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INDUSTRY 4.0 AND ENVIRONMENTAL SUSTAINABILITY: THE ROLE OF DIGITAL TECHNOLOGIES FOR THE CIRCULAR ECONOMY IN MANUFACTURING

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Ajnāna-timirāndhasya jñānāñjana-śalākayā |
cakṣur-unmīlitaṁ yena tasmai śrī-gurave namaḥ ||

(To the revered Guru, I offer my salutations who opened my eyes,
blinded by the darkness of ignorance, with the light of knowledge.)

I offer my deepest thanks to the Universe (Krishna) vast, mysterious, and far beyond my understanding, for carrying me through this PhD journey. At times, it felt like an unseen force gently held my hand, guiding me through moments I never thought I'd overcome. In the randomness of life, this path felt like a sacred thread woven just for me. Words like "thank you" feel too small for the grace I've received. To the Universe, I bow with gratitude for transforming this journey into not just a pursuit of knowledge, but a profound human experience that touched the very core of my being.

There are countless stories about how a teacher can change a student's life but one from the Greek has stayed with me deeply. Socrates had a disciple, Plato. Though Plato wrote many books, he never claimed the ideas as his own; every word, every thought, he attributed and dedicated to his teacher. I want to become like Plato. Not in intellect I know I am not as intellectually gifted, but I wish to carry even a fraction of his humility. If this thesis holds any value, the true soul of it belongs to my Guru, Prof. Nicola. I could never have reached this point without his guidance, trust, and silent strength, especially his patience when nothing went as planned. Through my life, I will always carry his teachings in my heart and work, with a profound sense of gratitude and reverence. For this, I remain forever indebted to him.

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Life's true achievement isn't measured by the number of awards one receives, but by how the journey began and how far one has come along the way. From an academic or scientific perspective, this journey has given me a wealth of knowledge, but philosophically, it has transformed the way I view life itself. As I pen this final thesis of my life, I find myself turning inward, tracing the contours of a journey that began long before; Once a quiet child on the last bench, bullied, unseen and doubted, I watched life from the margins. It wasn't brilliance but an unseen resilience that carried me through. This thesis is a tribute to that journey a whisper to my younger self: you were always enough.

A final thanks to my parents and my sister, whose support and silent encouragement have been a constant source of motivation throughout this journey.

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List of Abbreviations

AM - 3D Printing/Additive Manufacturing

AR/VR - Augmented or Virtual Reality

BDA - Big Data & Analytics

BLC - Blockchain and Cybersecurity

CC - Cloud Computing

CE - Circular Economy

CEP - Circular Economy & End of Life Practice

CII - Confederation of Indian Industry

CPS - Cyber Physical System

CPSDTS - Cyber Physical System, Digital Twin and Simulation

CSC - Circular Supply Chains

CSCM - Circular Supply Chain Management

CB-SEM - Covariance-based SEM

DF - Dominance Factor

DHI - Department of Heavy Industries

DOLS - Distribution, Outbound Logistics & Downstream Supply Chain Management

DTs - Digital Technologies

EEE - Electronic and Electrical Equipment

EOL - End of Life Treatment & Processing

HVI - Horizontal Vertical Integration

ICT - Information and Communications Technology

IIoT - Industrial Internet of Things

I4.0 - Industry 4.0

IoT - Internet of Things

IR - Industrial Robotics

LCA - Life Cycle Assessment

LiFE - Lifestyle for Environment

MAINT - Maintain, Technical Assistance & Repair

MCP - Multiple Country Publications

OGD - Open Government Data

OM - Operations Management

PD - Product Development

PLUS - Procurement, Inbound Logistics & Upstream Supply Chain Management

PLS-SEM - Partial Least Squares SEM

PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PROD - Production

PSS - Product-Service Systems

REVLOG - Reverse Logistics

SCP - Single Country Publications

SCI - Supply Chain Integration

SCMC - Supply Chain Management & Collaboration

SDGs - Sustainable Development Goals

SEM - Structural Equation Modelling

SLRs - Systematic Literature Reviews

SSCI - Social Sciences Citation Index

SSCM - Sustainable Supply Chain Management

SSCP - Sustainable Supply Chain Performance

SBMs - Servitized Business Models

WOS - Web of Science

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Abstract (*In Italian*)

Questa tesi di dottorato, dal titolo "Industria 4.0 e Sostenibilità Ambientale: Il Ruolo delle Tecnologie Digitali per l'Economia Circolare nel Settore Manifatturiero", discute il lavoro di ricerca svolto negli ultimi tre anni presso il Dipartimento di Ingegneria Meccanica e Industriale dell'Università degli Studi di Brescia nell'ambito di un progetto di ricerca cofinanziato dall'Unione Europea attraverso il Programma PON Ricerca e Innovazione 2014-2020, risorse FSE REACT-EU, Azione IV.5 "Dottorati su Tematiche Green".

La tesi indaga l'integrazione delle tecnologie dell'Industria 4.0 (I4.0) e delle pratiche di Economia Circolare (EC) nel contesto della sostenibilità ambientale nel settore manifatturiero. Il settore manifatturiero globale affronta sfide ambientali senza precedenti, guidate dall'esaurimento delle risorse, dalla generazione di rifiuti e da un modello economico lineare ("take-make-dispose") non sostenibile. In questo contesto, l'EC è emersa come paradigma trasformativo, che propone sistemi a ciclo chiuso, rigenerativi e ripristinativi, mirati a massimizzare l'efficienza delle risorse e minimizzare gli sprechi. Parallelamente, le tecnologie I4.0, come l'Internet of Things (IoT), l'intelligenza artificiale, l'analisi dei big data e la produzione additiva (3D printing), forniscono strumenti innovativi per abilitare pratiche circolari. Questa ricerca esamina tale sinergia per rispondere all'esigenza critica di crescita sostenibile, in un contesto di crescenti sfide ambientali e scarsità globale di risorse.

Nonostante l'ampia letteratura sull'interrelazione tra tecnologie I4.0, EC e sostenibilità ambientale, permangono lacune significative nella comprensione di come queste aree si stiano evolvendo congiuntamente. Studi recenti sottolineano la necessità di un'esplorazione più approfondita e di un passaggio da studi prevalentemente esplorativi e descrittivi a framework confermativi e prescrittivi, che definiscano più chiaramente obiettivi e metodologie in questo ambito. Tale transizione è cruciale per integrare efficacemente le tecnologie digitali nelle pratiche di EC e avanzare la comprensione del loro impatto combinato sulla sostenibilità e sulla gestione delle operations. Inoltre, la tesi esamina l'adozione dell'EC in un contesto regionale specifico (l'India), colmando il divario tra comprensione teorica e implementazione pratica. L'India, in quanto economia in rapida crescita con una vasta popolazione e modelli significativi di produzione e consumo, può trarre grandi benefici dall'adozione di principi di EC nel settore manifatturiero. Tali benefici includono una maggiore efficienza delle

risorse, la minimizzazione dei rifiuti e lo sviluppo di sistemi a ciclo chiuso, che sfruttano il potenziale economico dell'India affrontando al contempo sfide critiche nella sostenibilità ambientale. La tesi evidenzia quindi una significativa lacuna conoscitiva nella comprensione dell'evoluzione della ricerca su economia circolare (EC), sostenibilità ambientale e Industria 4.0 (I4.0), in particolare riguardo a come le tecnologie digitali migliorino la gestione delle operazioni e il livello attuale di adozione dell'EC tra i produttori indiani.

Per colmare questa lacuna, la tesi esplora tre domande interconnesse:

1. ***RQ1:*** Come si è evoluta la ricerca accademica su EC, sostenibilità ambientale e I4.0, e quali insight possono emergere da un'analisi bibliometrica per orientare le ricerche future?
2. ***RQ2:*** In che modo le tecnologie digitali influenzano i processi di gestione delle operations per supportare sostenibilità ambientale e circolarità?
3. ***RQ3:*** Quale livello di adozione di pratiche circolari è osservabile tra le aziende manifatturiere indiane?

La metodologia adottata è interdisciplinare, garantendo un'indagine sistematica degli obiettivi. La tesi adotta due prospettive metodologiche: un approccio orientato alla letteratura e uno orientato alla pratica.

L'approccio di analisi della letteratura combina analisi bibliometrica (quantitativa), analisi dei contenuti (qualitativa) e contingency analysis (statistica) per fornire una prospettiva multipla sulle domande di ricerca. L'analisi bibliometrica mappa l'evoluzione dei flussi di conoscenza all'intersezione di EC, sostenibilità ambientale e I4.0, costruendo una struttura intellettuale e identificando cluster tematici nel campo. Una revisione sistematica della letteratura è condotta per sviluppare un framework teorico che valuta gli impatti di sostenibilità e circolarità delle tecnologie digitali nella loro interazione con i processi di Operations Management (OM).

L'approccio orientato alla pratica si concentra invece sulla comprensione di fenomeni emergenti, affrontando la terza domanda di ricerca e migliorando la comprensione delle complessità e delle applicazioni nel mondo reale. In questa sezione, una metodologia basata su survey (modellazione descrittiva e *structural equation modelling*) esplora lo stato attuale della circolarità nelle aziende manifatturiere indiane. Questo approccio è utilizzato per la raccolta quantitativa di dati, il test di ipotesi e la validazione dei risultati, rafforzando l'affidabilità e la validità delle conclusioni. Offre inoltre insight empirici sull'implementazione pratica dei principi di EC in un contesto di economia emergente.

L'analisi bibliometrica identifica un corpus frammentato ma in rapida crescita di letteratura che collega EC, sostenibilità e I4.0, sottolineando la necessità di strategie olistiche che integrino prospettive tecnologiche, ambientali e operative. Un framework teorico dimostra ulteriormente come tecnologie digitali, come IoT e produzione additiva, migliorino i processi di OM, sebbene il loro impatto sulla sostenibilità dipenda dal coretto impego nei contesti operativi. Dal punto di vista empirico, la valutazione delle aziende manifatturiere indiane indica una moderata preparazione alla circolarità, con le grandi aziende in posizione leader, mentre le piccole e medie imprese (PMI) affrontano barriere sistemiche all'adozione dell'EC. Infine, lo studio enfatizza il ruolo della collaborazione, dimostrando che l'integrazione della collaborazione nella gestione della supply chain (SCMC) con modelli di business servitizzati (SBMs) promuove l'efficienza delle risorse e avanza l'implementazione dell'EC.

Dal punto di vista teorico, questo studio apporta contributi sostanziali ai campi dell'Industria 4.0, della sostenibilità ambientale e della letteratura sull'economia circolare, offrendo una panoramica bibliometrica completa e una comprensione strutturata dell'intersezione di questi domini critici rispetto ai processi di Operations Management (OM). Esso prepara il terreno per ricerche future identificando trend emergenti ed evidenziando lacune chiave che richiedono ulteriori esplorazioni. Dal punto di vista manageriale, i risultati offrono strategie attuabili per le aziende, orientando gli investimenti in tecnologie digitali (DTs) negli ambiti degli approvvigionamenti, della produzione e della logistica inversa, mentre si promuovono piattaforme collaborative e lo sviluppo di competenze. Il lavoro affronta sia i fondamenti teorici di I4.0, EC e sostenibilità, sia le loro implicazioni pratiche, supportando i produttori, specialmente nelle economie emergenti, nell'affrontare le sfide della sostenibilità ambientale e della gestione delle risorse. Integrando rigore accademico con risultati empirici, questa tesi offre una roadmap per sviluppare la sostenibilità ambientale nell'industria manifatturiera.

Abstract (*In English*)

This doctoral thesis has title "Industry 4.0 And Environmental Sustainability: The Role of Digital Technologies for The Circular Economy in Manufacturing" and discusses the research work carried out in the last three years at the Department of Mechanical and Industrial Engineering of the University of Brescia and research project co-financed by the European Union under the PON R&I 2014-2020 Programme, FSE REACT-EU resources, Action IV.5 "Doctorates on Green topics".

This thesis investigates the integration of Industry 4.0 (I4.0) technologies and Circular Economy (CE) practices within the context of environmental sustainability in the manufacturing sector. The global manufacturing sector faces unprecedented environmental challenges driven by resource depletion, waste generation, and unsustainable linear 'take-make-dispose' economic models. Against this backdrop, CE has emerged as a transformative paradigm, emphasizing closed-loop, restorative, and regenerative systems aimed at maximizing resource efficiency and minimizing waste. In parallel, I4.0 technologies such as the Internet of Things (IoT), artificial intelligence, big data analytics, and additive manufacturing, provide innovative tools for enabling circular practices. This research examines this synergy to address the critical need for sustainable growth amid escalating environmental challenges and global resource scarcity.

Despite the extensive literature on the interrelationship between I4.0 technologies, CE, and environmental sustainability, a significant gap remains in our understanding of how these areas are evolving together. Recent studies emphasize the need for deeper exploration and a shift from primarily exploratory and descriptive studies to confirmatory and prescriptive frameworks that more clearly define the objectives and methodologies within this nexus. This transition is crucial for effectively integrating digital technologies into CE practices and advancing the overall understanding of their combined impact on sustainability and operations management. Furthermore, the thesis examines the broader adoption of CE within a specific regional context (India) to bridge the gap between theoretical understanding and practical implementation. India, as a rapidly growing economy with a large population and significant production and consumption patterns, can greatly benefits by adopting CE principles in its manufacturing sector. These benefits include enhanced resource efficiency, waste minimization, and the development of closed-loop systems, which leverage India's economic potential while addressing critical challenges in environmental sustainability. Hence the thesis highlights a significant knowledge gap in understanding the evolution of research on the circular economy (CE),

environmental sustainability, and Industry 4.0 (I4.0), particularly regarding how digital technologies enhance operations management and the current level of CE adoption among Indian manufacturers. To address this objective, the thesis explores three interconnected questions:

RQ1: *How has academic research evolved regarding CE, environmental sustainability, and I4.0, and what insights can be gained from bibliometric analysis to inform future research?*

RQ2: *In what ways do digital technologies influence operations management processes to support environmental sustainability and circularity?*

RQ3: *What level of adoption of circular practices is observed among Indian manufacturing companies?*

To address these gaps, the methodology employed in this study is interdisciplinary, ensuring a systematic investigation of its objectives. The thesis adopts two methodological perspectives: a literature-oriented approach and a practice-oriented approach.

The **literature-oriented approach** combines bibliometric analysis (quantitative), content analysis (qualitative), and contingency analysis (statistical) to provide a multifaceted perspective on the research questions. The bibliometric analysis maps the evolution of knowledge streams at the intersection of CE, environmental sustainability, and I4.0, constructing an intellectual structure and identifying thematic clusters within the field. A systematic literature review is conducted to develop a theoretical framework that evaluates the sustainability, and circularity impacts of digital technologies in their interaction with Operations Management (OM) processes.

Furthermore, the **practice-oriented approach** focuses on understanding emerging phenomena by addressing the third research question and enhancing comprehension of complexities and real-world applications. In this section, a survey-based methodology (descriptive and structural equation modelling) explores the current state of circularity in Indian manufacturing companies. This approach is utilized for quantitative data collection, hypothesis testing, and validation of findings, thereby strengthening the reliability and validity of conclusions. It offers empirical insights into the practical implementation of CE principles within an emerging economy context.

The findings suggested that interdisciplinary integration is critical, as bibliometric analysis identifies a fragmented yet rapidly growing body of literature linking CE, sustainability, and I4.0, underscoring the necessity for holistic strategies integrating technological, environmental, and operational perspectives. A theoretical framework further demonstrates how digital technologies, such as IoT and additive manufacturing, enhance OM processes, though their sustainability impact hinges on strategic deployment across operational contexts. Empirically, the assessment of Indian manufacturing firms

indicates moderate circularity readiness, with larger companies leading in progress, while small and medium-sized enterprises (SMEs) encounter systemic barriers to CE adoption. Finally, the study emphasizes collaboration, showing that integrating supply chain management collaboration (SCMC) with servitized business models (SBMs) drives resource efficiency and advances CE implementation.
Theoretically, this study provides substantial contributions to the fields of Industry 4.0, environmental sustainability, and circular economy literature by offering a comprehensive bibliometric overview, network-based analysis, and a structured understanding of the intersection of these critical domains with respect to Operations Management (OM) processes. It sets the stage for future research by identifying emerging trends and highlighting key gaps that necessitate further exploration. Managerially, the findings offer actionable strategies for firms to prioritize Digital Technologies (DTs) investments in procurement, production, and reverse logistics, while advocating for collaborative platforms and skill development. The work addresses both the theoretical underpinnings of I4.0, CE, and sustainability, and their practical implications, supporting manufacturer particularly in emerging economies in addressing challenges in environmental sustainability and resource management. By integrating academic rigor with empirical findings, this thesis offers a roadmap for supporting environmental sustainability in manufacturing industries through the advancement of CE via I4.0.

Chapter 1. Introduction

The convergence of Industry 4.0 technologies and Circular Economy practices represents a transformative paradigm for manufacturing industries, enabling sustainable growth amid escalating environmental challenges and resource scarcity. This integration leverages digital technologies such as the Internet of Things, artificial intelligence, and big data analytics to optimize resource efficiency, minimize waste, and foster closed-loop systems. By aligning Industry 4.0's technological capabilities with Circular Economy principles, manufacturing sectors can transition from linear production models to regenerative, sustainable frameworks, addressing critical global imperatives for environmental stewardship and resource conservation. This synergy between Circular Economy practices and digital technologies not only optimizes resource efficiency and minimizes waste but also fosters innovation in product design, supply chain management, and end-of-life product handling, ultimately driving the transition to a more circular and environmentally responsible industrial paradigm. This thesis explores the synergistic relationship between Industry 4.0 technologies and Circular Economy practices, addressing the pressing need for innovative solutions to align industrial growth with environmental sustainability.

To comprehensively address this complex interplay, this research poses three distinct yet interconnected questions:

1. How has the academic landscape evolved regarding the integration of Circular Economy, environmental sustainability, and Industry 4.0, and what insights can be derived from a comprehensive bibliometric analysis of this interdisciplinary field to guide future research directions?

2. How do Digital Technologies acting on Operations Management processes contribute to fostering environmental sustainability and circularity?

3. To what extent did Indian manufacturing companies adopt circular practices?

The subsequent chapter will address sub-research questions related to each primary research question. An interdisciplinary approach will be used to address these questions. Bibliometric analysis is used to map the evolution of knowledge streams at the intersection of CE, environmental sustainability, and

I4.0, providing a comprehensive understanding of the intellectual structure and thematic clusters in the field. Content-based and contingency analysis are applied to develop a theoretical framework that evaluates sustainability, and circularity impacts of digital technologies through their interaction with Operations Management processes. Finally, a survey-based approach is adopted to assess the circularity of Indian manufacturing companies, offering empirical insights into the practical implementation of CE principles in an emerging economy context. The thesis is structured to address each research question systematically:

Chapter 4 presents a systematic examination of the scientific literature, analysing the intellectual structure and thematic clusters that connect CE, environmental sustainability, and I4.0. This chapter provides a foundational understanding of how these concepts have converged and evolved in academic literature. This chapter employs bibliometric analysis to identify key trends, gaps, and emerging research clusters.

Chapter 5 develops a theoretical framework to assess sustainability, and circularity impacts of digital technologies (DTs) through their interaction with Operations Management (OM) processes. Using systematic literature review methods, including content and contingency analysis, this chapter provides a structured understanding of how DTs enable CE practices in the operations management process. This chapter offers a nuanced understanding of how specific technologies influence various aspects of manufacturing operations to promote sustainability and circularity.

Chapters 6 and 7 introduce and apply the C-Readiness tool to evaluate the circularity readiness of the Indian manufacturing sector. This chapter presents findings from a survey-based assessment, highlighting the current state of CE adoption and identifying areas for improvement. These chapters bridge the gap between theoretical concepts and practical implementation, providing valuable insights into the current state and future potential of CE practices in Indian manufacturing industries.

This thesis aims to contribute to the understanding of how Industry 4.0 technologies and circular economy practices can be integrated. Figure 1. 1 shows the structure of the manuscript and the connections between the research questions and key findings.

