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Industry 4.0 Technologies in Circular Innovation: A Review of Sustainable Value Chain Studies

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Abstract

This paper explores the intersection of Industry 4.0 (I4.0) and the Circular Economy (CE). The paper's focus is to demonstrate how different factors, such as advanced technologies, can enable the transition of large corporations toward sustainable and circular value chains. The umbrella review has been conducted to identify key organizational enablers and technological innovations driving circularity in such organizations from an academic viewpoint. The paper presents a circular innovation framework in which technological and managerial aspects have been integrated to understand their holistic effect on different value chain steps, from product design to reverse flows. While technological aspects include multiple I4.0 technologies, such as additive manufacturing (AM), blockchain, and big data, and their use cases in the circular value chain, managerial aspects emphasize the role of stakeholders, leadership awareness, and cross-functional collaboration. The study mentions the need for a holistic approach involving all ecosystem actors to achieve a regenerative and sustainable future. This framework not only provides contributions to the academic world but also offers practical implications for large organizations seeking to enhance their circularity. The research concludes with recommendations for future studies to focus on in-depth analysis.

Keywords

Circular economy, Industry 4.0, Value chain, Circular innovation framework, Umbrella review

JEL Classification

Q01, Q56, L60, O32, M15, D22

Introduction

The world is currently facing different environmental, economic, and social challenges and the consequences can be observed in climate change, pollution, and biodiversity loss (Toth-Peter et al., 2023). Patterns of throwaway consumption and increased populations have resulted in underutilization of products, premature wastage, and an overall lack of consideration for the end-of-life implications of products (Rosa et al., 2020). The 2030 Agenda for Sustainable Development, outlined by the United Nations Member States, encapsulates a comprehensive action plan delineating 17 pivotal Sustainable Development Goals (SDGs) designed to bring about transformative change (United Nations, 2015). Large organizations are the main focus of this research due to the abundance of research already focusing on small and medium-sized enterprises (SMEs) and their transition journeys (Rizos et al. 2016; Kumar et al., 2020; Ahmadov et al. 2023; Ahmadov et al. 2024). Moreover, it should be noted that 80% of the global carbon emissions from 2016 through 2022 can be traced to just 57 companies (InfluenceMap, 2024).

Although adopting I4.0 technologies can theoretically facilitate the CE transition, the requirements, and the conditions are not yet fully established or understood (Toth-Peter, 2023). Singh et al. (2021) mention the importance of combining knowledge from several industries and understanding the barriers to adopting the circular economy throughout the product life cycles. The research on CE adoption typically exists as case studies that are closely linked to a sector, but the literature has not effectively synthesized knowledge gained across domains, particularly understanding underlying barriers to CE and where they occur in product life cycles. Fakhreddin (2022) raises questions regarding how a combination of several core I4.0 technologies be combined to maximize their contribution to supply chain performance.

Toth-Peter (2023) approaches the topic from a different perspective and mentions the need for more holistic, macro-level studies that could advance the understanding of transition processes at a higher level, true to the closed-loop nature of the CE. This includes the involvement of more stakeholders in future studies, such as producers, manufacturers, suppliers, designers as well as consumers within the same supply or value chain (Toth-Peter, 2023; Centobelli et al., 2020; Lopes de Sousa Jabbour, 2018).

This paper has adopted an exploratory research approach to understand the current progress of the research in

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industry 4.0 and circular economy nexus and investigates: how industry 4.0 technologies can facilitate circular value chains in large organizations and what are organizational enablers? It is important to have a systematic review of the existing literature to understand progress in the field, best practices, and the latest theoretical contributions. For this reason, a review of published review papers (umbrella review) on the industry 4.0 and circular economy area has been conducted. Based on this, available gaps and limitations have been discovered and the focus of the study has been narrowed down. Although the I4.0 and CE intersection has been an investigation area for different previous research articles, insight from practical implications from a holistic level is lacking. In this article, we are presenting a holistic circular value chain framework that encapsulates both technological and organizational factors as enablers for transitioning to and sustaining CE in large organizations based on the umbrella review of articles in the field.

Literature Review

The circular economy (CE) strategy is designed to help reduce virgin input materials and instead consume previously processed components that are made to close the ecological and economic loops of resource flows (Agrawal et al., 2022). The circular economy concept has gained widespread attention in different industries to address future challenges expected in the light of current environmental, economic, and social paradigms (Ellen MacArthur Foundation, 2013). The European Commission defines the circular economy as a system where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimized (Norouzi, 2022). The circular approach to resources can potentially provide environmental, economic, and social benefits to organizations when they replace the traditional 'take-make-use-dispose' system with the circular economy (Geissdoerfer et al., 2017). However, there are multiple barriers to the complete adoption of circular principles due to mainly lack of visibility on both operational (such as lack of information for complete product lifecycle) and financial (such as implementation costs, return on investments) levels (Lopes de Sousa Jabbour, 2018).

The fourth industrial revolution (I4.0) can be defined as a real-time, digital, and intelligent network of humans, equipment, and objects for the management of business operations and value-adding networks (Agrawal et al., 2022). Similarly, Neligan et al. (2022) describe these technologies as a "glue" between value-chain partners and other stakeholders by enabling data transfer and providing improved transparency along the value chain. Notably, recent advancements in Industry 4.0 (I4.0), the fourth industrial revolution, comprising technologies, such as additive manufacturing (AM), blockchain, artificial intelligence (AI), big data, internet of things (IoT), 3D printing, and robotics provide a link between the physical and virtual worlds and provide real-time data access (Birkel and Müller, 2021). The creation of new business concepts and the transition of traditional ways of work for sustainable development are facilitated by this connectedness (Kerin, 2019). The literature also emphasizes how Industry 4.0 technologies enable businesses to enable circularity and maximize production efficiency. These technologies can facilitate the tracking of resource consumption and emissions, which is essential for the effective implementation of circular economy principles (Ghaithan et al., 2023). Neligan et al. (2022) share that the outcome of the survey of 599 German manufacturing firms shows that digitalization makes resource efficiency measurable and savings potentials usable. In other words, a higher degree of digitalization in efficiency measures allows companies to achieve a higher level of resource efficiency which can enhance circularity.

