, tax breaks, and grants that reduce the financial burden on businesses, particularly small and medium-sized enterprises (SMEs), making the transition to sustainable practices more feasible. The development of green financing options, such as green bonds and sustainability-linked loans, is essential to secure the capital required for investments in sustainable technologies and practices.

Addressing the barrier related to the lack of training and skill competency, there is a call for the introduction of educational programs and initiatives aimed at skill development in areas pertinent to CE, I4.0, and sustainable supply chain management. The European Institute of Innovation & Technology (EIT) Manufacturing is an exemplary initiative that offers education and training programs tailored to equip individuals with the necessary skills for the future of the manufacturing sector.

The challenges associated with policy regulations and standards necessitate the establishment of clear, harmonized regulatory frameworks and standardization to ease the integration of CE and I4.0. Governments have a pivotal role in defining these standards, and aligning them with sustainability objectives to guide businesses in incorporating CE principles into their operations. The International Organization for Standardization (ISO) is at the forefront of developing standards that cater to the circular economy, serving as a guide for businesses in this transition.

Overcoming barriers related to customer awareness demands a concerted effort to educate and engage consumers on the benefits of CE and sustainable practices. Government-led campaigns, informative platforms, and labelling schemes are instrumental in increasing consumer awareness and stimulating demand for sustainable products and services. The Green Dot symbol in Europe exemplifies how policy can influence consumer behaviour towards sustainability, indicating a manufacturer's contribution to the recovery and recycling costs.

### 6.2.2 Theoretical Implications:

The enhancement of the dynamic capabilities framework, as revealed in this study, offers substantial contributions to the existing literature on dynamic capabilities by highlighting the pivotal role these capabilities play in the adaptation and integration of CE and I4.0 technologies within supply chains. Drawing on the seminal work of Teece (2007) and Eisenhardt and Martin (2000), this research elaborates on the specific dynamic capabilities—such as leveraging knowledge resources, fostering collaborations with key partners, and efficiently managing supply chain resources—that are indispensable in navigating the intricacies of CE and I4.0 integration. This detailed examination broadens the applicability of dynamic capabilities in the realms of sustainability and technological innovation, providing a nuanced perspective on operationalizing these capabilities to achieve competitive advantage in today's rapidly evolving business environment.

This study enriches the SCM literature, especially concerning CE and I4.0. it introduces a comprehensive framework that summarizes the transition towards sustainable and technologically advanced supply chain models. It responds to the demand for integrated research within these domains, as highlighted by Geissdoerfer et al. (2017) and Lasi et al. (2014), offering a robust foundation for future scholarly exploration at the intersection of sustainability, technology, and SCM. This encourages an interdisciplinary approach, inviting contributions from diverse fields such as information technology, environmental science, and organizational behaviour, to create a richer, more multifaceted understanding of SCM.

By blending CE principles with I4.0 technologies, this research contributes to a reimagined notion of supply chain sustainability. It advances the traditional environmental focus to include the transformative power of digital technologies in realizing sustainability objectives. This aligns with the insights of De Sousa Jabbour et al. (2018) and Pagell & Wu (2009), offering a comprehensive view of what constitutes a sustainable supply chain in the contemporary era, underscoring the synergistic potential of digitalization and circular practices (Seuring & Müller, 2008).

The exploration of barriers to the adoption of CE and I4.0 within supply chains also bears significant theoretical implications. Based on the literature the present paper highlights the critical role of government and industry collaboration in fostering sustainable business practices (Sarkis et al., 2011; Touboulic & Walker, 2015). This paper provides valuable insights into the specific challenges and their interdependencies. It suggests developing collaborative models for policy development, industry standards, and managerial frameworks conducive to adopting CE and technological advancements.