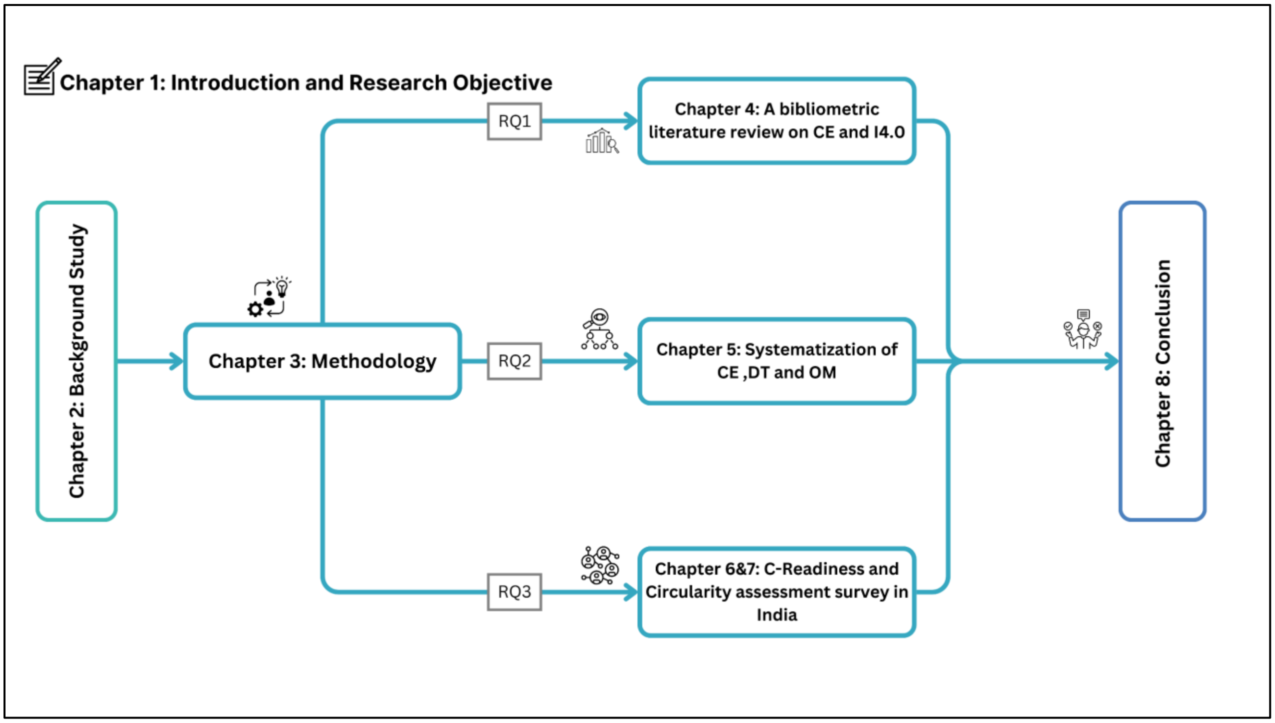


Figure 1. 1 Manuscript Structure and relations among research question and key findings

Chapter 2. Background

2.1 Background (Importance of sustainable development)

The global economy is experiencing substantial growth and transformation, with economic activity generating a $13 trillion economy, which could further increase five to ten times in the coming decades (World Bank Group, 2022). This traditional economic model of growth tends to drive higher demand for goods and services, leading to greater extraction of natural resources and energy consumption with generating substantial waste. Consequently, the traditional linear economic model, where resources are extracted, used, and then discarded, is unsustainable as it leads to the overconsumption of natural resources (OECD, 2022) and excessive waste generation, as shown in Figure 2. 1.

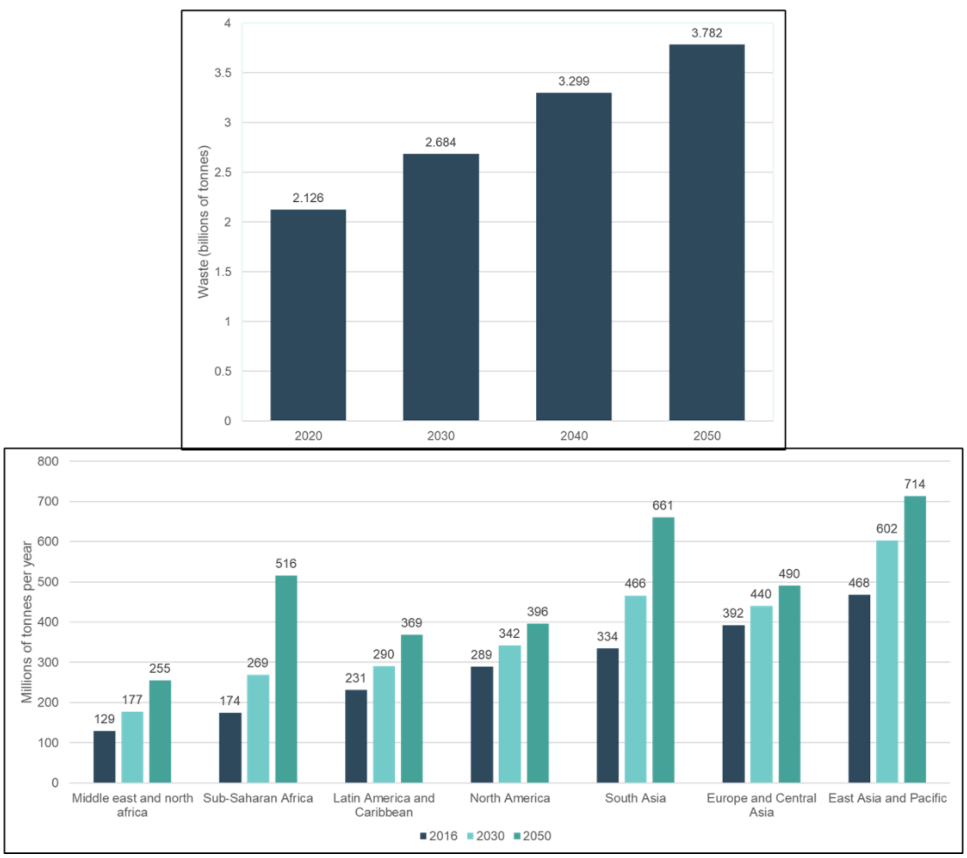


Figure 2. 1 Projection of global Waste Generation (a); Projection of Waste Generations per Region(b)(Sources: UNEP, 2024;World Bank Group, 2022)

For example, the rapid growth in the electronics sector has led to a significant increase in e-waste, with global e-waste generation rising from 34 billion kg in 2010 to 62 billion kg in 2022, averaging 7.8 kg per capita (Baldé et al., 2024). This waste generation leads to various environmental issues, including increased air and water pollution, solid waste accumulation, groundwater depletion, and the buildup of toxic chemicals and hazardous wastes. Furthermore, the generation of new and complex forms of waste has worsened environmental degradation, including issues such as soil erosion, desertification, and acidification (Bibri, 2019). Hence, addressing these multifaceted environmental problems has become a critical priority. With the global population projected to reach 9 billion by 2050, finding ways to accommodate humanity within the limits of our finite environment is the priority. The thought-provoking concept of "The Limits to Growth" (Meadows et al., 1978) has been a starting point for many debates on the interconnected nature of environmental damage and economic growth (Millar et al., 2019). The United Nations has also recognized the critical need to address the challenges of climate change and environmental sustainability. The UN's Sustainable Development Goals, particularly SDG 11 on 'Sustainable Cities and Communities,' SDG 12 on 'Responsible Production and Consumption,' and SDG 13 on 'Climate Action,' have focused explicitly on these challenges (Ogunmakinde et al., 2022; UNEP, 2024). Consequently, the concepts of "sustainability" and "sustainable development" have recently gained widespread attention and prominence over the past half-century. To achieve sustainable development, the focus should be pay on value creation rather than simply economic benefits and need to include all three aspects of "Triple Bottom Line," i.e., economic, environmental, and social (Birkel & Müller, 2021). Hence, the current economy must transition to a more sustainable model to balance ecological improvement with economic development and overcome the challenges posed by linear economic models, which create resource underutilization and generate waste at the beginning, during use, and at the end of the product life cycle (Schöggl et al., 2020).

Circular Economy (CE) has emerged as an alternative model within the broader framework of the Sustainable Development Goals (Ellen MacArthur Foundation, 2013). It systematically redesigns existing practices to address the root causes of resource overconsumption and waste generation, focusing on the restorative and regenerative model where products and materials are reused repeatedly (Bressanelli et al., 2019; Merli et al., 2018). This model transforms the industrial ecosystem by reducing raw material use and waste, maximizing resource value retention, and reintegrating products into the system at the end of their life cycle. It enhances the "multidimensional complex value" of resources, enabling improved control over resource utilization. By recognizing the intrinsic value of materials beyond their immediate use, CE promotes practices that enhance resource efficiency, reduce waste, and encourage sustainable production methods (Chan et al., 2018). This holistic approach has aroused the interest of businesses and policymakers over the last decade, as evidenced by the establishment of legislative frameworks and funding initiatives. Notable examples include the European Union's Circular Economy Action Plan, which aims to promote sustainable resource use (EU, 2016); China's eco-industrial policies, designed to enhance environmental performance across industries (CCICED, 2008); the UK's Circular Economy Package, which focuses on waste reduction and resource efficiency(DEFRA, 2020); and Australia's National Waste Policy, which attempts to minimize waste and improve recycling systems (Dcceew, 2018).

2.2 The concept of Waste and Circular economy

The manufacturing industry is one of the most polluting and resource-intensive sectors, which impacts consumer practices and compromises the finite resources available on Earth. It is therefore critical to focus extensively on the 12th Sustainable Development Goal: "Responsible Production and Consumption," which emphasizes efficient resource management and waste reduction. In a global context, it is estimated that 90 billion tons of waste are generated worldwide each year, yet only 9% of the total waste is recycled (UNEP, 2024). By recognizing the intrinsic value of waste beyond immediate disposal, it should be seen as a valuable resource for material recovery, energy savings, environmental benefits, and economic opportunities. Therefore, it is essential to establish a foundational understanding of the patterns of resource consumption and waste involved in the resource loop.

Waste could be defined as any kind of underutilization of resources (sundeep singh, 2018). The four categories of waste generated by a linear economic model are as follows (Lacy & Rutqvist, 2015):

1. Wasted resources
2. Wasted capacities
3. Wasted life cycle
4. Wasted embedded values

Wasted resources can be defined as material and energy that cannot be effectively regenerated over time. Furthermore, the materials and energy cannot be perpetually regenerated; rather, they are consumed and irretrievably lost upon utilisation (Lacy & Rutqvist, 2015). The emphasis is on wasted resources involving non-renewable or hard-to-recycle materials. To reduce wasted resources, various strategies can be implemented in both general and industrial settings, including enhancing resource efficiency throughout operations, identifying opportunities to substitute conventional materials with more eco-friendly and renewable alternatives, transitioning to renewable energy sources, and promoting responsible consumption practices. By minimizing the input of raw materials and energy, the overall wasted resources can be minimized (Ghisellini et al., 2016; Su et al., 2013).

Secondly, wasted capacities refer to the products and assets that are not utilized to their full potential. This is particularly evident in the case of consumer products, such as cars, which often remain idle and unused for most of their lifespan, typically up to 90% of the time. The underutilization of resources highlights the need for more sustainable and efficient consumption (Lacy & Rutqvist, 2015). To minimize wasted capacities, it is crucial to optimize resource utilization and maximize their ideal capacity. This can be achieved by increasing the productive and monetized usage of products and assets, thereby enhancing the value generated from their use rather than allowing them to remain underutilized (Lacy & Rutqvist, 2015). Promoting practices such as product and material reuse, and the sharing economy, can significantly reduce wasted capacities (Bressanelli et al., 2019).

Products often reach end of life prematurely due to planned obsolescence or a lack of second-life options (Lacy & Rutqvist, 2015). Wasted life cycle is defined as the gap between a product's potential lifespan and its actual lifespan. In fact, the product has an artificially short working life or is disposed of even if there is still demand for it for other users. If an organization emphasises creating products that prioritise durability and longevity, it can also redesign the product to sustain the value chain and extend its lifespan without becoming obsolete. Second, implementing take-back programs enables manufacturers to recover products and remanufacture them, thereby extending the product's life cycle. Additionally, encouraging repair and reuse among consumers can significantly reduce premature disposal, promoting sustainable consumption (Bressanelli et al., 2019; Centobelli et al., 2020; Suchek et al., 2021; Zisopoulos et al., 2022).

Finally, wasted embedded values are described as components, material, and energy not recovered from waste streams (Lacy & Rutqvist, 2015), resulting in lost opportunities for reintegrating these resources back into the natural cycle. To address this issue, implementing robust recycling (down- or up-cycling) programs is essential for reclaiming valuable materials and reintegrating them into the value chain. Additionally, promoting product design that facilitates disassembly and recyclability can enhance the recovery of materials at the end of a product's life cycle. Building awareness among stakeholders about the importance of resource recovery is critical to reducing wasted embedded values and promoting sustainable resource management (Corvellec et al., 2022; De Pascale et al., 2021; Romero et al., 2021).

Hence, CE has been widely encouraged by policymakers and academics as a way to reduce waste and use resources more effectively (Ellen MacArthur Foundation, 2013). Understanding the relevance of CE across ecological, economic, and social dimensions of sustainability is essential for evaluating progress towards broader sustainability goals. However, CE has faced criticism for its conceptual ambiguity, as it encompasses a different array of ideas across various disciplines, leading to confusion and a lack of coherence among stakeholders (Corvellec et al., 2022; Jerome et al., 2022; Kirchherr et al., 2017). This "blurriness" complicates its implementation, as there are over a hundred definitions of circularity, reflecting differing interpretations among practitioners such as policymakers, businesses, and consultants (Blomsma et al., 2018a). The absence of conceptual clarity can hinder the development of new knowledge and obstruct effective discussions, underscoring the need for a unified framework to guide CE practices and enhance collaboration among various actors involved (Kirchherr et al., 2023; Schulz et al., 2019).

2.3 Timeline of Circular Economy

Circular Economy is an umbrella concept that brings together different sub-concepts and inculcates them with a common emphasis on a shared underlying principle (Blomsma et al., 2019). The circular economy's origin is not proven or documented (Winans et al., 2017). However, the source of the CE can be traced back to different schools of thought (De Pascale et al., 2021; Ellen MacArthur Foundation, 2013; Lacy & Rutqvist, 2015). They include regenerative design, performance ecology, and the Cradle-to-Cradle concept. Principles of ecologically inspired design, influenced by regenerative design, enhance product development by enabling closed-loop systems (Cole, 2012). Similarly, biomimicry offers a framework for designing industrial systems that emulate natural processes, thereby promoting ecosystem conservation through its "Emulate-Ethos-Reconnect" approach (Mathews, 2011). The Cradle-to-Cradle philosophy fundamentally transforms the traditional "Cradle to Grave" model by viewing waste as a perpetual resource, which is pivotal to the concept of circularity within CE (Braungart et al., 2007). Additionally, industrial ecology advocates for eco-efficiency and zero waste, striving to convert waste into nutrients that circulate within biological and technological cycles while supporting the "Triple Bottom Line" (Braungart et al., 2007). Permaculture further emphasizes the conversion of waste into raw materials at lower costs while fostering self-sufficiency and environmental preservation by minimizing material extraction (Holmgren, 2002).

Moreover, the concept of CE has evolved significantly over the years, marked by key milestones and influential publications that have shaped its development. Kenneth Boulding's 1966 paper on ecological economics introduced the pioneering concept of a circular system, emphasizing resource reuse instead of disposal. This idea was famously presented in his work, "The Economics of the Coming Spaceship Earth" (Boulding, 1966). By 1989, Pearce & Turner, (1990) formally articulated the CE, emphasizing sustainable management of natural resources by integrating ecological and economic considerations. At an institutional level, the Chinese government implemented the first "Circular Economy promotion law" in January 2009 to address the imbalance between economic growth and the consequent environmental damage (CCICED, 2008; Su et al., 2013). Also, the CE model became popular in European policy in the 2010s.

A significant turning point occurred in 2013 when the term "Circular Economy" was formally defined, focusing on sustainability, resource efficiency, and waste minimization. The Ellen MacArthur Foundation emerged as a key advocate for CE, publishing the influential report "Towards the Circular Economy," which popularized the concept within business and policy circles (Ellen MacArthur Foundation, 2013). In 2015, the European Union adopted its Circular Economy Action Plan, aiming to transition member states towards circular practices that enhance resource efficiency and reduce environmental impacts (EU, 2016). As part of "Clean Energy for All Europeans," the "Eco-design Working Plan 2016 – 2019" was introduced at the end of 2016 (EURS, 2017). This plan contributed to the CE Action Plan by focusing on product design, making things more durable and easier to recycle (EU, 2016). In 2017, the European Commission launched the European Circular Economy Stakeholder Platform in collaboration with the European Economic and Social Committee. By 2017, other countries began integrating CE principles into their national policies, particularly in waste management and sustainable resource use (Dcceew, 2018; DEFRA, 2020). The linkage between CE and the United Nations Sustainable Development Goals (SDGs) further highlights its global relevance in promoting sustainability. In 2019, the European Commission published a full report on implementing CE Action Plan and declared that all 54 measures outlined in the action plan had been delivered or were in the process of being implemented (Ellen MacArthur Foundation, 2019). The European Commission launched a new Circular Economy Action Plan in 2020. This initiative was one of the cornerstones of Europe's new vision for long-term growth, called the "European Green Deal" (Fetting, 2020). Furthermore, a new eco design law is introduced, a set of initiatives aimed at speeding up the transition towards a circular economy in 2022. Hence, CE continues to evolve, with an increasing focus on integrating circular principles into a comprehensive socio-economic approach addressing waste, resources, production, and consumption. The timeline of CE is shown in the diagram in Figure 2. 2.

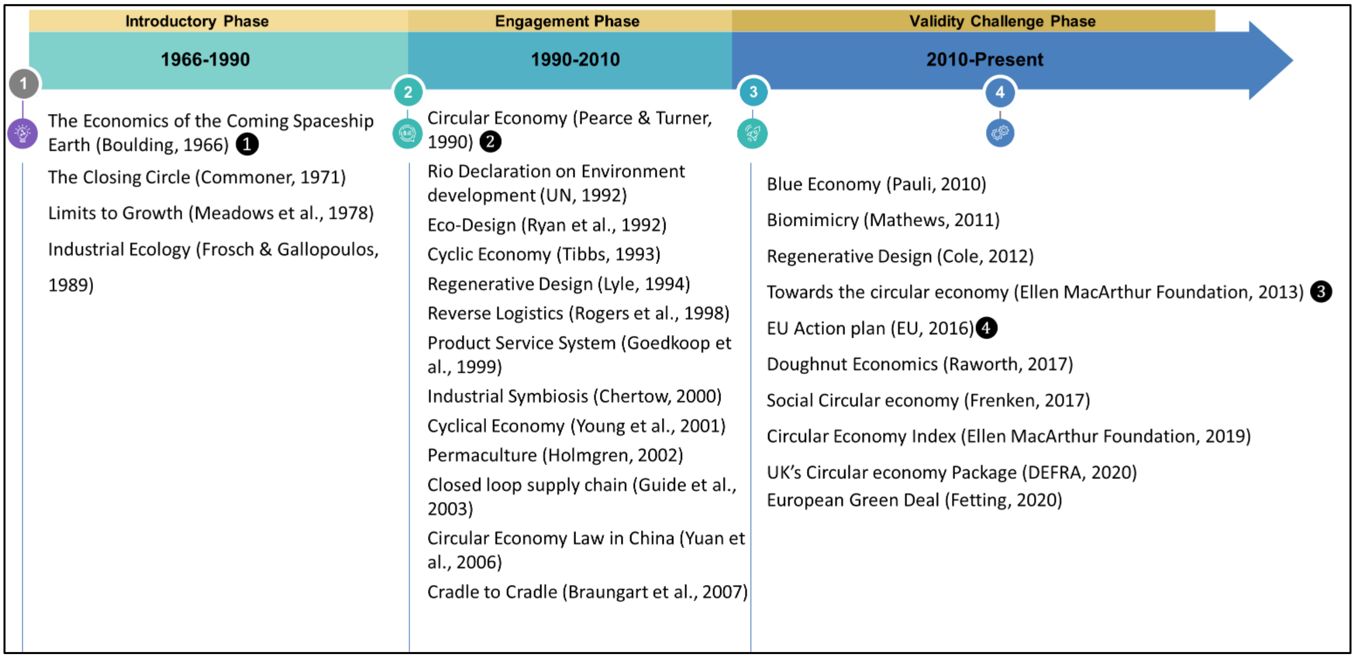


Figure 2. 2 Timeline of Circular Economy Concept

Through the evaluation of Circular Economy (CE) developments, the literature concludes that while CE philosophies are increasingly discussed among various stakeholders, they remain in a "progressive validation-challenged phase," underscoring the need for broader acceptance and robust validation. The timeline of CE development in Figure 2. 2 reveals the complexities and challenges associated with the concept. Firstly, it highlights the diverse interpretations of CE across multiple disciplines, which can lead to confusion among stakeholders regarding its implementation. Secondly, CE is characterized as an "essentially contested concept," indicating that its meaning can vary significantly across different groups and contexts, resulting in contradictions in perception and application. Lastly, although CE has gained traction and expanded in scope, this proliferation of ideas can lead to misunderstandings that hinder its acceptance as a coherent framework for sustainable development. Despite these challenges, the development of CE has been positive and progressive. However, many global communities remain unaware of the concept's importance and implications at the micro, meso, and macro levels of the economy.