Advancements in technological innovation offer a promising outlook for the adoption of CE in organizations. From the perspective of manufacturing companies, CE is meant to replace the end-of-life (EoL) concept with different R concepts, such as from 3R (reduce, reuse, recycle) to 10R (reduce, reuse, recycle, recover, remanufacture, redesign, rethink, repair, refurbish, repurpose, refuse), to redesign products, business models, and supply chains (Bjørnset et al., 2021). Kumar et al. (2020) state that the shift to sustainability and improved product lifecycle management throughout supply chains can be facilitated by technological developments and process digitalization. Therefore, this paper focuses on demonstrating how different factors, such as advanced technologies, can enable the transition of large corporations toward sustainable and circular value chains.

Methodology

Umbrella review, also known as an overview of reviews, is a comprehensive evidence synthesis method that aims to systematically retrieve and summarize the results of multiple systematic reviews. This is considered a pre-step to network meta-analysis and is valuable in providing a summary for experts in the field. However, a limitation of the umbrella review approach is that it can only report what researchers have investigated and published to date. Despite this limitation, umbrella reviews are valuable in assessing the credibility of current research in different fields (Alsulamy et al., 2020).

The search strategy in the paper followed a database-driven search and selected two databases, Scopus and the Web of Science. Search string used for this search is as follows: ("circul*") AND ("Big data" OR "Cloud Computing" OR "I4.0 Technolog*" OR "Artificial Intelligence" OR "Robotic" OR "Additive Manufacturing" OR "Augmented Reality" OR "Advanced manufacturing" OR "Blockchain" OR "Cyber-security" OR "Internet of Things" OR "Industrial simulation" OR "3d print*" OR "Industry 4.0" OR "Smart manufacturing" OR "Autonomous Robots" OR "Advanced

robots"). The result has been limited to only review articles in English and business and management fields. Additionally, non-peer-reviewed articles were excluded, but since both CE and I4.0 concepts are relatively new, there was no limitation on the publication years. To make sure that a certain quality threshold is maintained in the quality of articles, the Academic Journal Guide by the Chartered Association of Business Schools (ABS, 2021) has been consulted. Only articles with ratings above 3 stars have been selected except the Journal of Cleaner Production, which has been one of the most influential journals in the field (Rojanakit et al., 2022).

In the screening process, all articles have been read full text and only the articles with a focus on CE implementation and with I4.0 as an enabler were selected. Distribution of the articles based on publication years can be found in

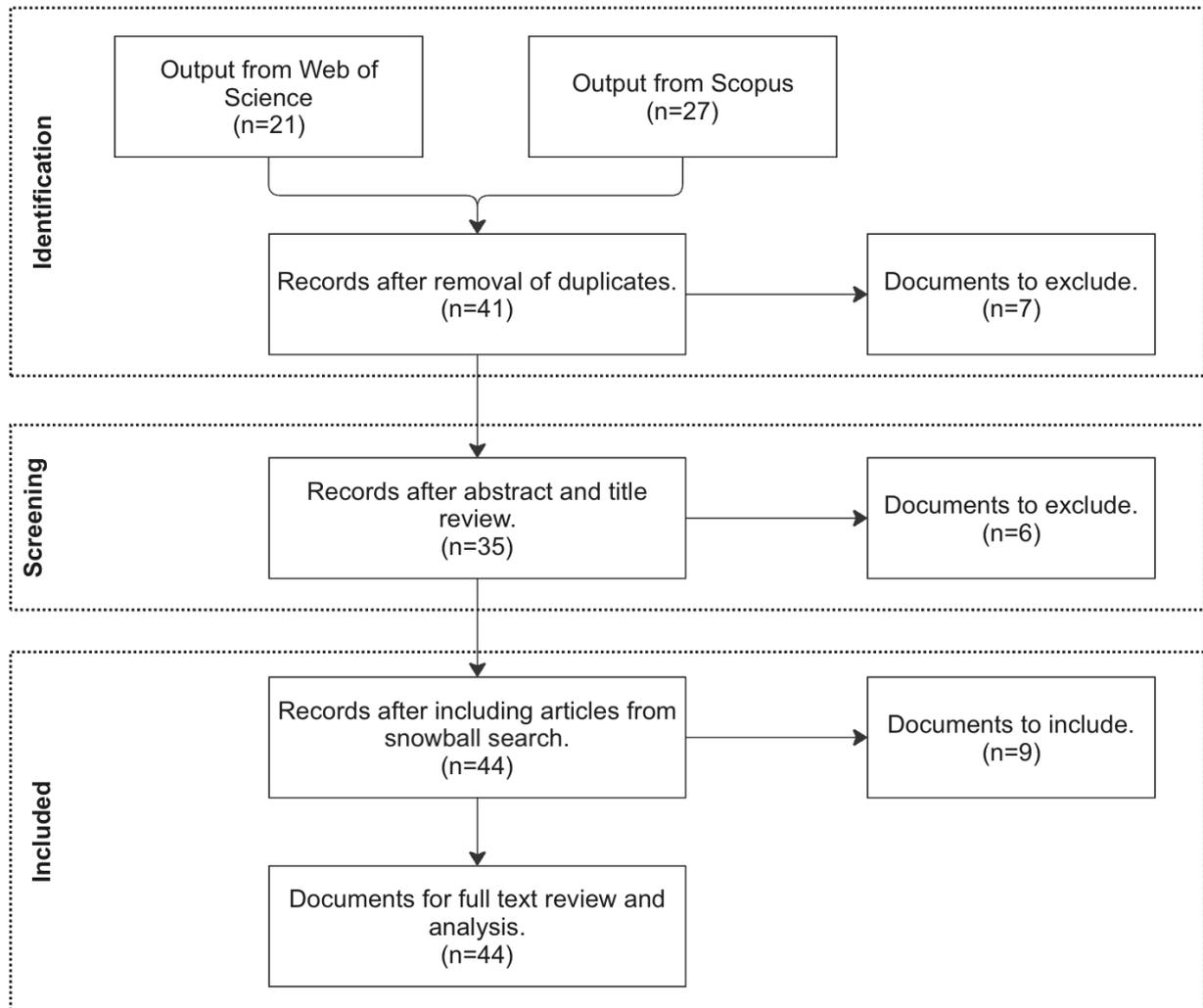


Fig. 1. Overview of the umbrella search process and study selection.