### 6.2.3 Managerial Implications

Businesses in the last couple of years have been motivated to adopt sustainability-related measures not only as a compliance obligation but for competitive advantage and innovation. This has led to a reevaluation of product design, materials utilization, and supply chain operations to diminish environmental footprints and optimize resource efficiency. The adoption of CE principles is

highlighted as a critical investment opportunity for businesses. This investment, as McKinsey & Company (2020) outlines, necessitates the development of new technologies and infrastructures capable of supporting product reuse, remanufacturing, and recycling, thereby maximizing the utility of resources and minimizing waste. Collaboration and partnerships across industries, and with governments, NGOs, and consumers, are indispensable for achieving a sustainable and circular business model. It is thus important to have collaborative networks in sharing best practices, propelling technological innovations, and collectively addressing environmental challenges (Deloitte 2021). Simultaneously it is important to have adaptive strategies related to regulatory frameworks and incentives that facilitate the adoption of CE models. This would ensure businesses are well-positioned to respond to policy shifts (KPMG 2021). businesses must actively communicate the environmental benefits and value of sustainable products to foster consumer demand for greener choices. Engaging and educating consumers about the sustainability of products and the importance of sustainable practices is also important (McKinsey & Company 2020). The role of digital technologies in enabling sustainable and circular practices cannot be overstated. Innovations such as the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain are pivotal in improving resource efficiency, enhancing supply chain transparency, and fostering the development of new, sustainable business models (McKinsey & Company, 2020).
Lastly, the emphasis on long-term value creation over immediate financial gains is advocated. This is based on considering the broader environmental and social impacts of business operations. This approach aligns with the growing investor interest in sustainable and responsible business practices, advocating for a shift towards more resilient, sustainable, and innovative business models (Deloitte, 2021).

**6.3 Limitations and Future Research Directions:**

While the study provides valuable insights, it has limitations that future research could address. These include the need for more empirical data to validate the proposed framework and to explore the specificities of different industries and geographic regions. Future research could also focus on quantifying the benefits of CE practices and on the development of new business models that facilitate the transition to CE within Industry 4.0. While this study provides a foundational understanding of the barriers to CSC 4.0 adoption, it acknowledges limitations such as the focus on bibliometric and TISM-MICMAC analysis without empirical validation. Future research could employ case studies or surveys to empirically investigate the relationships and impacts identified.

Additionally, exploring the role of emerging technologies like blockchain and AI in enhancing transparency and efficiency within circular supply chains represents a promising avenue for further investigation.

## 7. Conclusion

SC 4.0 and CE have emerged as the key concepts focused on renewable energy and regeneration thus increasing revenue, reducing cost, and making SCs resilient by adopting new technologies and linked to I4.0 (Suárez-Eiroa et al. 2019; Okorie et al. 2018; Stölzle et al., 2017). The present study attempts to fill the research gap by examining the relationship between the implementation of SC 4.0 and CE practices (Jabbour et al. 2019; Bai et al. 2020). The paper focuses on assessing the transition from Conventional SC to SC 4.0 and the barriers to further achieving CE by employing BA and TISM approaches. The paper indicates the evolution of SC 4.0 from the conventional SC by analyzing existing studies and indicates the addition of parameters related to sustainability as we move from green to sustainable to SC 4.0 to adopt CE.

While conducting the bibliometric analysis, only those papers that focus on CE and DSC were included. The keywords used were based on literature and interaction with experts. The keywords were limited to SC, CE, Digital technology or I4., Barriers & Challenges. The search was refined by focusing on the subject area, English language, content available and journal articles only. A total of 128 articles were identified and it was seen that most of the publications were in the years 2021 and 2022 though the focus on the area started in 2011-2014. The analysis of the selected papers spans 52 countries globally, with 33 percent of the papers focusing on India followed by the UK and China, thus indicating the global importance of the concept of SC 4.0.

The study also adopts the TISM (Total Interpretive Structural Modelling) approach to establish a relationship-based model as well as MICMAC analysis. The primary barrier for the circular SCs in the era of the I4.0 transition identified is the lack of knowledge about I4.0 technologies and circular approaches. The barriers identified have been categorized into four broad areas driving, autonomous, linkage and dependent barriers. Autonomous barrier with high dependence power is identified as challenges in customer awareness and participation. The dependent barriers have a weak driving power and strong dependence power and are namely, uncertainty about economic benefits and incentives; lack of collaborative network/strategy; and limited demand and acceptance by businesses. The linkage barriers consist of strong driving power and strong dependence power and are maximum in number. The major barriers are lack of data and knowledge management, lack of operational efficiency, lack of risk control, and unsupportive systemic changes. The barriers identified as drivers have strong driving power and weak dependence power. The barriers identified are a lack of top management planning/support, policy regulations and standards challenges, and financing challenges.

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