2.4 Definition of Circular Economy

Numerous definitions of CE have been proposed, highlighting its dynamic and evolving nature. For instance, Kirchherr et al., (2023) has compiled an extensive list of 221 CE definitions, while Ghisellini et al., (2016) has gathered 155 CE-related articles, illustrating the diversity of interpretations within the field. Some scholars, such as Millar et al., (2019) found that many definitions fail to incorporate a time dimension, which is crucial for understanding the long-term implications of CE practices. This multitude of interpretations has led to a lack of homogeneity, complicating comprehension among different stakeholders. Various articles discuss definitions centred on concepts like "decoupling economic growth from resource depletion", "value maintenance," "value creation", "Reduced value loss," and "waste reduction". Bocken et al., (2016) categorize CE into three broad areas: narrowing, slowing, and closing the resource loop, whereas Ellen MacArthur Foundation, (2015) identifies three design concepts within the CE vision: raising material efficiency, extending product life, and increasing recycling efficiency. Given this wide range of interpretations, most studies conclude that a commonly accepted definition is still necessary (Bressanelli et al., 2019; Lieder & Rashid, 2016). While most authors accept the definition of the CE described by Ellen MacArthur Foundation, (2013), which describes CE as "an industrial economy that is restorative and regenerative by intention and design". Hence, Table 2. 1 lists the definition of the CE discussed by various articles and authors. When available the number of citations received in the literature (from Google Scholar) is reported.

Table 2. 1 Definition of Circular Economy

#	Source	Definition	No of Citations
1	Ellen MacArthur Foundation, (2013)	"*An industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models.*"	Highly Cited (Report)
2	EU, (2015)	*"An economy where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste minimised."*	Highly Cited (Report)
3	Mckinsey, (2015)	*"Circular Economy offers major opportunity to increase resource productivity, decrease resource dependence and waste, and increase employment and growth."*	Highly Cited (Report)
4	WRAP, (2019)	*"In the circular economy, instead of taking resources from the earth, using them once, and disposing of them in a landfill, we keep them in use for as long as possible."*	Highly Cited

			(Report)
5	Deloitte, (2020)	*"In the circular economy, all resource extraction will be minimized, whether this is for material use or energy purposes, and will take place in a manner which ensures equal access to resources and ecosystem services for future generations. This will be done through optimal utilization of the resources already extracted, and by avoiding activities that generate pollution and emissions/discharges."*	Moderately Cited (Report)
6	Su et al., (2013)	*"An economy term for the reducing, reusing and recycling activities conducted in the process of production, circulation and consumption."*	1913 (till 2024)
7	Lewandowski, (2016)	*"Circular economy features based on a business model. He outlined a framework for converting existing business models into ones that are more sustainable by focusing on the 3R's Principles: Reduce, Reuse, and Recycle."*	1957 (till 2024)
8	Kirchherr et al., (2017)	*"An economic system that is based on business models which replace the 'end-of life' concept with reducing, alternatively reusing, recycling and recovering materials in production, distribution and consumption processes, thus operating at the micro level, meso level and macro level, with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations."*	8801(till 2024)
9	Geissdoerfer et al., (2017)	*"A regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling"*	9006 (till 2024)
10	Murray et al., (2017)	*"An economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human wellbeing."*	4036 (till 2024)
11	Masi et al., (2017)	*"The CE model is based on the concept of changing the take-make-use-dispose pattern into closed loops of material flows. Closed loops of materials are possible through different functions i.e. maintenance, repair, reusing, refurbishing, remanufacturing and recycling. This creates the synergy effect between economic development and the environment."*	431 (till 2024)
12	Iacovidou et al., (2017)	*"Circular Economy (CE) aims to create a systemic shift from linear to circular practices by ensuring materials, components, and products (MCPs) are effectively recovered and redistributed for reuse, recycling, or recovery. While this transition requires addressing overlooked or underestimated technical challenges, these factors play a critical role in enabling a successful and sustainable circular economy."*	303 (till 2024)
13	Korhonen et al., (2018)	*"A sustainable development initiative with the objective of reducing the societal production-consumption systems."*	4532(till 2024)
14	Lopes de Sousa Jabbour et al., (2018)	*"The circular economy (CE) is a system of production and consumption which aims to keep products, components, materials, and energy in circulation in order to continue adding, recreating, and maintaining their value over a long time period."*	1178 (till 2024)
15	Bressanelli et al., (2019)	*"An economic system restorative and regenerative by design, implemented by one or more supply chain actors through one or more of the four building blocks (circular*	603 (till 2024)

		product design, servitised business models, reverse logistics and enablers) in order to replace the end-of-life concept with reducing, alternatively reusing, recycling and recovering materials in production, distribution and consumption processes, for both technical and biological materials, with the aim to accomplish sustainable development."	
16	Rosa et al., (2020)	*"The CE is an industrial system that is restorative or regenerative by intention and design. This concept replaces the 'end-of-life' concept with restoration, shifts to the use of renewable energy, eliminates the use of toxic chemicals (which impair reuse), and aims for the elimination of waste through the superior design of materials, products, systems, and within this, business models".*	714 (till 2024)
17	D'Amato et al., (2020)	*"The circular economy, rooted in five decades of ideas regarding industrial ecology and metabolism, is focused on improving the efficiency and recycling capacity of the current consumption-production system through input reductions, eco-design, improved practices, waste reuse and recycling."*	379 (till 2024)
18	Sönnichsen & Clement, (2020)	*"Circular economy minimizes incineration and landfill; is regenerative and restorative by design; operates by default on renewable energy; maintains resources at their highest value at all times; inherently has a higher complexity than linear transactional value chains; and thus embeds a potential to decouple growth in the extraction of virgin resource from monetary growth."*	354 (till 2024)
19	Figge et al., (2023)	*"The circular economy is a multi-level resource use system that stipulates the complete closure of all resource loops. Recycling and other means that optimise the scale and direction of resource flows, contribute to the circular economy as supporting practices and activities. In its conceptual perfect form, all resource loops will be fully closed. In its realistic imperfect form, some use of virgin resources is inevitable."*	102 (till 2024)
20	Nandi et al., (2023)	*"The circular economy is focused on eliminating waste and overuse of resources. CE economic systems stress reuse, repair, and recycling in a closed-loop system to reduce inputs, pollution, and other wastes while minimizing carbon footprints."*	39 (till 2024)

While differing definitions of CE encourage its adoption across different industries and stakeholders, the lack of a standardized framework may create barriers to its consistent understanding and implementation.

The implementation of CE strategies necessitates a systematic approach that encompasses a comprehensive perspective, integrating environmental sustainability relationships, resource preservation, and interconnectedness across different implementation levels (Zisopoulos et al., 2022). This holistic view is important for understanding the core principles of CE, particularly the "R" principles and their varying implementation adoption, ranging from micro (individual products and firms) to meso (networks of companies) and macro (actions by cities, regions, and nations) levels

(Bressanelli et al., 2018; Morseletto, 2020; Obringer et al., 2021; Stahel, 2019; Zink & Geyer, 2017). By considering these dimensions, researchers and practitioners can better navigate the complexities of CE implementation, ensuring that strategies are not only effective but also efficient in promoting sustainable practices across different contexts.

2.5 R strategies Of Circular Economy

Circular strategies are important to CE and are often framed within the "R" framework, which has expanded and evolved over time. However, the existing literature highlights significant inconsistencies in the interpretation of these circular strategies, which underscores the pressing need for a unified language and standardized metrics to facilitate the successful implementation of CE.

The development of circular strategies involves complex interpretations and applications across different contexts, as shown by studies that define and categorize the "R-imperatives" associated with CE. Reike et al. (2018) identified 38 distinct R-imperatives, emphasizing the varied terminology associated with it, while Morseletto, (2020) discussed how the effectiveness of R strategies can vary significantly based on product systems and lifecycle stages. Additionally, Okorie et al., (2018) proposed a classification based on loop types, product types, and functions, while Henry et al., (2020) highlighted the significance of R strategies applicable for Circular Business Models within CE literature. Potting et al., (2017) discussed on 10R strategies further, categorizing them into three groups related to materials, product lifespan extension, and inventive usage. Papamichael et al., (2023) specifically address the fashion industry, proposing tailored Rs for waste management and new product development, which reflects the need for sector-specific adaptations of circular strategies. Valencia et al., (2023) support this notion by recommending socio-economic strategies utilizing a 9R approach for effective CE implementation. Digital technologies also play a crucial role in determining the feasibility of different R strategies, with Kristoffersen et al. (2020) providing a framework that integrates CE R-strategies with digital technologies.

Hence, the literature on CE presents a wide array of R frameworks and definitions, ranging from the foundational "3Rs" (Reduce, Reuse, and Recycle) to more comprehensive models that include up to 11Rs. While the core CE concept often revolves around the 3Rs, many scholars advocate a broader interpretation that incorporates additional strategies to maximize value retention. For instance, Potting et al., (2017) support the implementation of 10R strategies, recognizing their relevance at various levels, including products and materials. Recent publications from 2019 to 2022 have increasingly emphasized the significance of 10Rs and even 11Rs for value retention, with frequently mentioned terms including refuse, reduce, repair, recycle, restore, resolve, remanufacturing, refurbished, reorder, rent, replace, revive, renovation and reframe (De Pascale et al., 2021; Ghisellini et al., 2016; Kirchherr et al., 2023; Kristoffersen et al., 2019). Zorpas (2024) proposed a comprehensive framework aligning with CE principles, emphasizing the 10-R approach to retain value throughout the product life cycle and prevent value leakage (Lacy & Rutqvist, 2015; Uçar et al., 2020). This study focuses on the fundamentals of R-strategies within waste management principles, particularly addressing four forms of waste, as reported in Table 2. 2. Reducing material use in design and production can lower energy consumption and waste generation, which is a key strategy for managing wasted resources (Morseletto, 2020). Additionally, wasted capacities highlight underutilized products, suggesting that strategies should aim to recirculate or reuse parts through extended use cycles. The process of "parts harvesting" (Kirchherr et al., 2017), which involves recovering usable components from waste products for alternative applications, is considered part of the reuse category. Addressing wasted life cycles is crucial, as some products may reach their end prematurely (Ghisellini et al., 2016), where remanufacturing can play a significant role by incorporating parts from discarded items into new products. To address wasted embedded values at the end-of-life stage, CE practices often turn to incineration to recover energy from products, components, and materials. While recycling is considered a viable end-of-life solution that processes materials into new products, this method can result in a closing of the loop with poor energy conversion outcomes. Table 2. 2 categorizes various R-strategies based on waste concepts, advocating for waste avoidance and resource reduction over traditional management approaches. The proposed hierarchy prioritizes strategies that maximize value retention while minimizing resource consumption, although its applicability may vary based on material characteristics, technological capabilities, economic factors, and social acceptance (Calisto Friant et al., 2020; Kevin van Langen et al., 2021).

Table 2. 2 Comparison of 4R strategy to Other R strategy

RISE Framework- 4R strategy (Bressanelli et al., 2021)	Based on Linear Waste management	Circular strategies based on Production Value chain	Based on Value Retention (Kristoffersen et al., 2020)	CE value drivers (Murray et al., 2017)	Based on Circular Business Model (Henry et al., 2020)	10-R (Reike et al., 2018)	Relations with Kirchherr et al., (2017) Rs Framework	Based on material, product and Production level 10R strategy (Potting et al., 2017)
Reduce	Wasted resources	Smart Product use and manufacture	Restore, reduce & avoid the area of raw materials and Sourcing	Increase resource efficiency	R0-Regenerate R1-Reduce	R0-Refuse R1-Reduce R3-Repair R6-Repurpose-Rethink	R0-Reduce R1-Rethink R2- Reduce R3- Repair	R0-Refuse R1-Rethink R2-Reduce
Reuse	Wasted capacities	Extended life span of products and its part	Recirculating parts and products by extend the existing use cycles	Extended Life span	R2-Reuse	R2-Resell-Reuse R4-Refurbish	R3- Reuse R5-Refurbish	R3-Reuse R4-Repair R5-Refurbish
Remanufacturing	Wasted life cycle			Close the loop	R3-Recycle R4-Recover	R5-Remanufacturing	R6-Remanufact. R7-Repurpose	R6-Remanufacturing R7-Repurpose
Recycle	Wasted Embedded Values	Useful application of materials	Recirculate materials by extend use cycles of materials			R7-Recycle R8-Recover (Energy) R9-Remine	R8-Recycle R9-Recover	R8-Recycle R9-Recover

This framework serves as a foundation for further research and discussion on the significance of the 4R strategy adopted from (Bressanelli et al., 2018) as shown in **Error! Reference source not found.**, linking it to the physical flows of products and materials. Furthermore, the analysis of various R-strategies presented in Table 2, allows for comparisons with those discussed in other important literature. Ultimately, this comprehensive examination contributes to a deeper understanding of how to effectively transition towards a CE while maximizing resource efficiency and minimizing environmental impact.

2.6 RISE circular action and framework

The RISE 4R's circular strategies framework, adapted from the work of Bressanelli et al., (2018), is illustrated in **Error! Reference source not found.**. It serves as a foundation for further research and discussion on the significance of the 4R strategy adopted from (Bressanelli et al., 2018) linking it to the physical flows of products and materials. Furthermore, in Figure 2. 3 these strategies are compared with those discussed in other important literature.

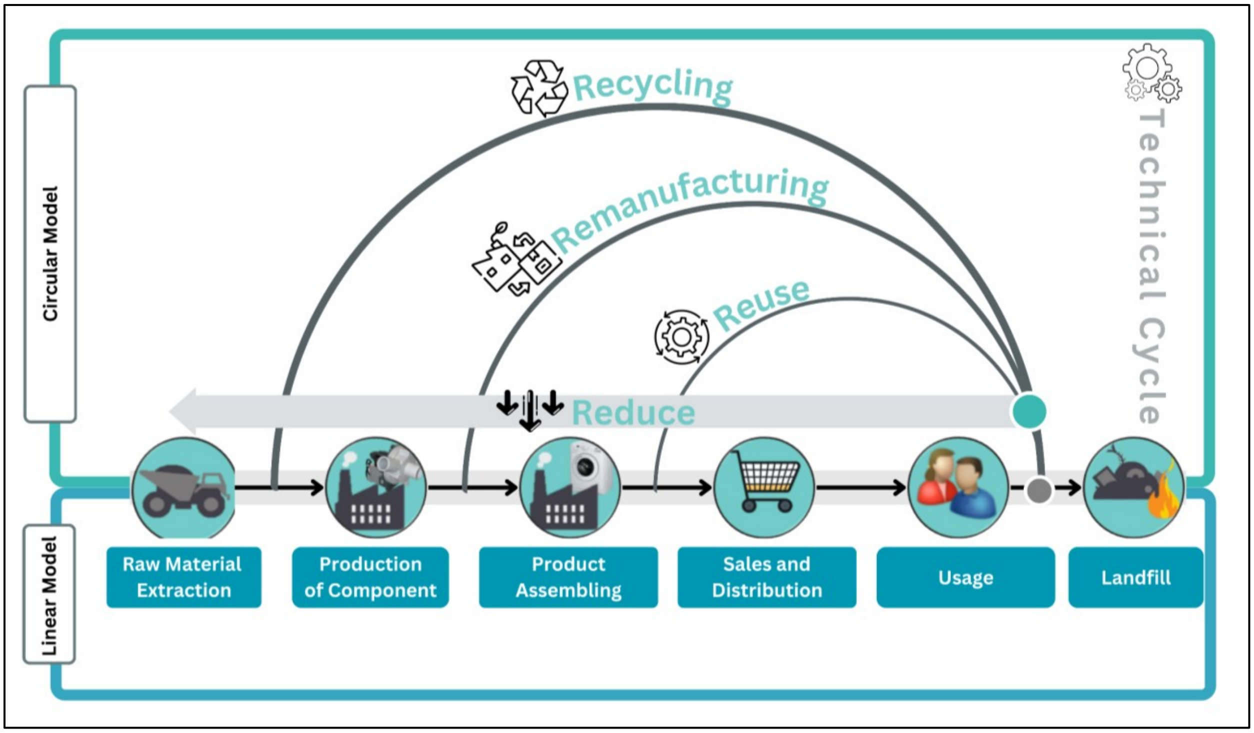


Figure 2. 3 4R Strategies

The framework is grounded in value-retention strategies and CE Value drivers, specifically focusing on increased resource efficiency, extended product lifespan, and closing the resource loop (Diaz Tena et al., 2021; Reike et al., 2018). This framework is divided into four distinct categories:

- R0 - Reduce: This strategy emphasizes minimizing resource consumption and waste generation at the outset.
- R1 - Reuse: It involves finding new uses for products without significant processing, thereby extending their life cycle.
- R2 - Remanufacture: This strategy focuses on restoring used products to like-new condition through disassembly and reassembly processes.

- R3 - Recycle: This category pertains to processing materials to create new products, which conserves resources and reduces landfill waste.

By categorizing these strategies, the RISE framework (as shown in Table 2. 3) provides a structured approach to understanding how different circular practices can be effectively implemented across various industries, ultimately contributing to a more sustainable economy.

Table 2. 3 Relationship between 4R's, CE value drivers and Value retention loop

4Rs Scheme	CE value drivers	Value retention loop
Reduce	Increase Resource Efficiency, Extend Life span	Absolute- Short Loop
Reuse	Close the loop	Short Loop
Remanufacturing	Close the loop	Medium-Long Loop
Recycle	Close the loop	Long Loop

R0 Reduce:

The “Reduce” strategy emphasizes the critical importance of minimizing material consumption and optimizing resource flows to mitigate environmental impact. This strategy is essential for achieving sustainability, as it directly tackles the overconsumption of resources and the waste generated from such practices. Geissdoerfer et al.,(2017) explore the reduction strategy in the context of 'closing loops,' which involves decreasing the total input of raw materials through improved design and enhanced process efficiencies. Similarly, Ghisellini et al., (2016) and Korhonen et al., (2018) define “Reduce” primarily as a means to lower material consumption and environmental effects, including waste generation. This broader perspective aligns with

Bressanelli et al., (2020), found that reducing consumption is vital for preventing waste before products even enter circulation. The objective of the “Reduce” strategy is resource efficiency, which entails narrowing the resource loop and decreasing resource consumption per unit of production (Henry et al., 2020). This focus on efficiency is echoed by Diaz Tena et al., (2021), who connect material reduction to design principles that prioritize lightweight design and the elimination of hazardous substances while maintaining product functionality. Wang et al., (2022) emphasize that the “Reduce” strategy aims to minimize waste generation at its source, urging businesses to rethink their production processes and product designs to eliminate waste before it occurs. Laskurain-Iturbe et al., (2021) discuss three contexts for the “Reduce” strategy: consumer-oriented, producer-oriented, and as a generic term. From a consumer standpoint, reducing consumption involves designing product-service systems that encourage less frequent purchases and promote efficient resource utilization. Conversely, from a producer's perspective, "Reduce" focuses on minimizing material use in manufacturing and packaging (Gebhardt et al., 2022). Some authors highlight consumer behaviour as a critical factor in waste reduction (Reike et al., 2018), while others emphasize production processes and design innovations (Bressanelli et al., 2020; Pinheiro et al., 2022). Additionally, the emphasis on dematerialization varies across studies; some authors consider it a fundamental practice within the "Reduce" strategy, while others do not explicitly mention it.