Source: Author's own.

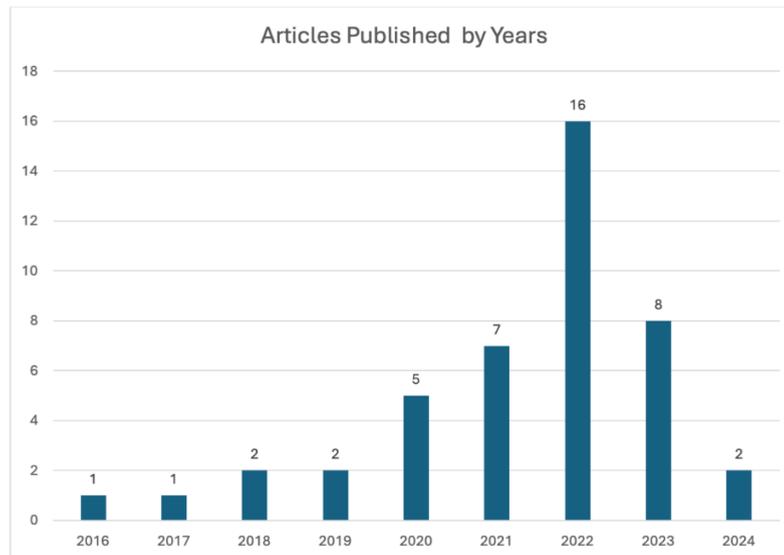


Fig. 2. Distribution of Articles Published Over the Years.

Source: Author's own.

Results

The wave of management and business research concerning the nexus of I4.0 and CE has mainly been published starting in 2018 and gained momentum during each following year. As most of the selected early publications have focused on a single I4.0-related technology at a time and its potential implications on the CE, more holistic approaches and deep management focus have been adopted by the papers in the later stages.

Technology Focus

The adoption of existing digital technologies to strengthen the connections between manufacturers, customers, and suppliers is essential to the success of remanufacturing in an I4.0 future (Kerin, 2019). The digitalization paradigm can be utilized by organizations to improve business profitability via a variety of actions such as efficiently utilizing resources, managing product life cycles, tracking residual value, and reducing the cost of transportation (Massaro, 2021; Linde et al., 2021; Ignacio et al., 2018). I4.0 refers to managing the entire supply chain, including product design, manufacturing, procurement, and transportation, by utilizing various I4.0 technologies, such as cloud computing, blockchain, artificial intelligence (AI), and the Internet of Things (IoT). Industry 4.0 adoption has been recognized as a key factor in organizations' ability to implement the circular economy (Yu et al., 2022). The new production technologies are being increasingly used at the industrial scale on account of their low production costs and high throughput. In light of increased efficiency, Ajwani-Ramchandani et al. (2021) brought attention to sustainable and waste-free packaging alternatives. Singh et al. (2021) highlighted the role of big data as an emerging trend to provide better information for system modelers and decision-making in circular economy implementation. Acciarini (2023) provided a comprehensive overview of the effects, benefits, drawbacks, and uses of big data in different business areas. Ahmed (2022) presents a thorough review of the applications of cyber-physical systems (CPSs) within each of the CE stages, the contribution of different CPS technologies to the sustainable development goals (SDGs), and the current state of the CE assessment tools. The review highlights the potential of CPSs for enhancing each stage of the CE in terms of efficiency and sustainability. It provides practical examples of how CPS tools can increase efficiency and reduce waste in the CE stages in organizations. Ertz et al. (2022) have focused on four key constitutive technologies of I4.0 (additive manufacturing (AM), artificial intelligence (AI), Internet of Things (IoT), and Big Data) that can contribute to design, access, maintenance, redistribution, and recovery phases of the product loop. Moreover, technologies such as big data, IoT, additive manufacturing, and blockchain can optimize value creation by increasing efficiency and improving performance (Chauhan et al., 2022; Dezaki et al., 2023; Sanchez et al., 2020). However, Rejeb et al. (2022) state that the implementation of IoT-enabled CE business models is also curbed by cybersecurity risks, privacy concerns, a lack of competencies, low connectivity between devices, and data-access issues. While the environmental burden of the IoT may be insignificant compared to the positive effects it can bring, the widespread implementation of IoT devices in the CE demands its lifecycle assessment to mitigate the consequent stress on the environment. In his other article, Rejeb (2022) mentions that blockchain technology can play a crucial role in facilitating the transition from a linear to a circular economy. Blockchain enables improved traceability and transparency of a product's lifecycle, from raw material procurement to ultimate disposition, which aligns with the principles of circular economy (Ajwani-Ramchandani et al., 2021). The implementation of blockchain in reverse logistics can facilitate the sharing of information and expertise among business entities, leading to cost savings and efficiency gains in the supply chain, which are important aspects of circular economy practices (Samadhiya et al., 2023; Atif, 2023).

Considering that most aforementioned authors have utilized an approach that focused on a single individual technology at a time, digital technologies should not be considered separately from each other. It was found that, in many cases, digital technologies are not applied as stand-alone but as complementary tools. For example, IoT technologies are used to collect various data, and big data analytics and AI are used to realize data management or processing and can also be applied to data mining. Future research outlook should focus on a more holistic view of the product life cycle and interdisciplinary perspectives to understand new application and implementation approaches for digital technologies.