Encouraging reduction can also be driven by compliance with legal regulations or by adopting consolidated eco-design practices that align with sustainability goals. Overall, the "Reduce" strategy serves as a foundational element in transitioning towards a more CE by promoting resource efficiency and minimizing environmental impact throughout product lifecycles.

R1 Reuse:

The principle of Reuse emphasizes the importance of extending the useful life of products to minimize resource, energy, and labour consumption in the production process (Grafström & Aasma, 2021). This strategy can take various forms, including direct reuse of products in their original condition, repurposing for different applications, and promoting sharing economies while maintaining the original functionality of items. Reike et al., (2018) noted that reuse can be viewed from multiple perspectives consumer-oriented, producer-oriented, and as a general concept. Long-life products and product life extensions exemplify reuse strategies that help slow resource loops by maximizing the usage and repurposing of commodities (Rovanto & Bask, 2021). Bressanelli et al., (2021) conceptualized reuse by focusing on the product as the reference point, emphasizing the recirculation of items in good condition. This process may include refurbishing or reselling the products, depending on the need. Awan et al., (2021) added that creative reuse encourages innovation by finding new applications for products beyond their original intent, thereby extending their utility. From a financial perspective, Bocken et al., (2016) argue that businesses can use reuse to generate new revenue streams through resale, refurbishment, or rental models. This approach not only leads to cost savings for both businesses and consumers but also reduces the demand for new products. Consumers should be encouraged to reuse by purchasing second-hand goods or seeking items that are lightly used and can be restored with minimal effort. The integration of reuse into Circular Business Models (CBMs) has been discussed in the literature. Henry et al., (2020) highlight that CBMs frequently incorporate reuse strategies to enhance product life cycles and minimize resource input. While some authors focus on reuse at the product level (Bakker et al., 2014; Bocken et al., 2016), others examine it at the material and substance levels. Lastly, reuse is often viewed as an umbrella concept encompassing various value retention strategies of a product, such as repair and refurbishment (Ghoreishi & Happonen, 2020; Potting et al., 2017). It is ranked higher than remanufacturing and recycling because it retains more resource value and minimizes the wasted capacity of the product by returning products to the economy after their initial use or by prolonging the life of products and their components (Henry et al., 2020). This multifaceted approach to reuse underscores its critical role in advancing CE objectives while promoting sustainability.

R2 Remanufacture:

Remanufacturing involves restoring used products to a like-new condition by replacing or reusing parts from discarded items and reconditioning them into new products. This process ensures that remanufactured items maintain the same level of quality, performance, and functionality as their original counterparts (Blomsma et al., 2018b; Hollander et al., 2017; Morseletto, 2020). This industrial practice involves several key steps: disassembly, inspection, cleaning, reconditioning, and reassembly of multi-component products (Lieder & Rashid, 2016). Some scholars also refer to this process as reconditioning, reprocessing, or restoration (Bakker et al., 2014). This process begins with the complete disassembly of the product, where each component is inspected and cleaned. If necessary, damaged parts are repaired or replaced. The final product may even represent an upgrade over the original if new parts are incorporated (Hatcher et al., 2014). While remanufactured products are expected to perform "like new," the retained quality is often described as "up to original state". However, some author recognize that their lifespan may be shorter than that of new products due to the use of recycled components (Gehin et al., 2008).

The remanufacturing process is a resource-efficient strategy that extends the lifespan of component parts, thereby enhancing sustainability (Kjaer et al., 2018). (Gehin et al., 2008) suggest that incorporating new parts can upgrade a product compared to its original state. The term "remanufacture" is particularly relevant when a product's overall structure remains unchanged while many components are replaced or repaired, effectively upgrading it to a more advanced state. This practice not only prolongs product usage but also minimizes environmental impacts by enhancing resource recovery (Kurniawan et al., 2022). It plays a crucial role in product recovery and life extension (Kirchherr et al., 2023), with studies showing that multiple remanufacturing cycles can significantly reduce CO2 emissions (Lieder et al., 2017). The economic advantages of remanufacturing are highlighted by Guide & Van Wassenhove, (2009), who note its potential to generate additional revenue through reconditioning products for resale (Kamble & Gunasekaran, 2021). Singhal et al., (2020) propose a strategic framework that integrates remanufacturing into broader business strategies and supply chain operations, emphasizing the need for a holistic perspective. Lieder & Rashid, (2016) compare resource-conservative manufacturing with remanufacturing, emphasizing the importance of multiple product lifecycles and the conservation of energy and materials. Furthermore, Khalid and Peng explore remanufacturing as an enabling technology within Industry 4.0, suggesting that advanced technologies can enhance the efficiency of remanufacturing processes. However, the feasibility and economic viability of remanufacturing depend on several factors, including product design, technological advancements, and market demand for remanufactured goods. As such, while remanufacturing presents significant opportunities for sustainability and economic growth, its successful implementation minimizes the wasted lifecycle of products and components.

R3 Recycle:

Recycling signifies "any recovery for any purpose" and has emerged as a crucial strategy for reprocessing materials into raw materials, thereby reducing the need for virgin resources. This process involves the recovery of materials, minerals, and energy to maximize resource efficiency by reusing products and materials at the end of their useful lives, ultimately providing economic value across multiple lifetimes (Grafström & Aasma, 2021; Lieder & Rashid, 2016; Tukker, 2015).

This strategy, aimed at closing resource loops focus on reusing materials through recycling and recovering recycled materials to avoid reliance on newly mined or virgin resources (Ghisellini et al., 2016; Kurniawan et al., 2022). Recycling encompasses a series of activities including the collection, sorting, processing, and repurposing of discarded materials. During this process, multiple quality levels may be employed to effectively separate and process waste. Advanced technologies such as shredding and melting are often utilized to extract high-purity materials from post-consumer and post-producer waste streams (J. Yang et al., 2022).

Moreover, recycling also occurs in business-to-business contexts, where production waste is recycled before it becomes mixed with other materials, termed "primary recycling" as opposed to "secondary recycling," which deals with end-of-life products collected by municipal waste systems (Stahel, 2016). Recycling and energy recovery are often easier to implement than other CE strategies, as they require minimal modifications to existing business models. However, these processes typically demand significant energy inputs for collection and processing, which can reduce the overall value retained from the materials. Effective material recovery often involves handling mixed streams of post-consumer or post-production waste, necessitating sophisticated and costly technologies such as shredding and melting to achieve nearly pure materials (Graedel et al., 2011). For certain materials, particularly metals, recycling can occur with minimal quality loss, allowing them to compete effectively with virgin materials. Nevertheless, the high energy requirements for collection and reprocessing can sometimes outweigh the benefits of recycling (Afonso et al., 2021; Ghisellini et al., 2016; Stahel, 2016). Additionally, inefficient processing technologies can lead to lower-quality recycled materials that struggle to compete in the market against products made from pure virgin resources. A significant distinction between recycling and "higher-value" R strategies is that recycled materials often lose the original product's structural integrity, allowing them to be repurposed in various applications (Kurniawan et al., 2022). Although recycling ranks lower in effectiveness within the R hierarchy, it remains a widely adopted practice (Ellen MacArthur Foundation, 2019; Henry et al., 2020; Lacy & Rutqvist, 2015). Hence, recycling plays a crucial role in minimizing the loss of embedded material value by recovering useful materials.

2.7 Implementation levels of Circular Economy

The implementation of CE is essential for assessing its effectiveness and impact across various value drivers. A holistic approach that considers the interactions between micro, meso, and macro levels is necessary to fully grasp the implications of CE implementation. Achieving significant progress in transitioning to a CE demands synchronized efforts across these levels, underscoring the importance of a cohesive and collaborative strategy (Ghisellini et al., 2016; Murray et al., 2017).

Macro-level initiatives are actions undertaken by governments and policymakers to facilitate the transition to a CE (Masi et al., 2018). The macro level emphasizes and promotes regional development for CE implementation (Murray et al., 2017; Yuan et al., 2006). The success of CE adoption heavily relies on supportive government policies and regulatory frameworks that include establishing legal frameworks for R strategies, implementing environmental taxes, and offering financial incentives for businesses embracing CE. A notable example is the EU Circular Economy Package, initiated by the European Commission in 2014, which serves as a comprehensive action plan to promote circular practices across member states.

On the opposite side, the implementation of CE strategies at the micro level is primarily driven by individual companies and manufacturers, as emphasized by Franco, (2017). Micro-level initiatives are crucial for advancing CE, as they focus on the specific actions of firms and organizations. However, achieving broader outcomes necessitates collaboration among various stakeholders. At this level, businesses are encouraged to adopt eco-design and cleaner production approaches, which can influence behaviours across all business activities.

At the meso level, the focus shifts from a single corporation to inter-firm cooperation via industrial symbiosis to build so-called eco-industrial parks, or to supply chains and districts. Effective CE implementation at this level requires transparency and cooperation along supply chains, as well as the development of a supportive ecosystem that includes collaboration between various stakeholders, such as suppliers, manufacturers, and local governments.

Industry associations can play a crucial role in facilitating the sharing of best practices, knowledge transfer, and the establishment of guidelines that can assist businesses in transitioning to circular practices. As mentioned above, CE initiatives that are linked to the meso-level include the creation of eco-industrial parks, which are shared properties on which firms collaborate to make better use of available resources (Masi et al., 2018).

Despite the significant potential benefits of CE, progress in its implementation at micro, meso, and macro levels has been relatively slow (Grafström & Aasma, 2021). To effectively realize the goals of CE and achieve sustainable development, it is essential to establish clear indicators, including levers, enablers, and drivers that facilitate this transition. Various studies highlight the importance of these indicators in addressing the challenges faced during CE implementation across different sectors (Elia et al., 2017).

2.8 A Framework for Circular Economy levers and Enablers

To systematically understand the complex relationships between various indicators, such as enablers, levers, and potential benefits in CE, a Levers-Enablers research framework was developed by

Bressanelli et al., (2021) as shown in Figure 2. 4. This framework serves as a practical tool for implementing CE practices at the micro level within organizations. It categorizes the factors that facilitate CE adoption into two main components: levers, which are specific tools and practices that organizations can implement, and enablers, which are the contextual conditions that support these implementations. Identifying specific levers empowers organizations to make informed strategic decisions regarding resource allocation for maximum impact during their transition to a CE.

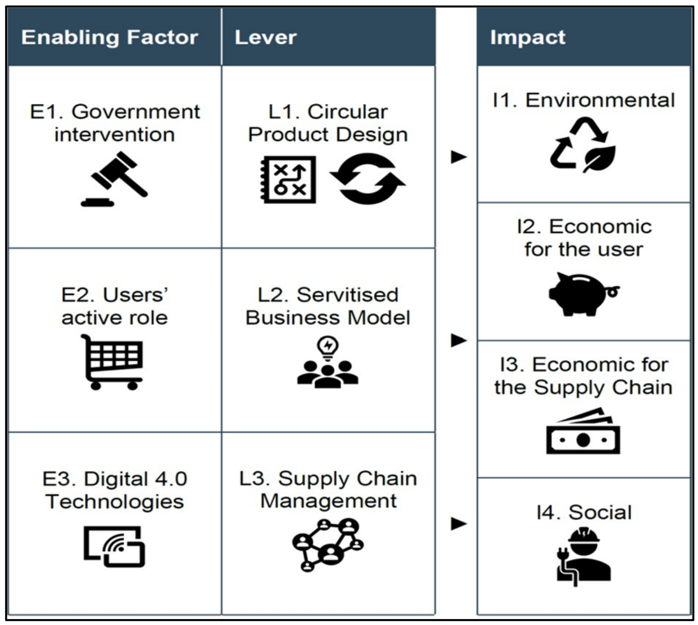


Figure 2. 4 Circular economy Enablers-Levers Framework (Bressanelli et al., (2021))

Levers are defined as actionable strategies that companies can employ to move towards a circular model. According to Bressanelli et al. (2021), common levers include circular product design, servitised business models, and effective supply chain management. These levers are characterized by their endogenous nature, meaning they are directly influenced by organizational decisions and investments. While these levers are critical for implementing CE practices, they may not be sufficient to cover all operations management processes in a manufacturing firm. The complexity of modern manufacturing operations often requires a more comprehensive approach that encompasses additional levers. Current frameworks do not explicitly optimize production processes for circularity, which is essential for minimizing waste and enhancing sustainability. Regular maintenance practices are vital for extending product life and ensuring optimal performance; thus, incorporating maintenance strategies as a lever could significantly promote longevity and waste reduction. While supply chain management includes reverse logistics, focusing on reverse logistics as a distinct lever could enhance recovery efforts for end-of-life products. This entails developing systems for the effective collection, sorting, and processing of returned items. Additionally, strategies specifically targeting end-of-life product management, such as disassembly for recycling or remanufacturing should be recognized as separate levers to ensure sustainable handling of products once they reach their end of life.

Enablers refer to external conditions that facilitate the implementation of levers, including digitalization, government interventions, and active user engagement. Enablers are exogenous factors that create a supportive environment for circular initiatives, making them essential for successful CE adoption.

The framework also highlights the potential benefits derived from effectively applying levers and enablers, categorized under environmental, economic, and social dimensions. By leveraging these strategies within a supportive context, organizations can achieve significant sustainability outcomes. Overall, the Levers-Enablers Framework offers a structured approach to understanding how CE principles can be effectively implemented within organizations. By distinguishing between actionable strategies (levers) and supportive conditions (enablers), this framework provides valuable insights into achieving sustainability goals through CE practices.

2.9 Industry 4.0 as an enabling factor

The scientific literature identifies Industry 4.0 and digital transformation technologies (I4.0-DT) as crucial enablers for transitioning to a CE aimed at achieving environmental sustainability. However, this transition faces various challenges, including technical, organizational, cultural, and financial barriers. The I4.0-DT offers opportunities for companies to navigate these hurdles while enhancing sustainability and competitiveness (Tavera Romero et al., 2021). I4.0-DT represents a significant shift in industrial value chains, where interconnected devices facilitate continuous information exchange among machines and humans. This digital transformation is crucial for implementing CE practices at the micro level, particularly in resource management and waste reduction through improved data management throughout a product's lifecycle. Further, it facilitates the development of circular business models (Huynh, 2022; Ingemarsdotter et al., 2020; Salvador et al., 2021), such as product-as-a-service, which encourages sustainable consumption by retaining product ownership with manufacturers. It enhances supply chain transparency, supported by technologies like blockchain, ensures secure tracking of materials and compliance with circular practices, improving stakeholder coordination. Moreover, Industry 4.0 technologies can significantly boost the performance of small and medium-sized enterprises (SMEs) by increasing productivity, flexibility, responsiveness, and environmental performance (Neri, Negri, Cagno, Franzò, et al., 2023). Bressanelli et al., (2022) identify several key functionalities of I4.0-DT, including improved product design, monitoring and tracking product activity, providing technical support, preventive and predictive maintenance, optimizing product usage, upgrading products, and enhancing renovation and end-of-life activities. Industry 4.0 technologies offer a range of capabilities that can significantly enhance industrial systems, with their effectiveness varying based on the complexity of the system (Oztemel & Gursev, 2020). These capabilities are categorized into four levels: Monitoring, where technologies oversee processes, safety, and maintenance, providing alerts for potential issues; Control, which builds on monitoring by analysing historical data to implement corrective actions during abnormal situations; Optimization, utilizing control data to improve outcomes through system modelling and simulation, acting as a decision support system; and Autonomy, the highest level where systems learn from results and make decisions independently based on provided databases. Collectively, these capabilities contribute to improved productivity, flexibility, responsiveness, and environmental performance in industries.

However, as I4.0-DTs continue to emerge, industries and companies adopt these technologies at varying rates, influenced by their specific operational requirements and processes. This variability has led to the absence of a universally accepted classification system based on their capabilities with mutually exclusive categories. Consequently, the literature reflects multi-interpretations and categorizations of I4.0-DT technologies. For example, the Boston Consulting Group identifies nine foundational technologies for I4.0, including Big Data, Autonomous Robots, and the Internet of Things (Russmann et al., 2015). Researchers like Dantas et al., (2021) and Taddei et al., (2022) have utilized this classification to explore the relationship between Circular Supply Chains (CSC), Circular Economy (CE), and I4.0. In contrast, Rosa et al., (2020) focused on five key I4.0 technologies relevant to CE, while Lopes de Sousa Jabbour et al., (2018) adopted a narrower classification of four technologies as defined by Kang et al., (2016). Zhong et al., (2017) categorized I4.0 into four categories from an intelligent manufacturing perspective, emphasizing the role of Information and Communications Technology (ICT) in integrating various technologies for data management. Further, Nascimento et al., (2024) classified I4.0 technologies based on smart production systems into three distinct types, and Bag et al., (2020), concentrated on four crucial I4.0 technologies for smart logistics and green supply chains. Kristoffersen et al., (2020)focused on three essential technologies—IoT, Big

Data, and Data Analytics—aimed at enhancing resource management for CE. Bressanelli (2021) examined five technologies within an enabler-lever framework, while Bai et al., (2022) expanded CE and sustainability discussion by including 13 different technologies, incorporating nanotechnology into the analysis. Garcia-Muiña et al., (2018) added Enterprise Resource Planning and Manufacturing Execution Systems to the conversation regarding circular business models. Lastly, Rajput & Singh, (2019) considered a comprehensive list of technologies including IIoT, Cloud Computing, Big Data, Simulation, Augmented Reality, Additive Manufacturing, and Cybersecurity.

Overall, the literature on the intersection of I4.0-DT technologies and CE reveals a fragmented landscape, with researchers identifying varying numbers and types of technologies. Different studies have examined the role of digital technologies in supporting CE, highlighting a range of I4.0 technologies including artificial intelligence, machine learning, Big Data analytics, blockchain, cloud computing, the Industrial Internet of Things (IIoT), additive manufacturing, robotics, cybersecurity, global positioning systems, information and communications technology, mobile technology, nanotechnology, simulation, sensors and actuators, digital twins, horizontal and vertical systems, and augmented reality. This comprehensive view indicates that while there is significant interest in the application of I4.0 technologies to enhance CE practices, a unified understanding is still lacking.

Digital technologies and Industry 4.0 (I4.0) include a broad spectrum of technologies and systems designed for industrial processes. These technologies can be classified in various ways according to their complexity, functional capabilities, integration levels, and the degree of automation. For this research, the study reviewed and adopted an I4.0 classification presented by Paschou et al., (2018) and Russmann et al., (2015) to investigate the nexus between CE and Industry 4.0 (I4.0) technologies. This classification identified nine key technologies relevant to the research, including the Internet of Things (IoT), Big Data Analytics (BDA) (including Machine Learning and other Artificial Intelligence methods), Cloud Computing (CC), Blockchain & Cybersecurity, Cyber-physical systems (CPS) (such as digital twins, simulation), Augmented and Virtual Reality (ARVR), Additive Manufacturing & 3D Printing (AM), Industrial Robotics (I.R.), and Horizontal and Vertical Integration (HVI). Table 2. 4 Define I4.0-DT technologies categorization and definition.