Stakeholder Focus

As one of the pioneers and prime authors in researching CE - I4.0 nexus from a management perspective, Lopes de Sousa Jabbour (2018) describes how advanced and digital manufacturing technologies can unlock the circularity of resources within supply chains and proposes a roadmap for organizations and businesses to guide them step by step into CE. The author has based the research on ReSOLVE – ‘regenerate, share, optimize, loop, virtualize, exchange’ – framework business models and provided different value-added I4.0 technologies about design, production, and (reverse) logistics operations in each business model.

Implementing a circular business model and I4.0 tools change the entire value chain of the business (Rosa et al., 2019). According to Toth-Peter (2023), transitioning to new business models requires a series of innovations in business models. Transitioning from a traditional to a circular business model involves changes in value proposition, value creation and delivery, and value capture. Eisenreich et al (2022) discuss the implications of circular solutions for a company's value chain processes using Porter's value chain framework. The circular transition requires collective focus from both internal and external actors (Lopes de Sousa Jabbour, 2018; Toth-Peter et al., 2023; Eisenreich et al., 2022). Internal factors include technology focus, quality resources, workforce motivation, and organizational flexibility (Lopes de Sousa Jabbour, 2018). External factors are related, but not limited to industry ecosystem, collaborations, and end-user perception (Toth-Peter et al., 2023, Eisenreich et al. 2022).

Even if the company has decided to embrace the CE strategy, it does not necessarily mean that its whole supply chain is willing or ready to embrace it as well (Kirchher et al, 2018). Therefore, it is important to plan the transition towards CE and Industry 4.0 within an organization as well as externally (Lopes de Sousa Jabbour, 2018). Eisenreich et al. (2022) mention that companies should co-create circular solutions with the whole supply chain, especially with customers and suppliers but also with other stakeholders such as the government, technical experts, designers, or research institutions. Khan et al. (2021) propose to extend the concept of the triple bottom line (TBL) to a 'quintuple bottom line' by including technological and organizational sustainability, as organizations, societies, environments, and technologies are mutually dependent under Industry 4.0. The integration of CE strategies transcends business boundaries, which requires the mobilization and integration of other parties and strong coordination and interconnections among supply chain actors to achieve optimum communication, monitoring, and information sharing (Toth-Peter, 2023). Gregory et al. (2020) concluded that the transition to CE depends on the recognition by stakeholders that no single actor can address the core issue alone. Collaboration is necessary to create value in the context of the business ecosystem. Brown et al. (2021) define collaboration as the deliberate and voluntary interactions between two or more organizations to achieve a shared objective that would be impossible for each to accomplish alone. Collaborative innovation refers to the collective learning that combines the knowledge, skills, and resources of the organizations to improve the collaborative production of unique ideas, goods, services, processes, or business models. Bjørnbet et al. (2021) and Hina et al. (2022) delve into the benefits and challenges of possible collaborations with different stakeholders including competitors.

Chari et al. (2022) mention that CE is very challenging to implement into business models and existing operational practices due to its high set-up costs and changes required at different system levels. Transitioning to CE involves multi-dimensional and multi-domain challenges such as complexity and uncertainty in design, material flow, service, and distribution phases. Larger companies are more likely to implement CE because they gain more economic and social benefits through their sustainable practices, are typically targeted by environmental regulations, tend to have more resources, and may risk investing in such practices. However, Kirchner et al. (2018) identified that the cultural barriers, specifically the lack of consumer interest and awareness together with the hesitant company culture are among the main CE barriers.

Scarpellini et al. (2020) establish that pressure from business stakeholders positively affects companies' environmental proactivity beyond regulatory requirements. Hina et al. (2022) elaborates that the essential drivers for implementing the CE approach are the company's stakeholders. The public continues to demand that organizations consider more responsible production and consumption methods, and these demands encourage CE practices (Jabbour, 2020). With the implementation of CE, companies need to be more strategic in selecting suppliers and consider both supplier's environmental conduct and geographical accessibility to narrow the loop (Hazen, 2021). Sustainability has become a popular goal, and it appears that consumers are demanding more ecologically friendly and sustainable solutions. Customers may not, however, act on it since there is a significant gap between intentions towards sustainability and actual consumption. For the circular economy to survive, people need to purchase remanufactured goods in addition to returning products after using them. Nonetheless, studies reveal that consumers

are generally unprepared to embrace remanufactured items and have a negative perception of them (Hazen, 2017). It was observed that customer preferences continue to favor new products over ones that have been recycled or repurposed. There is the perception that things that have been recycled or reused are nonetheless viewed as less appealing and durable. According to Bjørnbet et al. (2021), market conditions and consumer approval are frequently the driving forces for reuse techniques. The advancement of CE will be hampered by consumers' rejection of repurposed goods or goods manufactured from recycled materials (or by businesses' fear of it). Customers might not be prepared to spend the same amount of money on a refurbished or repaired product as they would on a brand-new one. To counterbalance the effects of buying new appliances, which use fewer resources during usage, versus continuing to use old ones, users can participate in the usage phase by either choosing when to replace appliances or by adopting better usage habits that will reduce resource consumption (Bressanelli et al., 2021). Users have a significant impact on how items are disposed of during EoL, which enhances the availability of materials for recovery operations including recycling, remanufacturing, and reuse. A product's design, and quality, in addition to the consumer's personal opinions, all play a role in the decision of whether or not to buy and use it. Price is the primary factor that buyers consider when making a purchase, not quality (Hina et al., 2022). Higher-quality components and product design are necessary for longer product life expectancies, which eventually raise costs and have a detrimental effect on consumers' decisions to buy such products.