Table 2. 4 Categorization of I4.0-DT

Digital Technology (DT)	Description
Internet of Things (IoT)	Internet of Things (IoT), Industrial Internet of Things, or Industrial Internet of Services refers to a network of connected devices that communicate with each other and share data. This technology can be used to track and optimize resource usage, reduce waste, and enhance energy efficiency using wireless and wired technologies, such as short-range, medium-range, and long-range wireless technology.
Big Data & Analytics (BDA)	Big Data & Analytics (BDA), Artificial Intelligence (AI), and Machine Learning refers to a technology, where it discusses the collection, analysis, and interpretation of large and complex datasets.
Cloud Computing (CC)	Cloud Computing refers to the technology that permits the storage and analysis of massive amounts of data on remote servers. This technology can reduce the need for on-premises infrastructure and enable the creation of virtualized environments that can be easily duplicated and shared
3D Printing/ Additive manufacturing (AM)	Additive manufacturing and 3d printing (AM) consider as the fabrication technique involves the progressive deposition of material onto a substrate, layer by layer, enabling the creation of high-complexity parts that personalized goods require.
Blockchain and Cybersecurity (BLC)	Blockchain technology is a secure, decentralized system for recording transactions. It can be used to track supply chain activities, improve traceability, and ensure product authenticity, control and protection of processes and systems that operate online, identification of changes and vulnerabilities, and verification of authorized users.
Augmented or Virtual Reality (AR/VR)	Augmented reality or Virtual reality (AR/VR) refers to the merging of real and virtual worlds to produce new environments and visualizations where physical and digital objects co-exist and interact in real time.
Cyber physical system (CPS), Digital twin and simulation (CPSDTS)	Cyber-physical systems, Simulation or digital twin or related term considered as the technology that integrate physical and virtual components, virtual model of physical object to monitor and control manufacturing processes.
Industrial Robotics (IR)	Industrial robotics encompasses the deployment of robots in industrial environments for the purpose of automating tasks, enhancing efficiency, productivity, flexibility, facilitating interactions with other machines, and ensuring safe collaboration with humans.
Horizontal vertical integration (HVI)	Horizontal and Vertical integration software discusses the integration of the structural changes in the organization, the management of physical objects, and the establishment of connections with information systems (e.g. Enterprise resource planning).

2.10 I4.0 adoption for CE: research gaps and challenges

Studies regarding DTs are either focused on environmental sustainability, waste management, and resource efficiency, or are centred on digital technology innovation (Diaz et al., 2021). Despite the extensive literature on Industry 4.0 (I4.0) technologies and their relationship with CE, a significant gap exists in understanding how these areas are evolving together. Specifically, current research highlights a need to shift from exploratory and descriptive studies towards confirmatory and prescriptive frameworks that better define the objectives and methodologies within the CE-I4.0 nexus (Birkel &

Müller, 2021; Rosa et al., 2020). This transition is essential for effectively integrating digital technologies into CE practices and for advancing the overall understanding of their combined impact on sustainability and resource management. This section discusses some of the common research gaps on Industry 4.0 adoption for CE; however, the subsequent chapters will explore these research gaps in more detail.

There is a growing recognition of the need for a solid theoretical foundation for the relationship between CE and Industry 4.0 (I4.0) technologies; however, empirical evidence supporting the effectiveness of I4.0 in promoting circular practices at the micro level is lacking. Current studies often highlight this absence of quantitative data, which is essential for establishing a robust theoretical framework linking digital technologies to circular practices (Neri et al., 2024). This gap indicates a pressing need for researchers to formulate hypotheses and conduct studies that provide concrete evidence on how I4.0 technologies can facilitate cleaner production, enhance environmental sustainability, and improve circularity across various industries.

As organizations increasingly adopt technologies like the Internet of Things (IoT), big data, and blockchain, understanding their combined potential to enhance resource efficiency, reduce waste, and improve sustainability is crucial. However, comprehensive studies investigating how these technologies can effectively collaborate within CE frameworks are lacking. Current research often neglects the interdependencies between the technologies within value chains for achieving circularity. Despite the growing recognition of the synergistic effects of digital technologies in enhancing CE practices, there remains a significant research gap concerning the transparency and communication of sustainability benefits across value chains. Specifically, research should investigate the mechanisms through which digital technologies can enhance stakeholder engagement and trust in circular initiatives, as well as their role in driving broader adoption of sustainable practices (Rejeb et al., 2022). Addressing these gaps through empirical research and a holistic view is vital for advancing CE strategies across different sectors in manufacturing.

Chapter 3. Methodology

This chapter outlines the methodological foundation of the research, providing a rigorous and well-structured approach to addressing the core themes and answering the thesis's research question. Research methodology is described as "an operational framework that organizes facts to clarify their meaning" and as "a procedural framework guiding the research process" (Tobi & Kampen, 2018). It ensures a systematic and coherent investigation of the research objectives.

This thesis outlines a comprehensive and multi-faceted methodological approach. The study employed two distinct methodological perspectives: a literature-oriented methodological perspective and a practice-oriented methodological perspective as shown in Figure 3. 1 (Karlsson, 2016). The literature-oriented approach focused on exploring the theoretical framework by systematically analysing, synthesizing, and critiquing existing literature on CE, Industry 4.0 and environmental sustainability to answer Research Question 1 & 2. The primary purpose of this step is to contextualize the state of art and to identify critical gaps in knowledge, justifying the necessity of the research and framing its novelty.

The practice-oriented perspective is suitable for investigating new phenomenon by posing "how" or "why" questions hence employed to address Research Question 3. It enables a deep understanding of both the complexity and the fundamental nature of the phenomenon under examination (Voss et al., 2002). It allows for an in-depth exploration of specific phenomena, contexts, or real-world applications. Further, the Survey methodology is used by collecting quantitative data from a larger sample, testing hypotheses, and validating patterns observed in the literature. This two-step approach enhances the reliability and validity of the conclusions by mitigating the limitations associated with both methodologies. The literature-oriented perspective eliminates redundancies and introduces novelty, while the practice-oriented approach enhances the depth and broader applicability of the findings.

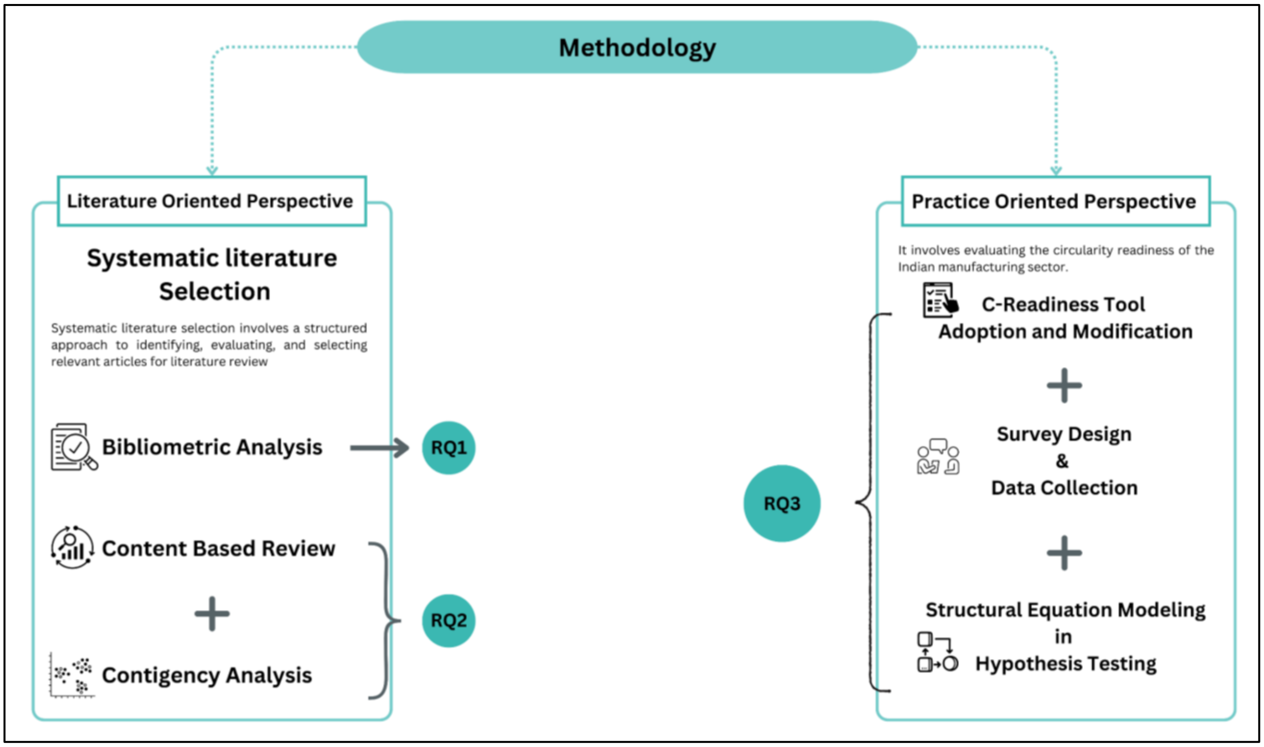


Figure 3. 1 The overall methodology followed in this study

3.1 Literature Oriented Perspective

Literature Oriented perspective is conducted due to its exploratory-explanatory objectives. After the literature selection, the sequential approach includes bibliometric analysis, content analysis, and contingency analysis, which were carefully selected to systematically build foundational theoretical knowledge while addressing methodological limitations at each stage. Bibliometric analysis, while effective in mapping broad scholarly trends through quantitative metrics (e.g., citations, keyword frequencies), risk oversimplifying complex themes by providing only a broad overview without examining in depth (Zhi & Ji, 2012). To address this limitation, content analysis is used to examine different aspects through qualitative interpretation of textual and thematic elements (Gold et al., 2010). This phase enriches the data by uncovering contextual and narrative insights, thereby mitigating bibliometrics' tendency to overlook semantic depth (Osgood et al., 1995). Finally, contingency analysis examines how contextual variables (investigated in content-based analysis) interact with each other identified in prior stages. So, this is provided with a thematic framework that structures the interrelated themes. These analyses are discussed in detail below.

3.1.1 Bibliometric analysis

Bibliometric analysis is a widely used tool for quantitatively analyzing literature published in specific research areas. By employing a range of indicators and methods, it can uncover the structural characteristics and patterns of underlying science and technology, as well as assess development trends and identify potential future research directions (Zhang et al., 2017). Although this is not a new approach, bibliometric methods have already been used as instrumental in mapping fields such as management science, where they have introduced quantitative rigor into the traditionally subjective evaluation of literature (Di Stefano et al., 2010; Ramos-Rodríguez & Ruíz-Navarro, 2004).

Bibliometric analysis allows researchers to base their findings on aggregated bibliographic data produced by other scholars who express their perspectives through citations, collaborations, and publications (Li et al., 2009). When this data is systematically aggregated and analyzed, it puts forward insights into the field's structure, social networks, and topical interests. Bibliometric analysis offers a quantitative approach to describing, evaluating, and tracking published research. These methods are supported in systematic literature reviews even before content-based analysis begins, by guiding the researcher to the most influential works and mapping the research field without subjective bias.

Bibliometric methods serve two primary purposes: performance analysis and science mapping analysis (Cobo et al., 2011). These methods encompass five major techniques: citations, co-citations, bibliographic coupling, co-authorship, and co-word analysis (Zupic & Čater, 2015). Performance analysis aims to evaluate research and publication output by examining metrics such as publication counts, citation frequencies, and impact factors. This approach allows for the assessment of academic productivity and influence of individual researchers or research entities such as universities or geographical regions. Further, science mapping analysis employs quantitative approaches to visualize the structure and evolution of scientific fields and disciplines (Boyack & Klavans, 2014). By constructing structural representations of scientific domains, science mapping facilitates the examination of how disciplines, fields, specialties, and individual papers are interconnected. This comprehensive approach enables researchers to gain insights into the relationships and dynamics within and across scientific domains, supporting a deeper understanding of knowledge structures and research trends. In science mapping analysis, two distinct citation analysis methods are frequently employed: bibliographic coupling (Garfield, 2001) and co-citation (Small, 1973). Bibliographic coupling occurs when two articles reference a common third article in their bibliographies, suggesting a likelihood that the two articles address related subject matter. The "coupling strength" between two articles increases as they share more citations with other works (Kessler, 1963). Conversely, co-citation analysis examines the frequency with which two articles are independently cited together by one or more subsequent publications (Small, 1973).

The bibliometric analysis started with searches using specific keywords that effectively capture the research theme and establish clear selection criteria. The bibliometric analysis depends on the source of the bibliographic data. Bibliographic data for indexed documents, including article title, article type, authors, author institutional affiliations, keywords, abstract, number of citations, journal name, publisher name and address, publication year, volume, issue number, and a list of cited references, is available from different databases. The Social Sciences Citation Index (SSCI) from Web of Science (WOS) and Scopus databases are the most frequently used for bibliometric analysis and bibliographic data. The most commonly used bibliometric software packages support the importing of data from Scopus and WOS (Donthu et al., 2021; Zupic & Čater, 2015). The Scopus database was chosen for our research due to its broader journal coverage, its capability to better capture interdisciplinary research areas, and its extensive metadata coverage, which is crucial for bibliometric analysis (Mongeon & Paul-Hus, 2016). Further, the analysis starts with data preprocessing, which involves cleaning the data by removing duplicate or incomplete cited references. This step addresses issues like the presence of multiple versions of the same publication and different spellings of an author's name. The data is consolidated, with author or journal entries aggregated under a single spelling, and all other variations eliminated. Similarly, for co-word analysis, different representations of concepts must be pre-processed and cleaned. For example, the concept of "circular economy" can be discussed in various forms, such as "circular economy" (singular), "circular economy practices", "CE" (abbreviation), and "the circular economy". Furthermore, for standardization, words should be converted to their root forms.

Fourth, Bibliometric analysis employs various software tools to transform raw bibliographic data, such as exports from Web of Science and Scopus, into similar matrices for further analysis. Several key software tools have gained popularity among researchers, including VOS viewer (van Eck & Waltman, 2014), Gephi, Bibliometrix (Aria & Cuccurullo, 2017), CiteSpace (Chen, 2006), SciMAT (Cobo et al., 2011), BibExcel (Persson et al., 2009), and Sitkis (Schildt & Mattsson, 2006). Additionally, exploratory factor analysis, cluster analysis, and multidimensional scaling can be performed using R and SPSS analytical tools. For instance, VOSviewer, developed at Leiden University, offers versatile visualization capabilities for bibliometric networks and supports a wide range of data sources (van Eck & Waltman, 2014). These tools provide various functionalities, including co-authorship analysis, citation network visualization, bibliographic coupling, co-word analysis, and performance analysis of authors, institutions, and journals. These software tools enable the processing, analysis, and visualization of large bibliographic datasets, offering insights into research trends, collaboration networks, and knowledge structures. The final step in bibliometric analysis involves interpreting the findings. Documents that appear in the analysis need to be thoroughly examined to reach valid conclusions.

This research employed four bibliometric analysis methods, including co-author analysis, co-word analysis, citation analysis, and bibliographic coupling. We used co-author analysis, co-word analysis, citation analysis and bibliographic coupling in this research to find the most influenced research articles, factors determining co-authorship, dynamics of the conceptual structure of a field and intellectual structure of recent/emerging literature. These methods allowed us to identify influential collaboration patterns, factors on co-authorship, the dynamic evolution of the conceptual structure, and the intellectual structure of recent and emerging literature. The data was obtained from the Scopus database, which contains information about thousands of scholarly publications, including authorship, affiliation, and citations. Bibliographic coupling was used to establish the similarity relationship between articles (Martyn, 1964). The analysis in this study serves to identify clusters of related articles. The bibliometric maps were constructed using VOS viewer software. In this research, Bibliometric analysis is used to enhance the rigor and structure of further literature reviews. While bibliometric analysis predominantly focuses on quantitative metrics, it often lacks rigorous qualitative insights. By incorporating content analysis, researchers can enrich systematic literature reviews, producing a more detailed and thorough insight into the research development.

3.1.2 Content Based Analysis

In this research, Bibliometric analysis is used to enhance the rigor and structure of further literature reviews. However, bibliometric analysis is primarily quantitative, so the rigorous qualitative aspects are missing (Wallin, 2005). Therefore, Gaur & Kumar (2018) suggested to supplement the analysis with a qualitative content-based analysis. Content analysis can enhance systematic literature reviews by providing a more comprehensive overview of the research landscape.

A systematic literature review aims to show the current state of research in a particular field. It summarizes existing research by finding patterns, themes, and research gaps in academic work, thus contributing to theory development (Tranfield et al., 2003). It is an unbiased, transparent, and objective approach that enables scholars, scientists, and academics to identify relevant research based on citation frequencies and predefined criteria. Systematic Literature Reviews (SLRs) can be categorized into two types (Webster & Watson, 2002). The first addresses mature topics with an established body of literature, aiming to synthesize and extend existing knowledge through a proposed conceptual model. The second attempt to identify emerging topics and develop a conceptual model from this nascent theoretical foundation.

Among the different SLR methodologies, content analysis-based studies have been widely adopted. Krippendorf, (2004) defines content analysis as "a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use". This approach can be further characterized as a form of conceptual analysis, evaluating key concepts within the literature (Stock & Boyer, 2009). Seuring & Gold (2012) advocated for the use of content analysis in literature reviews, emphasizing its efficacy in conducting robust SLRs. They also noted that the method's rigor could be enhanced by integrating qualitative approaches with quantitative analysis. Elaborating on the characteristics and application of content-based analysis, Seuring et al., (2020) highlighted its flexibility in data analysis, allowing for either inductive or deductive approaches. However, the researchers emphasized the labour-intensive nature of content analysis, which necessitates meticulous planning, as retrospective modifications are challenging to implement. This constraint often limits the number of studies that can be realistically analysed. To address this, the researchers recommend adopting a comprehensive set of constructs derived from multiple established frameworks. It is generally more practical to initially code a broader set of items and refine the focus later, rather than restarting the analysis to incorporate additional constructs (Sauer & Seuring, 2023).

Our qualitative content analysis followed a three-step research process: Planning the review (material collection), Conducting the review, and Material evaluation, guided by Tranfield et al. (2003) This approach enhances the replicability, traceability, reliability, and validity of the findings (Seuring & Gold, 2012).

Stage 1: Planning the review: This stage involved identifying the need for the content-based analysis, preparing the proposal, and developing the review protocol as outlined in the study's previous sections.

Stage 2: Conducting the review: We initiated the material collection using Scopus databases, chosen for their comprehensive coverage of management and environmental science journals. Keywords and search strings were meticulously designed to capture all relevant articles within the study's scope. Data extraction and coding were performed using Microsoft Excel, where a spreadsheet tabulated codes derived from the theoretical framework and cross-referenced them with individual papers. This involved marking specific cells to indicate the presence of a code within a paper.

Stage 3: Material evaluation: The analysis proceeded in two stages. First, a descriptive analysis was conducted to examine the temporal distribution of the 195 selected journal articles and their publication sources. Second, a content analysis was performed using the initially identified theoretical lenses. This phase focused on constructs related to the circular economy, Industry 4.0 technologies, and operations management processes, enabling deeper insights into each analytical category.

Content-based reviews can be susceptible to researcher bias and may lack methodological rigor (Tranfield et al., 2003). Furthermore, content analysis results are typically confined to individual constructs, thus limiting the scope. To address the limitations of content-based reviews, we conducted a contingency analysis. This approach, proposed by Krippendorff (2012) used quantitative methods to uncover relationships between constructs and draw broader, statistically supported conclusions.

3.1.3 Contingency-based analysis

Beyond using content analysis and qualitatively interpreting the results, applying contingency analysis provides an opportunity to quantitatively assess links among constructs and items (Krippendorff, 2012). Developed by Osgood et al., (1995), this method builds on the observation that "symbols often occur in pairs of opposites, that concepts or ideas form clusters," allowing us to identify correlations between pairs while avoiding the assumption of causality. However, interpreting these correlations requires theoretically grounded reasoning to explain causal linkages. Recently, two types of contingency analysis have been discussed in the previous literature based on the adopted unit of analysis. For example, De Lima et al., (2022) used the entire paper as the unit of analysis, where the frequency count of constructs was calculated by counting a construct if it was mentioned at least once in a paper. However, each paper contributed only one count per construct, regardless of how many times it appeared. Furthermore, correlations were derived based on two constructs appearing together in a single paper. In contrast, Tröster & Hiete, (2018) analysed individual text passages (e.g., arguments or ideas) as units, offering in-depth understanding and stronger statistical validity for thematic patterns (Hettiarachchi et al., 2022). Contingency analysis leverages the frequencies of individual codes collected during content-based analysis to identify pairs of categories that co-occur in research papers more frequently than expected based on their individual occurrence rates. This method allows for a better understanding of the co-occurrence of the constructs and their relationships, supported by statistical validation. Contingency tables (or cross-tabulations) are used to assess these relationships, and statistical significance is determined through various tests, including Pearson's chi-squared test, to identify significant associations (Pearson, 1904). Based on the identified interrelations from the contingency analysis, causal loop diagrams are constructed to visually depict the respective interconnections and determine the most relevant relationships.

This integrated approach combines bibliometrics, content analysis, and contingency testing to enhance methodological rigor. Bibliometric patterns guide content analysis, which in turn informs contingency testing. The framework not only bridges methodological gaps but also enhances the validity of findings by systematically integrating exploratory mapping, explanatory interpretation, and contextual validation.

3.2 Practice-Oriented Perspective

This chapter discusses the survey-case study methodology, widely recognized as suitable for theory-building research in areas of research that have not been extensively studied (Eisenhardt & Graebner, 2007). We employ an abductive approach, starting with preliminary theoretical frameworks to guide the research, which are then shaped with empirical findings (Dubois & Gadde, 2002; Karlsson, 2016). The Exploratory survey research is conducted in the initial phases of studying a phenomenon to expand on the relatively underexplored concepts. It aims to identify which aspects of a topic to measure, determine effective measurement methods, and uncover new dimensions of the phenomenon when no existing model or framework is available. This foundational work helps guide more structured, in-depth research later by refining focus and methodology.

In our practice-oriented perspective, we followed a two-step approach. In the preliminary step, we adopted a modified version of the C-readiness tool developed by Bressanelli & Saccani, (2025). Additionally, we designed a survey to implement this tool, assessing circular readiness in the Indian manufacturing context. Finally, we applied structural equation modelling to develop the theoretical construct and understand the principles underlying this framework. Each step of the process is described and discussed in detail below.

3.2.1 C-readiness Tool

The transition to a Circular Economy (CE) presents a significant challenge for manufacturing companies, as it requires systemic transition at the micro level in product design, production processes, business models, and supply chains (Pigosso & McAloone, 2021). The scientific literature has increasingly focused on the Circular Economy (CE) in recent years, yet it has offered limited practical guidance on implementing CE within manufacturing organizations. To address this gap, the C-readiness assessment tool has been developed to support manufacturing companies in transitioning to CE. These frameworks evaluate an organization's current level of circularity and provide a preliminary evaluation of its readiness for this transformation. However, previous works investigating CE readiness assessment for manufacturing organizations at the micro level have been scattered and inconsistent. By addressing these limitations, Bressanelli & Saccani, (2025) developed a new tool (called C-Readiness) for assessing the readiness of manufacturing companies for the Circular Economy and for prioritizing Circular Economy actions for decarbonization. To design the tool, the author conducted a comprehensive review and critical comparison of nine existing seminal tools for measuring circularity. The author identifies several limitations in current Circular Economy (CE) assessment tools for manufacturing firms. First, there is a lack of consensus on the evaluative criteria and key indicators necessary to assess organizational readiness for CE adoption (Camacho-Otero & Ordoñez, 2017; de Oliveira & Oliveira, 2023). A significant concern is that some tools do not comprehensively cover all key CE implementation areas. For instance, they may neglect important aspects such as the supply chain perspective (Evans & Bocken, 2016) and circular opportunities within production processes (Sacco et al., 2021). Furthermore, these tools focus on evaluating a company's readiness for CE transition but often overlook the crucial aspect of decarbonization. Consequently, manufacturing firms often lack sufficient guidance on how to prioritize strategies that integrate circular economy principles with carbon emission reduction goals. These limitations collectively contribute to a gap between CE assessment and practical implementation. The author suggests that more holistic and integrated assessment approaches are needed to guide manufacturing firms effectively in their transition towards a circular economy with reduced carbon emissions. However, the tool has limitations: it uses qualitative assessments that are simpler to implement but less accurate than quantitative evaluations, and it is designed for manufacturing companies, applied at a micro level. The development of the conceptual tool comprises four sequential steps. First, identifying key implementation areas to establish the scope of analysis. Second, listing and selecting critical evaluation elements relevant to the framework. Third, converting these elements into evaluative questions accompanied by a scoring system (e.g., likeart rating scale). Finally, establishing systematic linkages between the identified implementation areas and potential decarbonization opportunities, guided by Life Cycle Assessment (LCA) methodologies.

The tool consists of 33 evaluation elements categorized into six areas critical for implementing Circular Economy (CE) in manufacturing organizations, as shown in Table 3. 1 . A five-level scale was then designed to assess each evaluation element. The organization's comprehensive C-Readiness score is calculated as the weighted average of scores across these six areas. To prioritize Circular Economy actions aimed at decarbonization, this score is combined with the carbon footprint of the company's representative product. A Life Cycle Assessment (LCA) of the product is conducted to segment its carbon footprint across different life cycle stages: raw materials extraction (15%), production and assembly (10%), distribution and transportation (5%), usage (65%), and end of life (5%). The tool then correlates Circular Economy investment areas to these life cycle stages, indicating where targeted investments can reduce environmental impact. Further, a prioritization matrix categorizes areas based on their carbon footprint relevance and C-Readiness score, helping companies strategize their investments in circular economy areas. The C-Readiness model has been implemented in a web platform to automate data collection and the reporting of results. To assess Indian manufacturing companies, the C-readiness tool is modified to incorporate Indian standards and government regulatory norms. Prior to conducting the study, a pilot study involving 10 companies was carried out to validate the tool's applicability. Finally, a descriptive statistical analysis was conducted using data collected from the C-readiness assessment tool to provide a comprehensive understanding of the Indian manufacturing industry's readiness for adopting circular economy principles.

Table 3. 1 Key Areas and Evaluation Elements for Circular Economy Readiness for Indian manufacturing firm (Adopted form Bressanelli & Saccani, 2025)

Key Area	ID	Evaluation Elements
1. Product Structure	1.1	To what extent the materials used in your products are biodegradable, recyclable, and/or recycled?
	1.2	Does your product contain toxic materials, such as materials subject to India Chemical Management and Safety Rules (CMSR) directives and/or disposal restrictions?
	1.3	Does your product contain critical materials from the availability and supply perspective? (e.g. antimony, fluorite, phosphorus, magnesium…)

	1.4	Do you have any environmental product certification (e.g. ECOMARK, C2C, GRS...)?
	1.5	To what extent were the product or its parts or components designed in a circular manner?
2. Production Process	2.1	How much do production scraps and rejects affect the overall produced volumes, in terms of amount of wasted material (by weight, volume, …)?
	2.2	Is there a monitoring system on consumption (of energy, water, compressed air, etc.) generated by the process/production system?
	2.3	Do you use energy from renewable sources?
	2.4	Have you started any industrial symbiosis projects?
	2.5	Is there an environmental management system in the company?
3. Business Model	3.1	Do you offer a line of used (second-hand) and/or remanufactured products?
	3.2	Do you have an offer proposal alternative to the sale of the good (e.g. long-term lease, pay-per-use/performance…)?
	3.3	Do you offer the possibility to share the product among multiple users?
	3.4	Do you use any platform for the buying and selling of production scraps/rejects?
	3.5	To what extent do you collaborate with suppliers and/or partners of the value chain to co-design products and processes with a view to Circularity?
4. Supply chain	4.1	Do you track your product, components and materials along the logistics chain to prevent them from being released in the environment (e.g. through sensors, Internet of Things, RFID)?
	4.2	Do you select your suppliers also considering environmental and/or social criteria? (e.g. suppliers with lower environmental impact and/or zero-km products supplied through short supply chain)
	4.3	What materials do you use for the packaging of your products?
	4.4	Do you optimize your distribution network also from the environmental impact minimization point of view?
	4.5	Do you prefer means of transportation with reduced environmental impact, i.e. low-emission means of transportation (e.g. rail transport instead of road transport, electric vehicles, …)?
5.Regeneration and End of life	5.1	Does your company organise any initiatives to recover end-of-life products, components and materials?
	5.2	Do you manage and control activities to recover end-of-life products (logistics infrastructure, sorting platform, etc.)?
	5.3	Are there any initiatives (also external to your company) to reuse and recondition products?
	5.4	Are there any initiatives (also external to your company) to regenerate components?
	5.5	Are there any initiatives to recycle materials?
	5.6	At the end of the product life, what physical share (in terms of weight, volume, …) of it ends up as landfill waste – and is thereby not used in another way (no reuse, no regeneration, no recycling)?
6. Green Culture	6.1	Did you take any action to reduce or eliminate disposable plastics in the offices and/or in the plant?
	6.2	How is the consumption of drinking water managed in your company?
	6.3	How is tea/coffee consumed in your company?
	6.4	To what extent is plastic used in the canteen area?
	6.5	Do you practice separate collection of waste in the offices and/or common spaces of the

		company?
	6.6	Did you take any action to encourage the sustainable mobility of your employees?
	6.7	To what extent do you communicate your environmental performances within your communication, marketing, promotion strategy?

3.2.2 Survey & Structural Equation Modelling

In this final section, the survey is designed to assess C-readiness in Indian manufacturing, aiming to capture the key aspects and their interrelationships, such as supply chain collaboration, servitized business models, and circular economy practices. To test and validate their relationships, hypotheses are designed and validated through statistical analysis. The survey is a commonly adopted research methodology in management science, supporting the process of translating theoretical domains into empirical domains. It is a systematic research method used to collect quantitative or qualitative data from predefined groups of respondents (e.g., individuals, organizations) through structured questionnaires, interviews, or observational techniques (Karlsson, 2016). This approach is subdivided into multiple interconnected subprocesses: beginning with theoretical framework design, followed by survey design and pilot testing. Subsequent phases include data collection to evaluate the theoretical framework, data analysis, and interpretation of findings. When meticulously designed with appropriate sample sizes, validated instruments, and robust analytical frameworks, surveys offer a powerful means to advance both theoretical and empirical understanding across disciplines such as management, circular economy, and sustainability.

In this section, we discuss the theory-testing survey, a methodology designed to advance knowledge by empirically evaluating hypotheses (Karlsson, 2016). The process begins with operationalizing theoretical constructs, which involves the clear identification, labeling, and definition of all constructs. It then defines the roles of constructs (e.g., independent, dependent, intervening, moderating), key linkages between them, and the anticipated nature and direction of relationships, supported by explanations of why these relationships are expected (Bentler, 1990). It is critical to establish boundary conditions under which the proposed relationships are hypothesized to hold. The methodology's strength lies in its structured design, which standardizes data collection, employs probability sampling to enhance generalizability, and controls for confounding factors through demographic or contextual variables.

A survey of the Indian manufacturing industry was conducted via an online platform-based questionnaire. The researcher then collected and processed the responses, performing data preparation steps such as cleaning the dataset, addressing missing values, assessing reliability, and checking for biases before proceeding to modelling. Following this, Confirmatory Factor Analysis (CFA) was employed to evaluate the measurement model's reliability and validity (Hayes et al., 2017). This entailed defining the measurement model by linking observed indicators to latent constructs and developing a path diagram to visualize these relationships, including indicator loadings and error terms (G. Dash & Paul, 2021). After validating the CFA, structural modelling was conducted to analyse hypothesized relationships between constructs using statistical tools such as regression coefficients. The model's goodness of fit was rigorously evaluated using absolute, incremental, and parsimonious fit indices to assess alignment with observed data.

There are two prominent structural equation modelling (SEM) methods discussed in the literature: covariance-based SEM (CB-SEM) (Byrne, 2013) and partial least squares SEM (PLS-SEM) (Ringle, 2015). Both methods are considered complementary, with the choice between them depending on the research objectives CB-SEM for theory testing and PLS-SEM for theory development and prediction, respectively. When the goal is to test and confirm existing theories, CB-SEM is the more appropriate methodology (G. Dash & Paul, 2021). For this study, CB-SEM was chosen to align with the objective of testing established theoretical relationships. The analysis was performed using IBM SPSS, Amos and Jamovi, software packages selected for their methodological alignment, user-friendliness, and widespread adoption in SEM research (Byrne, 2013; Jamovi, 2024).

Researchers conduct structural equation modelling (SEM) to analyse relationships among constructs by testing hypotheses using statistical tools such as regression coefficients, thereby validating these relationships with empirical data (Hair et al., 2010). Evaluating SEM and measurement models requires various statistical measures and fit indices, which can be divided into absolute, incremental, and parsimonious categories (Hooper et al., 2008). Absolute fit indices assess how well the proposed model fits the data without comparison to an alternative model, determining the match between the sample data and the a priori model. Incremental fit indices compare the model's fit against a baseline null model, reflecting its relative improvement, while parsimonious fit indices penalize model complexity to Favor simpler, more efficient models. Key indices include the chi-square (CMIN/df), which measures discrepancies between predicted and observed covariance matrices (values ≤ 3 indicate good fit, though sensitivity to sample size is a limitation) (Hooper et al., 2008), and the Goodness-of-Fit Index (GFI), reflecting the proportion of variance explained by the model (thresholds ≥ 0.90, ideally

>0.95 for small samples) (Bentler, 1990). The Adjusted Goodness-of-Fit Index (AGFI) adjusts GFI for degrees of freedom, also targeting ≥0.90. The Root Mean Square Error of Approximation (RMSEA) advocates for parsimony, with values ≤0.07 indicating good fit (Steiger, 1980). Residual-based indices include the Root Mean Square Residual (RMR), quantifying residuals between sample and model covariance matrices (values closer to 0 suggest better fit, though interpretation depends on scale properties), and its standardized counterpart, the Standardized Root Mean Square Residual (SRMR), which ranges from 0 to 1 (≤0.05 indicates excellent fit). Normed Fit Index (NFI) compares model chi-square to a null model (≥0.90 indicates good fit), while the Non-Normed Fit Index (NNFI/TLI) favors simpler models and is less sample-size dependent (≥0.90 ideal) (Hooper et al., 2008). The Comparative Fit Index (CFI), focusing on latent variables, follows similar thresholds. Parsimonious measures (PGFI, PNFI, PCFI) penalize complexity, with ≥0.50 generally acceptable (Hayes et al., 2017). Finally, based on SEM findings, researcher synthesize results to draw conclusions. This final step synthesizes the research findings and delivers actionable research implications that can guide future studies or practical applications related to the constructs under investigation.

Chapter 4. Circular Economy, Environmental sustainability and Industry 4.0 technologies: A bibliometric literature review

This chapter serves as the cornerstone of the theoretical foundation for this thesis, presenting a comprehensive bibliometric analysis of articles at the intersection of Circular Economy, Environmental Sustainability, and Industry 4.0 technologies. Building upon the context established in later sections, this chapter aims to find the current state of research, track the field's trajectory, identify knowledge gaps and emerging trends, and provide a holistic understanding of the field's landscape. By employing a rigorous bibliometric approach, this research provides a comprehensive analytical mapping and quantitative overview interdisciplinary research landscape, helping researchers and managers in understanding existing knowledge domains, evaluate current standing, and strategically identify emerging research directions at the intersection of Industry 4.0 technologies, environmental sustainability, and Circular Economy, thereby laying a solid foundation for the subsequent chapters of this thesis and advancing our understanding of these interconnected domains.

4.1 Literature Review Design

4.1.1 Research gap and objective

The scientific literature on CE, I4.0 technologies and environmental sustainability has experienced exponential growth in recent years. Previous research has established connections between I4.0 and CE. For example, Kristoffersen et al. (2020) discussed thorough theoretical and practical review on the smart circular economy paradigm, which explicitly connects the technical mechanisms of I4.0 technologies with the operational strategies of CE. Additionally, further discussions have focused on the design and implementation of circular manufacturing processes, highlighting the integration of CE with I4.0 technologies (Corsini et al., 2023; Fraga-Lamas et al., 2021). Previous studies have also explored the relationships between I4.0 and sustainability, concentrating on sustainability performance, practices, and the impact of various moderating factors (Beltrami et al., 2021; Ejsmont & Gladysz, 2020). Likewise, earlier literature has examined the connections between CE and sustainability, analysing their similarities, differences, and interrelationships at micro, meso, and macro levels (Geissdoerfer et al., 2017; Nikolaou et al., 2021). These reviews have typically analysed a limited number of papers or addressed narrow aspects of the field, as seen in the works of Korner et al., (2020), Montag, (2023) and Nara et al., (2021). This approach has resulted in a fragmented understanding of the broader landscape and the interconnections between these critical areas of research. This fragmentation in the existing literature underscores the need for a more comprehensive approach that synthesizes the complex interactions between CE, I4.0 technologies, and environmental sustainability, paving the way for a deeper understanding of their collective impact on sustainable development and innovation.

While previous literature reviews have attempted to link I4.0 technologies with CE or environmental sustainability, they have not provided a comprehensive overview of the broader subject. To establish this gap, a preliminary analysis of previous literature reviews on CE, I4.0 technologies, and environmental sustainability has been conducted. The results are summarized in Table 4. 1.

Table 4. 1 Previous Literature Reviews on Circular Economy, Sustainability, and Industry 4.0 Technologies.

Article	**Objective, scope, and topics investigated**	**Search database**	**Articles and period coverage**	**Methodology**	**Literature analysis**	**Limitations**
Nikolaou et al.(2021)	To explore the interrelations, parallels, and variances of CE and Sustainability through investigation at micro, meso, and macro dimensions.	Web of Science. Scopus; Google Scholar	Not specifically mentioned (around 4,500 articles); From 2011 to 2021	Bibliometric review	Descriptive analysis	The analysis does not consider I4.0 and discusses no technological solutions for implementing CE and sustainability.
Montag (2023)	To examine theoretical conceptualization of circular supply chain and sustainability	Web of Science; Scopus	127 articles; From 2010 to 2022	Bibliometric analysis	Descriptive and network analysis	I4.0, though crucial, lacked specific discussion. From a bibliometric perspective, only a few articles were considered, and a distinct delineation between sustainability and circularity was absent.
Korner et al.,	To examine the barriers	Web of	78 articles	Bibliometric	Descriptive	The article's scope is

(2020)	of additive manufacturing through the lens of business model innovation and sustainability.	Science; Scopus	From 2006 to 2020	review	analysis and content analysis	technologically limited to additive manufacturing, and it is further limited by insufficient coverage of future scope.
Hettiarachchi et al. (2022)	To conduct a bibliometric analysis on the literature pertaining to I4.0-driven operations and supply chains in the context of the CE	Web of Science	414 articles From 2003 to 2020	Bibliometric review	Descriptive analysis	The scope is limited to the application of quantitative methods in sustainable supply chain management, and a small sample size of 22 was used for the cluster analysis.
Ejsmont & Gladysz, (2020)	To evaluate the relationship between sustainability and Industry 4.0.	Scopus	162 articles From 2012 to 2017	Bibliometric review	Descriptive and network analysis	CE is treated as a side topic. Limited number of articles included in the bibliometric analysis
Neto et al., (2023)	To evaluate the adoption of I4.0 in conjunction with CE and eco efficiency tools to accelerate sustainability	Web of Science; Scopus Emerald	122 articles From 2003 to 2019	Bibliometric review	Descriptive	The objective is narrowed down to the use of eco-efficiency tools
Khan et al., (2021)	To explore the implications of I4.0 by looking at three core topics: Triple Bottom Line, Sustainable Business Models and CE.	Web of Science; Scopus IEEE explorer; ProQuest	81 articles From 2012 to 2020	Systematic literature review	Descriptive and content analysis	The analysis does not include bibliometric results
Ghobakhloo et al. (2021)	To examine the concept, scope, definition, and functionalities of Industry 4.0, along with its implications for	Web of Science; Scopus	745 articles From 2014 to 2020	Bibliometric review	Descriptive analysis	Sustainability and CE are not included in search criteria; rather they are only discussed as side

	sustainability					topics during the analysis
Wu et al., (2022)	To examine the role of AI, BC and IoT to advance sustainability in three specific contexts (Smart city, energy system, and supply chains)	Web of Science	960 publication From 1996 to 2020	Bibliometric review	Descriptive analysis and thematic analysis	CE is not considered in this review. The article adopted a narrow perspective in terms of technology investigated (only Artificial intelligence, Blockchain, and IoT).
Tavares-Lehmann & Varum, (2021)	To understand the interrelationship between I4.0, Sustainability and CE to promote a shift towards green economy	Web of Science	393 articles From 2015 to 2021	Bibliometric review	Descriptive	This article is an editorial piece that considers CE as a side and marginal topic, lacking a research agenda.
Abideen et al., (2021)	To investigate the advantages of I4.0technologies in influencing circular supply chains and circular business models.	Web of Science	96 publication From 2010 to 2021	Bibliometric review	Descriptive analysis	Sustainability is overlooked in this analysis since the focus is only on circular supply chains and business models.
Hettiarachchi, Brandenburg, et al. (2022)	To conceptualize the integration of Additive Manufacturing and CE	Web of Science; Scopus	51 articles From 2012 to 2020	Systematic literature review	Content analysis	The technological perspective is limited to additive manufacturing. The analysis does not include bibliometric results

From the studies we found, for instance, Ejsmont & Gladysz, (2020) examined the connection between sustainability and Industry 4.0 without considering the circular economy. Montag investigated sustainability, supply chain management, and the circular economy without incorporating Industry 4.0 in the search terms, although the authors suggested the application of Industry 4.0 technologies in circular supply chains for future research. Hettiarachchi et al. (2022) focused exclusively on quantitative methods employed to study sustainable supply chains, and Neto et al. (2023) limited their discussion to the implementation of eco-efficiency tools. Khan et al. (2021) conducted a thorough content-based analysis but specifically focused only on sustainable business models. In other instances, CE or environmental sustainability were not central to the research but rather treated as peripheral topics in the discussion of results. This research builds on the existing studies to address these limitations by:

1. Simultaneously integrating CE, environmental sustainability, and I4.0 perspectives.
2. Providing comprehensive coverage of the broader subject matter, rather than focusing on specialized investigations.
3. Analysing a larger number of articles to enhance the breadth and depth of the research.