From the internal stakeholders' perspective, strong management support and collaborations between different stakeholders in the whole supply chain have been emphasized as critical enablers (Lopes de Sousa Jabbour, 2018; Centobelli, 2020). Eisenreich et al. (2022) emphasize the need for executive support in terms of developing needed competencies, accessing new technologies, and financing transition from linear to circular way of work. Brown et al (2021) support this view by stating that leadership is critical for championing circular vision, attracting internal and external stakeholders, and maintaining the activities for circular vision. According to Rizos et al. (2016), leadership—a facet of an organization's culture—is crucial for CE initiatives. An organization's move to the CE may be made easier by the attitude, expertise, and dedication of its workforce (G. Traditional management systems must be replaced by more innovative systems to fit together I4.0 and circularity requirements (Bag, 2021).

Moreover, the author mentioned the importance of performance measurement indicators to track and control the level of circularity in the organization. Process metrics for environmental flows or natural resources (energy and raw materials) are rare in the literature and practically non-existent in practice. Flow rates, cycle periods, and comparable metrics are usually established and measured only from the economic perspective. (Hazen et al., 2021). Performance measurement should be based on both financial and non-financial indicators such as collected waste or energy consumption. Ahmed (2022) emphasizes the need for a standardized comprehensive CE measuring or rating system to allow organizations on different levels of the economy to improve their circularity. It discusses the current state of CE assessment tools and suggests the importance of a flexible system with a wide range of indicators to measure circularity accurately. Performance indicator sets should take into account a company's shift from purely monetary-based rationalities to a robust full-cost accounting of doing business, including social and ecological externalities. They should also aim to reflect corporate ecological performativity by accounting for corporate impacts on environmental conditions, often through the adoption of novel performance indicator sets (Hoffman, 2020).

Theoretical Findings

Considering that research on the CE-I4.0 nexus is still in its emerging phase, most articles do not specify certain theoretical approaches. Toth-Peter (2023) identified stakeholders, systems, and dynamic capability theories as the most dominant ones among reviewed articles. Moreover, focusing on internal resources and capabilities as sources for sustainable competitive advantage in case resources are unique, non-imitable, and rare, resource-based view (RBV) theory has also been proposed by Jabbour (2018) to understand what resources and capabilities are necessary to reinforce strategies towards CE. The extension of the conventional Resource Based View (RBV) of organizations, the Dynamic Capabilities View (DC) supports organizations in moving from static to uncertain and dynamic contexts by drawing on their current resource base. The DC concentrates on resource development, acquisition, and exploitation, whereas the RBV concentrates on selection from already-existing resources. To remain competitive, organizations must reorganize their capacities and resources to meet new demands and adapt to shifting conditions (Chari et al., 2022). Belhadi et al. (2022) define organizational capabilities as a firm's capacity to deploy its resources, tangible or intangible, to perform a task or an activity to improve performance. Bag et al. (2021) mention that today's companies need the flexibility, visibility, and resilience that the I4.0 offers to sustain the reuse and recycling operations. Markard et al. (2012) support that future research could investigate transition theories to see how they reflect the complexity and interconnected nature of sustainable business models (Centobello et al., 2020). In addition to these, Freeman (1984) mentions that through the lens of stakeholder theory, it can be understood that, due to changes in the external context, organizations need to contingently adjust their responses to stakeholders to avoid underperformance. Eisenreich (2021) defines a stakeholder as "any group or individual who can affect or is affected by the achievement of the firm's objectives". Similarly, Jabbour et al. (2018) also support stakeholder theory in this context to map the expectations of primary stakeholders about sustainability performance and to prioritize the implementation of Industry 4.0 technologies. Part of the framework (Fig. 2) proposed in this paper is inspired by stakeholder theory as the main message it aims to deliver is that the CE in organizations can

be achieved by collective effort and in a holistic manner, involving all the internal and external stakeholders in the given ecosystem. Chiappetta Jabbour (2019) highlights the significance of culture, teamwork, and empowerment and their positive effects on the adoption of CE business models at the company level.

Discussion

Based on the findings from the literature, hereby, a conceptual framework (Fig. 3) has been presented. Although this framework has been influenced by the previous works by Porter (1985), Hanafizadeh (2011), Eisenreich (2022), and Toth-Peter (2023), it presents a more comprehensive and holistic conceptual understanding of grasping technological and managerial aspects of the value chain with the guidance of stakeholder approach in more details under one illustration. On one hand, the technological part consists of different I4.0 technologies and their existing and potential applications in different areas of the company's value chain. On the other hand, in the central part, the managerial aspects have been mentioned. Finally, in the core, shared values have been emphasized to highlight the need for collective effort among all stakeholders in the whole ecosystem to make the CE transition happen.

Defining product characteristics and requirements as early as possible during the development phase is possible through circular design as it has a direct effect on the product life extension and end-of-life management (Toth-Peter, 2023). To advance the regenerative economic model, circular design is critical because it ensures that products are designed and manufactured with sustainability as their main goal, reducing waste, and optimizing resource efficiency. When a product operates efficiently over its life cycle, fewer resources are used and less waste, pollution, and emissions are produced. Not only can this reduce resource consumption, but new materials or secondary raw materials can also be used in place of input materials; new technologies can be implemented; and aspects of recycling, reparability, and closed-loop recycling can be taken into account when designing a product that is long-lasting and suitable for reuse, even at the planning stage (Neligan, 2018).

From a technological perspective, two main enablers could be additive manufacturing and digital twins. Virtual replicas of real-time assets, such as production and manufacturing systems, and inventory equipment can be interacted with through simulation modeling tools to evaluate, improve, and control the performance through the help of digital twin technologies. Furthermore, 3D printing, as part of additive manufacturing (AM), is seen as a facilitator for the CE due to its ability to prevent material losses during the process and conserve resources through the use of accurate, digital measurements. When these two technologies are combined, virtual twins take use of AM's speedy creation, testing, and refinement of prototypes, which improves product development, shortens time to market, and promotes innovation in a variety of industries.