This study aims to address gaps in the current understanding of the circular economy field and build the knowledge foundation of the circular economy field through the following research questions:

1. How has the integration of Circular Economy (CE), environmental sustainability, and Industry 4.0 (I4.0) evolved in academic literature over time?
2. What are the main journals publishing research at the intersection of CE, environmental sustainability, and I4.0?
3. What are the most influential authors, institutions, and countries contributing to the integrated study of CE, environmental sustainability, and I4.0?
4. How have citation patterns and collaborative networks developed in the literature connecting CE, environmental sustainability, and I4.0?
5. What are the intellectual structure and thematic clusters of research connecting Circular Economy (CE), environmental sustainability, and Industry 4.0 (I4.0) as revealed through bibliographic coupling analysis?
6. What are the under investigated areas or research gaps in the literature addressing the connections among I4.0 technologies, CE, and environmental sustainability?

4.1.2 Methodology

To systematically identify and analyse relevant literature, this study employed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework (Moher et al., 2009). The process is visually represented in Figure 4. 1, which outlines the number of articles at each stage. The initial literature search was conducted using Scopus, utilizing a Boolean search strategy on 'title-abstract-keywords' with two keyword groups. The first group focused on Industry 4.0 and digital technologies, including keywords like 'Industry 4.0 technologies' and 'Digital Technologies' and included terms such as 'Internet of things', 'Cyber physical system', 'Cloud computing', 'Industrial robotics', 'Data analytics', 'Big Data', 'Additive manufacturing', '3D printing', and 'Industry 4.0'. The second group centred on 'CE' and 'Sustainability'. To ensure reliability, the search query was executed five times, consistently yielding 7,732 records up to December 31, 2022.

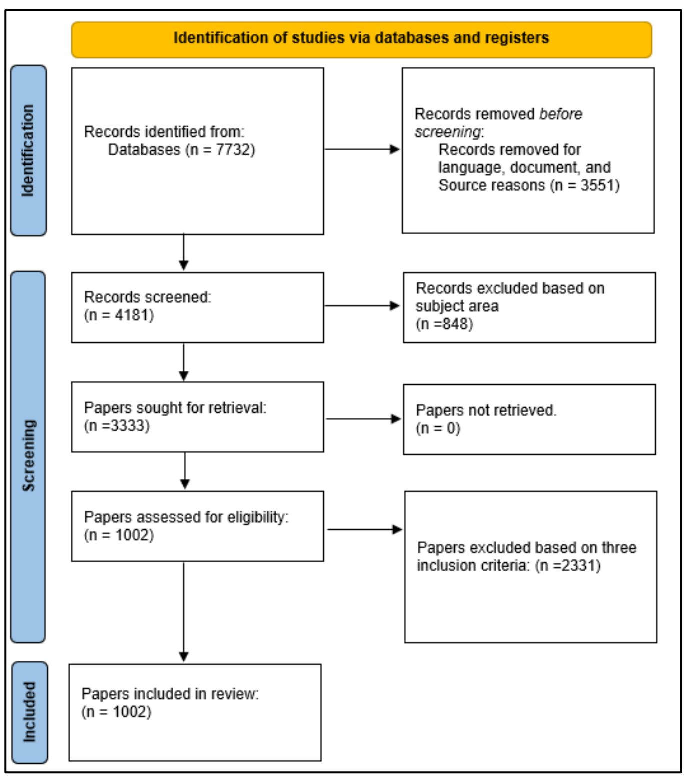


Figure 4. 1 Flow diagram for the selection of literature for Bibliometric literature reviewed based on PRISMA

Then, a rigorous screening process was conducted to ensure the high quality of the articles. We carefully excluded all articles written in languages other than English. The results were further refined by restricting the selection to only peer-reviewed journal articles and comprehensive review papers,

while excluding less formal publication types such as books and conference proceedings. Finally, after narrowing down the subject area to the disciplines most relevant to this study including engineering, business management, operations, services, manufacturing, decision science, interdisciplinary studies, and environmental science a total of 3,333 studies were meticulously selected for analysis.
Then, we manually checked titles and abstracts based on three inclusion criteria:

1. The article must have a strict or specific focus on I4.0 technologies, digital technologies, or Industry 4.0, rather than discussing these topics in general terms.

2. The article must have a strict or specific focus on CE or environmental sustainability, rather than discussing these topics in general terms or merely acknowledging sustainability or CE as a relevant trend or theme.

3. The article must focus on the technical side of the Ellen MacArthur Foundation's Butterfly Diagram (Macarthur, 2013). This side aims to retain the value of technical products, components and materials at the highest value encompassing processes such as reuse, repair, remanufacturing, and recycling.

The articles that met all three criteria were selected for further analysis, resulting in a final set of 1,002 articles.

4.2 Descriptive Analysis

4.2.1 General Statistics

A comprehensive analysis of 1002 articles published between 2010 and 2022 in 301 different journals, authored by 3066 individuals, reveals significant trends in research at the intersection of Circular Economy (CE), sustainability, and Industry 4.0 (I4.0) as shown in Figure 4. 2. The sample comprised 848 articles and 154 reviews, as classified by Scopus, collectively receiving 32,614 citations. The temporal distribution of publications demonstrates a sharp increase in interest over the past decade, with a pronounced acceleration beginning in 2017. From 2010 to 2014, annual publications remained minimal, ranging from just 1 to 7 articles per year. However, a turning point occurred in 2015 when the number of articles exceeded 10 for the first time. The growth trajectory became more pronounced from 2017 onward, with annual publications rising exponentially. By 2021, this number peaked at 248 articles. Notably, over 80% (879) of the papers were published after 2019, underscoring a recent surge in academic focus on these interconnected fields. The year 2013 saw a particularly high average citation count, attributed to the influential work of Huang et al. (2013)Additionally, 2018 and 2020 received the highest number of global citations. This data underscores the growing importance and research momentum in the fields of CE, sustainability, and I4.0, especially in recent years, with a significant uptick observed between 2019 and 2020 as these topics became top priorities in the academic community.

Finding No1: *Since 2017, there has been a significant increase in the number of articles demonstrating an upward trend.*

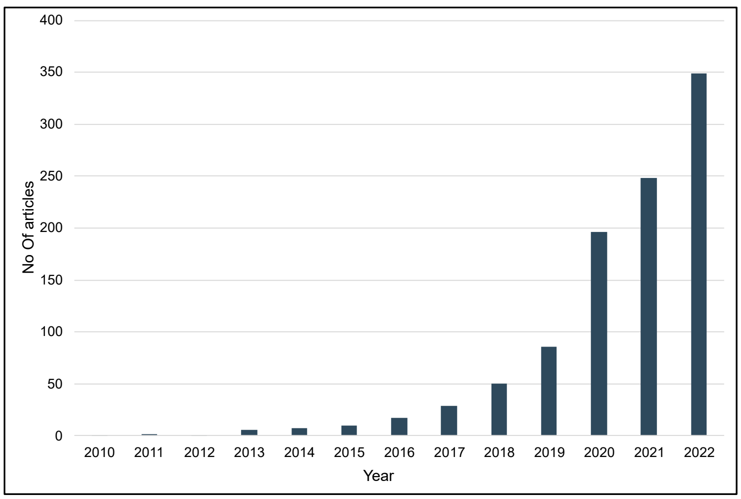


Figure 4. 2 Number of articles published by year.

4.2.2 Country Statistics

This section describes the most productive and influential countries in terms of the number of publications based on corresponding author country. In this analysis is associated with a single country based on the affiliation of the corresponding author. Table 4. 2 shows the ranking of 20 most active countries. The top ten countries in terms of published articles based on corresponding author country are China, India, Italy, the United Kingdom, the United States, Spain, Brazil, France, and Germany, which account for 50% of all published articles. The Netherlands has the highest average number of citations per publication at 60.1, followed by France, China, and Germany with values of 55.4, 48.2, and 47.4, respectively. While China leads in both publication volume and total citations, other countries demonstrate significant impact in different metrics; the countries that received the most citations are the United Kingdom, the United States, Italy, and India, in that order. The findings suggested that concerns about the CE, sustainability, and I4.0 are more prevalent in developed countries like Italy, the United States, and Germany, as well as developing economies with large consumer societies like China and India. This is understandable since the CE and I4.0 aim to achieve sustainable production and consumption by reducing environmental impact. Additionally, the table analyzed the patterns of contributions and collaborations made by various countries to the publication. During the analysis of country statistics, Single Country Publications (SCP) and Multiple Country Publications (MCP) were evaluated. The Multiple Country Publications (MCP) index calculates the proportion of articles that have at least one author who comes from a country different from the corresponding author. MCP indicates the number of articles that have at least one author who comes from a country different from the corresponding author, whereas SCP indicates the number of articles where all the authors are in the same country. China leads also in the number of MCP (60), followed by UK (36), India (33) and Italy (24).

Finding No 2: *According to the number of articles published, China stands out as the leading country in research on this topic, with India, Italy, the UK, and the USA following close behind. The geographical distribution of publications showcases two distinct clusters of active countries - one comprising large industrial economies such as Italy, the UK, the USA, Germany, and Spain, and the other consisting of developing economies with sizeable consumer societies, namely China and India.*

Table 4. 2 Top 10 countries based on number of publications

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

4.2.3 Journal Statistics

The 1,002 studies were published across 301 different academic journals. Of these, only eight journals published 15 or more articles related to Circular Economy (CE), Sustainability, and Industry 4.0 technologies shown in Table 4. 3. These journals include Sustainability (223 articles), Journal of Cleaner Production (107), Energies (21), Business Strategy and the Environment (20), International Journal of Advanced Manufacturing Technology (19), Resources, Conservation and Recycling (17), Production Planning and Control (16), and the International Journal of Production Research (16). Together, these journals account for 43% of the total sample. In terms of total citations, the Journal of Cleaner Production leads with 6,176 citations, followed by Sustainability with 5,080, and the International Journal of Advanced Manufacturing Technology with 2,719. Notably, the latter has the highest average citations per article (143.1), followed by the International Journal of Production Research (94.6), Resources, Conservation and Recycling (74.0), International Journal of Production Economics (64.0), and Journal of Cleaner Production (57.7).

Finding No 3: *Overall, The Journal of Cleaner Production emerges as the most influential publication in the field, leading in total citations with a cite score of 15.8 and 6,176 citations, representing 11% of all publications in the sample, it shows a high citation-per-publication ratio, a strong H-index, and a notable impact factor.*

Table 4. 3 Top 10 journal published in the subject

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

4.2.4 Article Citation Analysis

To identify the most influential articles, citation analysis is performed on the database, where the article serves as the unit of analysis. The number of times an article is cited and co-cited by other articles is analysed to explain the connections between articles and research topics. There are two types of analyses performed to understand influential papers: local citation analysis and global citation analysis. Table 4. 4 lists the 10 authors with the highest number of local citations, and Table 4. 5 lists the top 10 globally cited papers in the sample. Local citations refer to citations received by an article from other papers within the sample of 1,002 articles in the collection. On the other hand, global citations refer to citations received by articles from extensive data sources such as Scopus and Web of Science (WOS).

Table 4. 4 The top 10 local cited article

Author(s)	**Document**	**Year**	**Journal**	**Local Citations**	**Global Citations**
Lopes de Sousa Jabbour et al. (2018)	Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations	2018	Annals of Operations Research	137	451
Müller et al.(2018)	What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability	2018	Sustainability (Switzerland)	72	427
Yadav et al. (2020)	A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: An automotive case	2020	Journal of Cleaner Production	67	201
Kiel et al. (2017)	Sustainable industrial value creation: Benefits and challenges of industry 4.0	2017	International Journal of Innovation Management	66	346
Ford & Despeisse, (2016)	Additive manufacturing and sustainability: an exploratory study of the advantages and challenges	2016	Journal of Cleaner Production	66	787
Machado et al., (2020)	Sustainable manufacturing in Industry 4.0: an emerging research agenda	2020	International Journal of Production Research	60	242
Ghobakhloo (2020)	Industry 4.0, digitization, and opportunities for sustainability	2020	Journal of Cleaner Production	59	376
Dev et al., (2020)	Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance	2020	Resources, Conservation and Recycling	58	156
Rosa et al., (2020)	Assessing relations between Circular Economy and Industry 4.0: a systematic literature review	2020	International Journal of Production Research	57	202
Bressanelli et al., (2018)	Exploring how usage-focused business models enable circular economy through digital technologies	2018	Sustainability (Switzerland)	52	228

Among the top ten authors with the highest number of local citations, lopes de Sousa Jabbour et al. (2018) received the highest count with 121 local citations within the sample of 1002 articles. The top-cited articles examine various facets of synergies between Industry 4.0 technologies and CE principles, including implementation challenges, the role of digital technologies in enabling CE practices, and the potential benefits of sustainable manufacturing in the context of Industry 4.0. A common thread among these influential papers is their focus on Industry 4.0 technologies and their application to various aspects of supply chain management, circular business models, and operations management. The studies cover a wide range of topics, including life cycle sustainability assessment, plastic recycling, environmental implications, and smart circular product design strategies. While most papers discuss CE from a general perspective, some employ specific frameworks such as the Resolve framework (Lopes de Sousa Jabbour et al., 2018; Machado et al., 2020). From the top 10 globally and locally cited articles, various perspectives highlight the transformative role of Circular Economy (CE) strategies supported by Industry 4.0 technologies. These include enhanced human-machine interaction, service innovation, and significant cost reductions achieved through agile and flexible manufacturing. Advanced technologies such as cyber-physical systems and IoT are improving production efficiency, enabling product personalization, and driving supply chain digitization to enhance transparency and optimization. Simultaneously, these advancements support waste reduction, resource optimization, and the creation of self-sustaining production systems while mitigating environmental impacts such as CO_2 emissions and pollution. Moreover, value chains are being restructured through organizational innovation, with digital technologies like digital twins playing a crucial role in advancing sustainable product life cycle management.

Table 4. 5 The top 10 Global cited article

Authors	Documents	Year	Journal	Local Citation	Global Citation
Tao et al., (2018)	Digital twin-driven product design, manufacturing, and service with big data	2018	International Journal of Advanced Manufacturing Technology	18	1191
Huang et al., (2013)	Additive manufacturing and its societal impact: A literature review	2013	International Journal of Advanced Manufacturing Technology	34	1180
Ford & Despeisse, (2016)	Additive manufacturing and sustainability: an exploratory study of the advantages and challenges	2016	Journal of Cleaner Production	60	787

Kusiak (2018)	Smart manufacturing	2018	International Journal of Production Research	36	580
Gebler et al. (2014)	A global sustainability perspective on 3D printing technologies	2014	ENERGY POLICY	38	487
Lopes de Sousa Jabbour et al (2018)	Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations	2018	Annals of Operations Research	121	451
Müller et al. (2018)	What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability	2018	Sustainability (Switzerland)	65	427
Ghobakhloo (2020)	Industry 4.0, digitization, and opportunities for sustainability	2020	Journal of Cleaner Production	53	376
Manavalan & Jayakrishna, (2019)	A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements	2019	Computers and Industrial Engineering	36	363
Kiel et al.(2017)	Sustainable industrial value creation: Benefits and challenges of industry 4.0	2017	International Journal of Innovation Management	61	346

It is quite interesting to see that Ford & Despeisse, (2016) has the 3rd highest global citation in the table, but based on the local citation, the article has been ranked fifth. A comparison of the two tables reveals that five articles are common to both, but only one of the three globally most cited papers is also among the ten locally most cited papers.

Finding No 4: *This analysis reveals the most influential papers focusing on their synergistic application in supply chain management, sustainable manufacturing, and business model innovation, while highlighting discrepancies between local and global citation patterns that suggest nuances in the field's internal discussion compared to its broader academic impact.*

4.2.5 Author Statistics

This section presents an analysis of the most prolific authors in the fields. Based on data extracted from the SCOPUS database and analysed using Biblioshiny, Table 4. 6 summarizes the contributions of the 15 most productive authors across various metrics. Anil Kumar emerges as the author with the highest number of publications, having produced 18 papers with 460 global citations and an H-index of 9. However, Bag S. leads in terms of global citations (896) and H-index (12), while BIBRI SE boasts the highest average citations ratio (72.9). Notably, the analysis highlights a significant concentration of productive authors from the United Kingdom, who have collectively contributed almost 50 papers to the field.