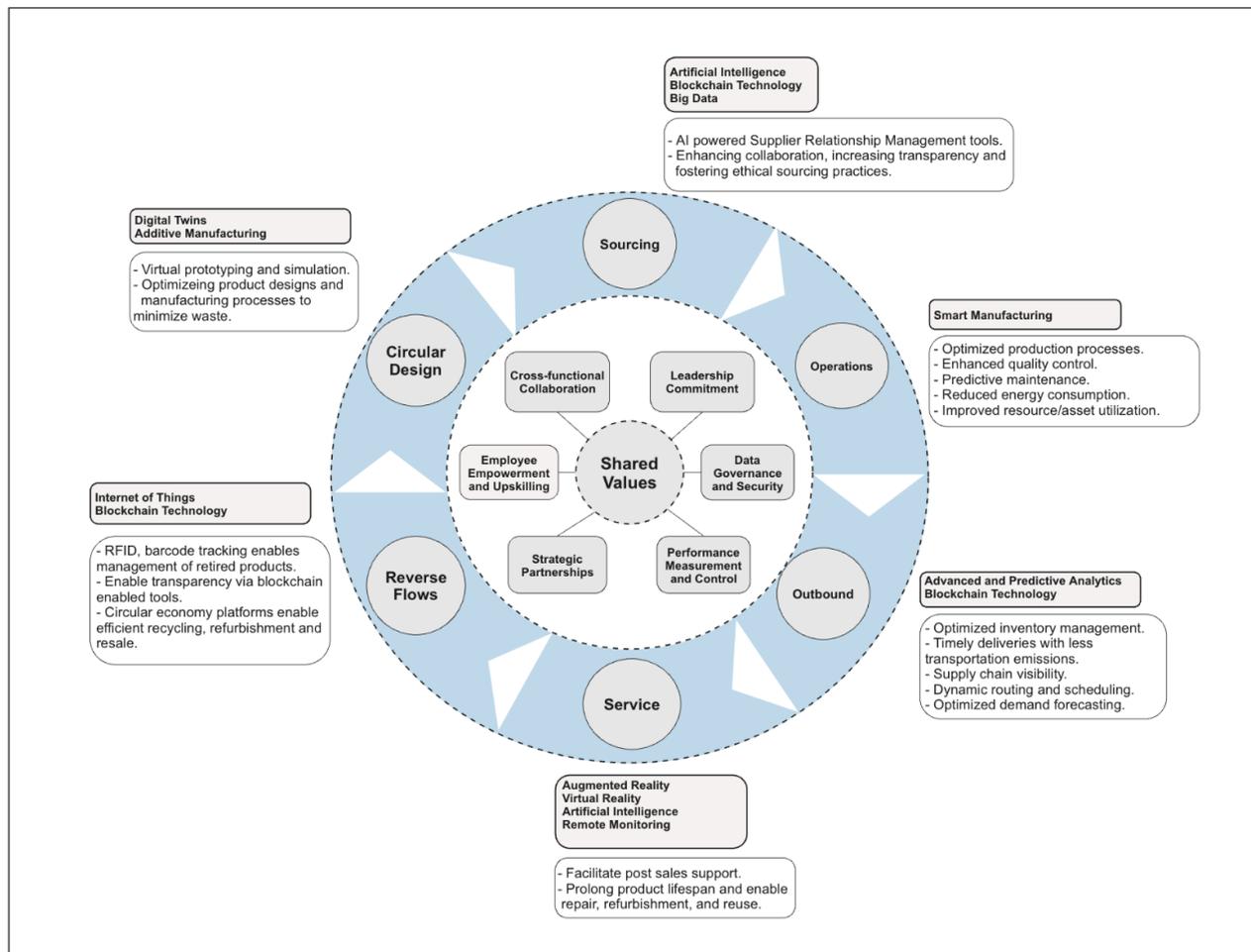


Fig. 3. The Circular Innovation Framework: Harnessing Industry 4.0 for Sustainable Value Chains.
Source: Author's own.

Sourcing and outbound steps of the value chain have remained to have relatively less research output (Eisenreich, 2022). The supply chain department's involvement in green purchasing may help businesses choose suitable suppliers for their projects. Likewise, suppliers' creative and technological skills in the design process can improve green design performance, and their integration and coordination with SC members foster cooperative activities and information exchange. The goal of circular purchasing is to purchase environmental products to lessen their negative impact on the environment, which entails collaborating with suppliers (Yu et al., 2022). Considering this, the framework proposes AI, blockchain, and big data to be potential candidates to have a positive impact on an organization's circularity endeavors from a sourcing perspective. The mentioned technologies can help the organization to improve forecasting capabilities, better measure overall supply chain effectiveness and order management, and enhance the decision-making process in terms of time and effect. Blockchain-enabled interfaces may allow the organization to collaborate with different vendors and suppliers in the same ecosystem with more transparency, traceability, and trust, envisioning also the legitimacy and moral insurance of the received resources and materials (Toth-Peter, 2023; Rejeb et al., 2022). From an outbound and delivery perspective, AI-assisted dynamic routing and scheduling will result in lowered emissions, increased overall efficiency, and more optimized business-to-customer deliveries, and hence, more customer satisfaction.

As one of the most important parts of any value chain, in the operations part, the primary focus is related to the manufacturing and production systems. As a hub of the majority of I4.0 technologies, the operations involve I4.0 applications and tools, that bring digitalization, automation, and data-driven decision-making into manufacturing processes. From a technological perspective, getting raw materials from inbound areas to transforming these inputs into valuable final outputs is possible with integrated, robust, in-time, and dynamic production and material planning, predictive maintenance, increased quality and compliance, and live equipment performance monitoring systems. Cloud computing, robotics (autonomous robots), IoT applications (sensors), and AI act as enablers of such operational systems. I4.0 technologies enhance the dynamics, efficiency, quality, and control of manufacturing equipment. As a result, I4.0 is an enabler for the organization to have better quality outputs, cost savings, and streamlined operations to have a competitive advantage in difficult and dynamic market conditions.

In the service part of the chain, proactive equipment issue oversight and enabled predictive maintenance can help users and customers reduce overall downtime and increase operational efficiency. This can be enabled by AI and IoT-powered remote monitoring solutions. Moreover, additions of augmented and virtual reality (AR and VR) tools

allow services to be more time-efficient and under professional guidance. Given technologies support organization's goals related to customer satisfaction and support different CE frameworks such as repair, reuse, and refurbishment and increase product life cycles and end-of-life. Users' acceptance is very critical in the consumption of circular products. Research suggests that customers mainly focus on consuming products that have been produced with less negative impact on the environment and feel compelled to use green products in response to various factors (Silintowe and Sukresna, 2022). However, more up-to-date research must be done to understand changing consumer behavior considering recent developments in the field.

Circularity in the manufacturing ecosystem is promoted by blockchain and the Internet of Things (IoT), which are essential for simplifying and optimizing the handling of returned goods and materials. A decentralized, unchangeable ledger that tracks a product's whole lifecycle is made possible by blockchain technology, guaranteeing authenticity and transparency in reverse flows. The blockchain records every product's path, from original purchase to return and possible resale or recycling, enabling traceability and regulatory compliance. Furthermore, real-time tracking and condition monitoring are made possible by IoT sensors embedded in returned goods, which streamlines the sorting, refurbishing, and recycling procedures. These sensors give producers useful information about the state of their products, enabling them to decide whether to repair, reuse, or dispose of them.

The shared values idea has been adapted and influenced by McKinsey's 7S framework (Hanafizadeh, 2011). In the original model, shared values of the organization have been interconnected to its style, strategy, staff, structure, systems, and skills (McKinsey & Company, 2008). In this framework, shared values represent the need for collective effort and action from different parties, especially inside the organization, in the first place, and then, among all ecosystem actors to reach a common goal of circularity across different domains. Wahyudi et al. (2023) emphasize that firms engaging in open innovation practices, including partnerships and collaborations tend to achieve better performance. Ahmadov et al. (2024) imply the stakeholder pressure and collaboration to be important determinants of shaping sustainability practices in organizations. Di Maria (2022) mentioned the term "supply chain integration" (SCI) describes the purposeful cooperation of all parties engaged in value-added activities, such as product design, procurement, manufacturing, assembly, warehouse management, sales, and distribution, that provide goods, information, and services to the end user. SCI generally promotes information exchange, process simplification, and interest alignment along the supply chain, all of which improve operational and financial performance as well as the performance of the supply chain itself. To close, narrow, or slow the loops, businesses must review their production procedures and product lines in ways that necessitate obtaining and integrating expertise from various fields. This will improve administrative and supply chain collaboration.

Management interest is the main factor influencing the adoption of circular economy techniques in Industry 4.0. Any implementation is likely to end if there are no expectations from leadership (Awan, 2021). Strong and determined leadership commitment is essential to foster circular decision-making, organizational adaptation, and have collaborative and innovative culture. Collaboration pathways between various stakeholders are critical for enterprises to navigate the complexities of transitioning to circular practices (Ahmadov et al., 2024). Nurturing alignments between different units of the organization and encouraging cross-functional collaborations, the management unit can promote I4.0 technologies to be integrated across all functions of organizational value chains. Successful transition requires the workforce to be more technology-friendly to be capable of interacting with different digital tools and solutions. Valencia-Arias et al. (2024) mentions that effective knowledge management practices in enterprises have direct effect on the organizational performance and innovation. Training and upskilling human resources are necessary complements of circularity transition in a given organization. This is also supported by Eisenreich (2022), as the author mentions that the mindsets of top management and employees are equally important success factors for the implementation of circular solutions, as they can impede or foster the transition toward a CE. From an ecosystem perspective, the exchange of know-how, co-innovation, and strategic partnerships among different actors in the same market and ecosystem increase the circularity possibilities even further. In such a reality, organizations need to make sure about the strong data governance and security measures to be applied to be confident in digital infrastructure and to facilitate smooth cooperation between different actors. Moreover, while introducing and achieving circularity targets one by one is significant and important for a given organization in the sustainability direction, it should be noted that maintaining, measuring, and controlling the state-of-the-art processes afterward are also among major challenges. Initiatives for continuous improvement and performance measurement can potentially help to reach accountability while advancing circularity and sustainability objectives. These common principles work together to form strong bonds that enable businesses to their goals towards a circular economy while encouraging creativity, adaptability, and long-term environmental care together with the strong influence of open innovation, cross-functional, and supply-chain-collaboration on the CE-friendliness of a corporate culture (Eisenreich, 2022; Colucci, 2021).

Implications and Future Research

The presented framework can offer scholars a foundation for further research in the operations, management, and technology domains with a specific focus on CE, I4.0, supply chain management, and sustainability. The interrelated representation of these domains suggests that the CE transformation is not a stand-alone process, and it is, therefore, necessary for enterprises to examine and comprehend the intricate relationships between various

components in the organization (Toth-Peter, 2023). Whereas past research has focused on technology and managerial domains separately in most cases, this manuscript merges these in a holistic approach. From a technological perspective, the framework points to the different technological instruments in the I4.0 domain and their value added in different parts of the value chain, such as blockchain technology in sourcing and additive manufacturing in circular design activities. From a managerial perspective, the research implies the role of strong leadership commitment and cross-functional collaboration as internal drivers. Moreover, it should be noted that the paper mentions the need for even more holistic and macro-level interactions between ecosystem actors to speed up and maintain the CE position of the company.

Practitioners might benefit from the existing research in this domain and take into account the output to compare and assess their state-of-the-art situation and incorporate potential I4.0 technologies in their organizations as the framework guides enhancing operational efficiency and achieving circularity across different domains of the value chain. For high-level management, this research can act as an assessment methodology to understand the preparedness of their organization for implementing I4.0 technologies and CE principles. They can address organizational enablers and barriers, develop strategic initiatives to drive circular innovation, and boost the competitiveness across market.

For the future direction, from a technology focus, it should be noted that more in-depth research that focuses on one I4.0 technology at a time in real settings is needed (Toth-Peter, 2023). This gap in the existing research suggests a need for studies that not only investigate such technologies within actual industry settings but also evaluate their effect on existing systems, operational efficiency, sustainability, and overall organizational performance and link their benefits to the organization's SDGs (Dadsena et al., 2023).

A deeper outlook and more research are needed for the performance domain in CE (Eisenreich, 2022). The author suggests that measuring the effectiveness of common performance indicators for CE, such as utilization rates for different equipment in operations, is a potential area of research for the future. This can entail creating new measurements or improving current ones to better capture the complex nature of circular operations. New metrics would also better reflect the sustainability impact of various practices. Furthermore, by comprehending how these performance metrics interact with organizational tactics, more focused actions that improve environmental and economic results may be possible. Future studies could assist close the gap between theoretical models and the realities of industrial operations by concentrating on the actual use of these indicators, giving organizations looking to enhance their CE performance a more precise direction.

Luzzini et al. (2024) suggested to study further the implications of moving from the current endless growth paradigm to a post-growth paradigm for enterprises and their value chains. This includes analyzing selective downscaling in supply chain practices and examining systems thinking in supply chain governance. The authors suggested re-evaluating competitive advantage theories in the post-growth context.

On the management level, future research could examine how entrepreneurs understand and apply circular models, how they assist CE, and how entrepreneurship changes and shapes the organization (Toth-Peter, 2023). Despite their critical role in driving innovation and implementing circular principles, entrepreneurs' viewpoints and experiences are still inadequately studied. Existing studies suggest that in today's increasingly changing environment, conventional dimensions of competitiveness, such as cost, quality, flexibility, and delivery are no longer sufficient for firms to gain momentum in the market. Companies must modify their strategies and practices to address the new challenges, including the growing consumer demand for eco-friendly products, more stringent environmental regulations, and heightened public consciousness regarding environmental protection (Jiao, 2020). Further investigation is required to determine how various leadership styles are critical to promoting circularity in organizations (Eisenreich, 2022). Future research could investigate areas like developing green skills, fostering a circularity culture within organizations, and examining the interplay between circularity and Industry 4.0 to enhance sustainability. Additionally, studies on the role of transformational leadership in adopting circular practices may shed light on how leaders can effectively motivate and guide their teams toward sustainable goals (Bhattacharya et al., 2024).

From a holistic perspective, some studies suggest that more practical insights and longitudinal studies are needed, considering all stakeholders in the same ecosystem in which the organization is located (Köhler et al., 2021). This will help to explain the dynamics between different organizations and help to understand the best ways to reach circularity across the ecosystem. Research in this field could examine the interactions and behaviors of various stakeholders, from customers and suppliers to regulators and community organizations, and how these interactions and influences shape the ecosystem's overall sustainability. Furthermore, by being aware of the interdependencies and possible conflicts of interest among stakeholders, more cooperative methods to circularity—where advantages are shared, and problems are solved together—may be developed. Such studies could also look into how ecosystem-level laws and policies can be created to promote circular activities and guarantee that all parties involved are working towards the same sustainability objectives.

The majority of the research has been focused on the manufacturing industry. Further research is needed in the context of different industries and regions (Jiao, 2020). Gomez and Lee (2023) focused on the food industry and

provided avenue for further research on the integration of supply chain management and food economic research. On the other hand, Colucci (2021) mentioned that the fashion sector provides a rich framework for researching the implementation of circular ideas because of its distinct issues relating to quick production cycles, strong consumer demand, and a major environmental effect. How circularity might be included in the fashion value chain—from design and production to consumption and end-of-life management—may be the subject of future studies. In addition, it is necessary to re-examine the theories of the resource-based perspective and the dynamic capacity view to thoroughly map the needs of major organizations and the interdependencies between external and internal stakeholders.

Conclusion

The article provides an outlook on CE and I4.0 nexus from an exploratory research perspective. The main aim of the research was to understand how different factors can facilitate CE in large organizations alongside I4.0 technologies and digitalization. The main reason for focusing on large corporations was due to 80% of the global carbon emissions from 2016 through 2022 can be traced to just 57 large companies (InfluenceMap, 2024). This study presents a circular innovation framework in which technological and managerial aspects have been integrated to understand their holistic effect on different value chain steps, such as from product design to reverse flows. The framework shows that the majority of the companies in the world have similar requirements for their value chains and there are multiple potential areas of improvement depending on the digitalization level that the organization possesses. The framework provides information regarding how management and technology domains interact across value chains and enables organizations to rethink and transform traditional cradle-to-grave linear systems into cradle-to-cradle systems with the help of available I4.0 technologies. Furthermore, the framework also highlights the important organizational enablers to realize the transition process and effective implementation and adoption of CE in value chains. These enablers include data governance, employee empowerment, cross-functional collaboration, strategic partnerships and collaborations, leadership commitment, and performance measurement. The limitations of the research are mainly on the methodological part as focusing mainly on review papers in the management domain can result in the potential loss of articles in different domains, such as engineering and materials science.

The research has some limitations. First of all, the research methodology is based on the review of the review articles, in other words, the umbrella review, which might limit the extent of the included publications and the articles that focus on a single I4.0 & CE domain at a time. Moreover, the umbrella review focuses primarily on articles within the business and management domains, potentially omitting significant contributions from other relevant fields such as engineering and materials science. This narrow focus could limit the comprehensiveness and applicability of the findings. The paper discusses a broad range of I4.0 technologies (e.g., IoT, AI, blockchain) without delving deeply into the specific challenges and limitations associated with each technology's implementation in CE. The study may underrepresent how dynamic and ever-changing these technologies have become. The conceptual model and approach can be further enhanced to get beyond these restrictions. To avoid such limitations, the conceptual model and methodology can be further improved.

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