Table 4. 6 The top 15 contributing authors in the field of I4.0 technologies, CE and sustainability

Authors	University	No of Articles	Sum of citation	Average citations per publication	Article with highest citation	Year	Source title	Cited by
Kumar A	London Metropolitan University, London, United Kingdom	18	460	25.6	Industry 4.0 as an enabler of sustainability diffusion in supply chain: an analysis of influential strength of drivers in an emerging economy	2020	International Journal of Production Research	145
Agrawal R	Indian Institute of Technology Delhi, New Delhi	15	137	9.1	Integration of continuous improvement strategies with industry 4.0: a systematic review and agenda for further research	2021	TQM Journal	37
Bag S	University of JohannesburgS outh Africa	15	896	59.7	Big data analytics as an operational excellence approach to enhance sustainable supply chain performance	2020	Resources, Conservation and Recycling	175
Luthra S	Ch. Ranbir Singh State Institute of Engineering and Technology, Jhajjar, Haryana	13	679	52.2	A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: an automotive case	2020	Journal of Cleaner Production	201
Garza-Reyes Ja	University of the West of England, Bristol	11	712	64.7	Exploring industry 4.0 technologies to enable circular economy practices in a manufacturing context: a business model proposal	2019	Journal of Manufacturing Technology Management	313
Khan Sar	Xuzhou University of Technology, Xuzhou	11	310	28.2	Industry 4.0 and circular economy practices: a new era business strategies for environmental sustainability	2021	Business Strategy and the Environment	85
Ghobakhloo M	University of Hormozgan, Bandar Abbas, Iran	10	542	54.2	Industry 4.0, digitization, and opportunities for sustainability	2020	Journal of Cleaner Production	376
Kazancoglu Y	Yasar University, İzmir	10	216	21.6	Blockchain technology and the circular economy: implications for sustainability and social responsibility	2021	Journal of Cleaner Production	101
Kumar V	University of the West of England, Bristol	10	216	21.6	Blockchain technology and the circular economy: implications for sustainability and social responsibility	2021	Journal of Cleaner Production	101

Mangla Sk	University of Plymouth, Plymouth, United Kingdom	10	723	72.3	A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: an automotive case	2020	Journal of Cleaner Production	201
Tseng M-L	Asia University, Taichung, Taiwan	9	317	35.2	Toward sustainability: using big data to explore the decisive attributes of supply chain risks and uncertainties	2017	Journal of Cleaner Production	159
Yu Z	Chang'an University, Xi'an, China	9	301	33.4	Industry 4.0 and circular economy practices: a new era business strategies for environmental sustainability	2021	Business Strategy and the Environment	85
Bibri Se	Norwegian University of Science and Technology,Norway	8	583	72.9	The iot for smart sustainable cities of the future: an analytical framework for sensor-based big data applications for environmental sustainability	2018	Sustainable Cities and Society	330
Yang Y	The University of Texas at Arlington,United States	8	259	32.4	Big data meet cyber-physical systems: a panoramic survey	2018	IEEE Access	136
Singh Sp	Indian Institute of Technology Delhi, Delhi	7	467	66.7	Connecting circular economy and industry 4.0	2019	International Journal of Information Management	207

This geographical concentration of highly productive authors from the United Kingdom underscores the country's prominent role in driving research at the intersection of Industry 4.0, the circular economy, and sustainability. Further, a bibliometric indicator known as the Author's Dominance Factor is employed to further comprehend an author's impact. When combined with other bibliometric indicators, the DF facilitates a more comprehensive understanding of an author's prominence and role within their academic community. The Dominance Factor (DF), introduced by Kumar et al. (2019), is a pivotal metric in bibliometric analysis that assesses the productivity and influence of individual researchers within their fields. Defined as the ratio of multi-authored papers where the researcher is the first author (Nmf) to their total number of multi-authored papers (Nmt), the DF score ranges from 0 to 1. A higher DF score signifies greater research leadership or influence, with high-scoring authors often regarded as more prolific and impactful, as highlighted by Firdaus et al. (2019). This metric is particularly relevant in disciplines characterized by extensive collaborative research, as it differentiates between authors who spearhead research initiatives and those who contribute primarily as co-authors. Table 4. 7 indicates that Bibri S.E. and Bag S. have the highest

Author's Dominance Factor (DF), whereas Kumar A and Luthra S have lower DF values of 0.11 and 0.08, respectively.

Finding No 5: *While Anil Kumar leads in publication count, Bag S. stands out in global citations and H-index, and BIBRI S.E. excels in average citation ratio. The Author's Dominance Factor further refines these rankings.*

Table 4. 7 Dominance Factor of the top 10 contributing authors in the field of I4.0 technologies, CE and sustainability

Authors	No of Articles	First authored	Dominance factor
Kumar A	18	2	0.11
Agrawal R	15	7	0.47
Bag S	15	14	0.93
Luthra S	13	1	0.08
Garza-Reyes Ja	11	0	0.00
Khan Sar	11	6	0.55
Ghobakhloo M	10	4	0.40
Kazancoglu Y	10	3	0.30
Kumar V	10	0	0.00
Mangla Sk	10	2	0.20
Tseng M-L	9	2	0.22
Yu Z	9	1	0.11
Bibri Se	8	7	0.88
Yang Y	8	1	0.13
Singh Sp	7	0	0.00

4.2.6 Keywords co occurrence analysis

Keyword Co-occurrence Analysis is a bibliometric method that maps and visualizes the conceptual structure of a research field. It examines the frequency with which keywords appear together in academic publications, revealing the main themes, trends, and relationships within a body of literature. We conducted a keyword co-occurrence analysis to reveal the thematic structure of the field. Keywords serve as indicators of the most crucial terms in the articles, expressing the intellectual themes and structure of the research fields. Based on the frequency of the author keywords shown in Figure 4. 3, we present the most prominent keywords, highlighting a thematic focus in these works. We created a network diagram based on the keywords, and clusters were formed based on close relationships with different keywords. In the initial phase, metadata from 1002 papers were prepared for analysis in Biblioshiny.

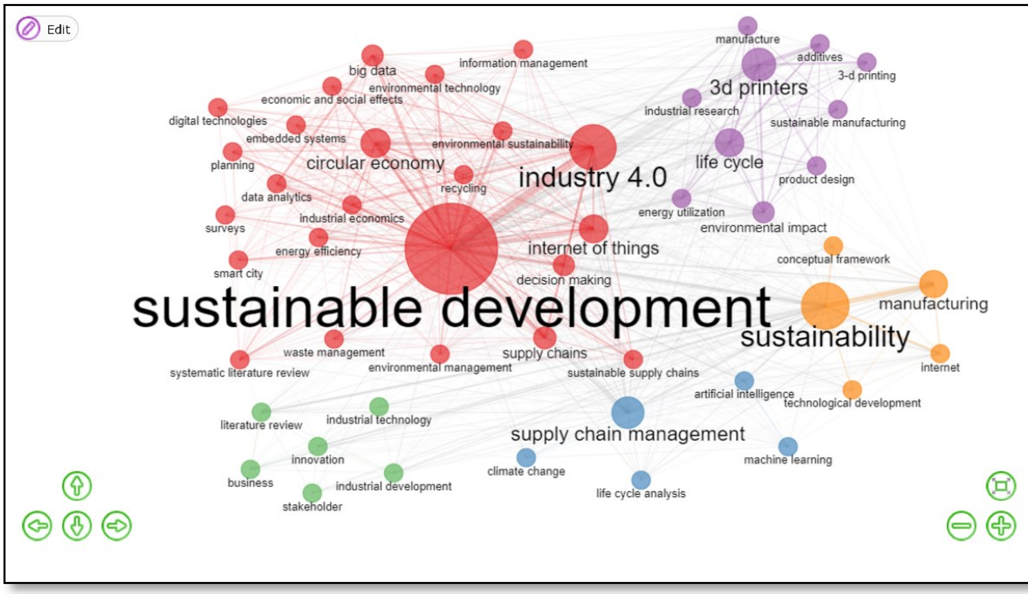


Figure 4. 3 Network visualization of the most frequent keywords associated with I4.0 technologies and CE

We considered the full count of keywords and identified 3,859 keywords in the articles, which were further reduced by considering only the keywords that occurred more than 10 times. We then removed keywords that were unrelated or conflicted with others, such as "practical implication," "originality value," "study," etc. We examined keyword abbreviations and merged them to create a consistent structure. For example, "CE" and "Circular-Economy" were considered the same term "Circular Economy" because they referred to the same topic. Table 4. 8 depicts the frequency of the keywords. The most frequently used keywords are "sustainable development," "sustainability," "industry 4.0," "supply chain management," "manufacturing," "3D printers," "internet of things," "circular economy," "life cycle," "decision making," "big data," "supply chains," and "energy utilization." The keyword "sustainable development" has been used most frequently, with 407 occurrences. To deepen the analysis, we also found a few other thematic keywords, such as "3D printers," "life cycle," "decision making," and "energy utilization," which indicate a novel theme emerging in relation to CE and I4.0 technologies.

Table 4. 8 Top 25 keywords on CE, Sustainability and I4.0

Group	Keywords	Frequency	Ranking Based on Frequency
1	sustainable development	403	1
	sustainability	215	2
	waste management	56	17
	environmental sustainability	47	22
2	circular economy	111	5

	recycling	69	12
3	industry 4 0	174	3
	3d printers	106	7
	internet of things	100	8
	big data	66	13
	additives manuf.	56	15
	data analytics	56	16
	internet	50	19
	artificial intelligence	43	24
	3D printing	39	25
4	manufacturing	114	4
	supply chain management	109	6
	life cycle	83	10
	decision making	83	9
	supply chains	76	11
	environmental impact	57	14
	energy utilization	51	18
	industrial economics	49	21
	energy efficiency	45	23
	Literature Review	450	20

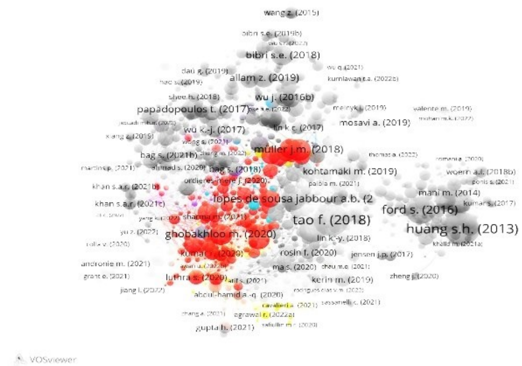
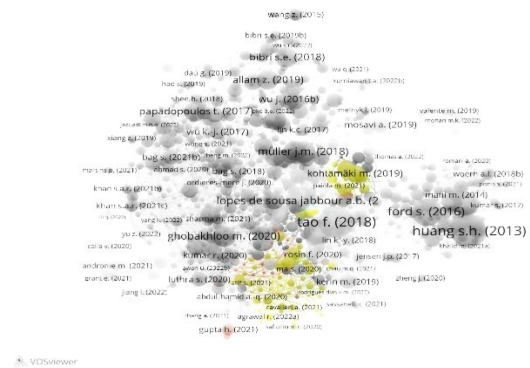
The analysis produced the keyword occurrence network shown in Figure 4. 3. Using cluster analysis, we defined five clusters based on the co-occurrence of closely related keywords in the articles. Each cluster was assigned a distinct colour to represent the underlying themes of the co-occurring words. The network visualization in Figure 2 includes circles, text labels, connections, and coloured areas. Labels and circles represent the keywords, and the size of the label and circle reflect the weight of the item (i.e., the frequency of the keyword). The position distance or connection strength between the two items represents the strength of their affinity. The positioning of elements within the visualization is significant, with the distance between items or the strength of their connection representing the affinity between keywords. This spatial arrangement allows researchers to intuitively grasp the relationships between different concepts and their relative importance within the field. By analyzing the size, positioning, and clustering of keywords, researchers can identify core concepts, emerging trends, and potential areas for future investigation in the rapidly evolving landscape of Circular Economy, Industry 4.0 technologies, and sustainability. This visual representation enables a quick and intuitive understanding of the major themes, their relationships, and their relative importance within the research domain, providing valuable insights for future research directions and the development of the field. Based on the author's classification of the top 25 most frequent keywords into four groups - sustainability, circular economy, Industry 4.0 (I4.0), and other directly relevant topics - several key insights emerge about the research landscape. Notably, new thematic keywords such as "Internet of Things" and "Big Data" have gained prominence in recent years, alongside additive manufacturing. These technologies stand out as the most influential among the nine I4.0 technologies considered in the study, underscoring their growing importance in driving innovation and transformation in sustainable and circular practices. Additionally, the increased attention given to sustainability and sustainable development goals reflects their recognition as global priorities, indicating a growing alignment between I4.0 technological advancements and sustainability objectives. This trend suggests a convergence of research interests towards more holistic and integrated approaches to addressing environmental and economic challenges, highlighting the interconnected nature of sustainability, circular economy, and Industry 4.0 in current research.

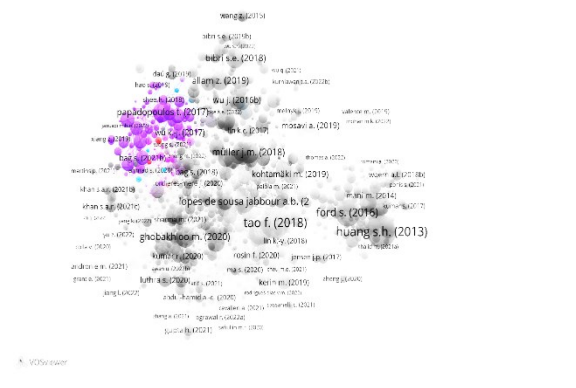
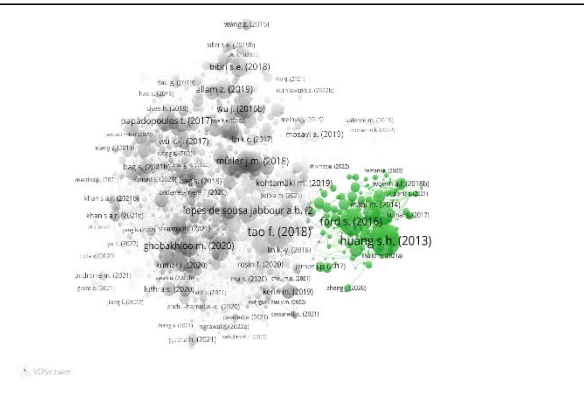
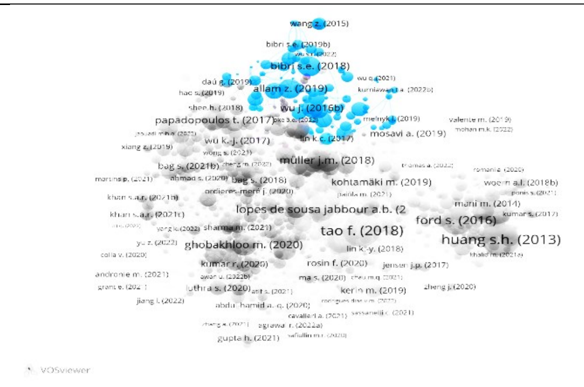
4.3 Bibliographic coupling

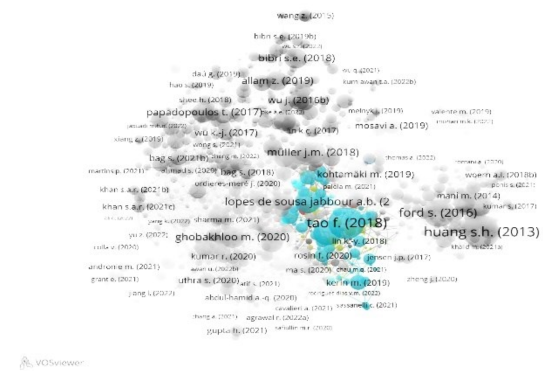
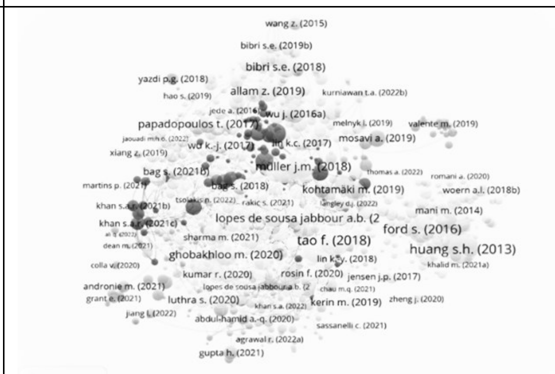
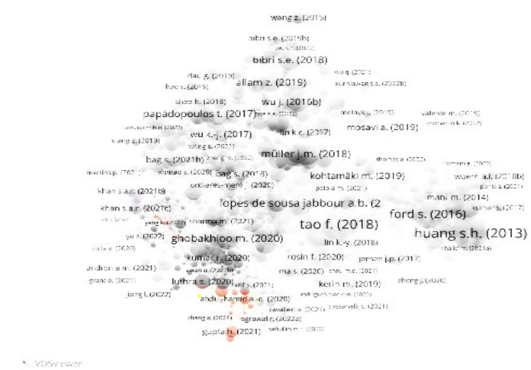
Utilizing VOS viewer software, we conducted a cluster analysis based on bibliographic coupling to examine similarities between publications in the fields of Circular Economy, Industry 4.0, and sustainability. This method, which analyzes shared references, assumes that articles with common citations likely have similar content. Bibliographic coupling offers several advantages, including enhanced visibility of recent or less-cited publications, creation of thematic clusters, and identification of emerging literature based on shared citation patterns. This approach is particularly effective for publications within a specific time frame, providing a more current and precise picture of the evolving research landscape compared to co-citation analysis. The VOS viewer software, developed by van Eck & Waltman (2014), visualizes connections between documents, revealing underlying structures and connections between different research areas. By analysing the bibliographic coupling network, we created thematic clusters that provide insights into the field's conceptual landscape. In our study, we input bibliographic information from 1002 articles, employing the fractional counting method. To ensure equal representation of all publications, regardless of their citation count, we set the minimum number of citations to zero. This approach was particularly important given the recency of many articles in the sample, which may have few or no citations but could potentially indicate emerging research hotspots. Following this initial process, we removed 102 articles that showed minimal bibliographic linkage with others, resulting in a final network of 900 coupled documents. The bibliographic coupling analysis using VOS viewer resulted in the identification of eight distinct clusters, as detailed in Table 4. 9.

This table provides a comprehensive overview of each cluster, including their primary research topics, dimensions (measured by the number of articles in each cluster), and a visual representation. The largest cluster, Cluster 1, and the smallest Cluster 8, represent different aspects of the research landscape. Notably, Cluster 7 covers the longest time span, featuring articles dating back to 2011. Each cluster is described in terms of primary research topics, dimensions, and visual representation, offering a comprehensive overview of the thematic distribution and evolution of research in Circular Economy, Industry 4.0, and sustainability. This clustering approach allows for a nuanced understanding of the thematic distribution and evolution of research in these interconnected areas.

Table 4. 9 Research clusters based on bibliographic coupling

ID	Name of the cluster	Time range	No. of articles	Most frequent keywords	Visual representation
1	General linkages between sustainability and Industry 4.0 topics (Red)	2017-2022	N=170	Sustainable development, Industry 4 0, Sustainability	
2	General linkages between Circular Economy and Industry 4.0 topics (Yellow)	2016-2022	N=104	Circular economy, Industry 4.0, Digitalization, circular business model,	

3	Industry 4.0 and Big Data analytics for supply chain circularity and sustainability (Purple)	2014-2022	N=96	Supply chain management, Big Data, Sustainability, information management	
4	Additive Manufacturing for circularity and sustainability (Green)	2013-2022	N=140	3D Printers, Additive manufacturing, Life cycle	
5	Urban Sustainability (Blue)	2012-2022	N=119	Smart city, Waste management, Big data	

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

4.3.1 Cluster 1: General Linkages Between Sustainability and Industry 4.0 Topics

Cluster 1, the largest cluster with 170 publications, focuses on the interplay between sustainability and Industry 4.0 (I4.0) technologies. It explores how I4.0 can enhance sustainability and sustainable development, addressing environmental, economic, and social performance. It is observed that the papers in this cluster discussed different methodologies, including systematic literature reviews and framework conceptualization, often relying on expert-based opinions. In fact, the articles in this cluster focused on exploratory research, mainly adopting qualitative approaches, and focusing on the development of conceptual frameworks. Expert based opinion methods are used to prioritize, categorize, ranks, and identify the relationship between different constructs. For instance, Ghobakhloo et al., (2021) identifies various functions of I4.0 technologies that support sustainability and establishes contextual relationships between these functions through expert opinions. Nara et al. (2021) conducted a systematic literature review to identify key performance indicators, grouping them based on expert opinions and validating them through a survey of technical specialists and managers. The cluster highlights I4.0's significant potential to contribute to sustainable development through resource efficiency enhancement, waste reduction, and product design improvement. For instance, Felsberger & Reiner (2020) investigated the effectiveness of I4.0 technologies like smart factory technologies, data-driven technologies, and shop floor equipment technologies across different sustainability dimensions. El Baz et al. (2022) empirically evaluated sustainability drivers influencing I4.0 technology adoption, emphasizing the importance of management support. The research also highlights challenges facing the integration of I4.0 technologies into sustainable practices. These challenges include social issues including high implementation costs, scarcity of expertise and skills, and social issues such as income and employment polarization (Birkel & Müller, 2021), along with concerns regarding data privacy, security, and the effectiveness of government policies (Beltrami et al., 2021). Besides practical implementation challenges, several opportunities for future research arise from this cluster. From an organizational perspective, a promising future research direction involves investigating the application of I4.0 technologies to improve personalized information and knowledge management (Felsberger & Reiner, 2020; Ghobakhloo, 2020). In addition, investigating how sustainability can drive the adoption of I4.0 technologies would be also highly relevant (Beltrami et al., 2021b). Cluster 1 reveals the intricate relationships between I4.0 technologies and sustainability, highlighting both the potential benefits and challenges in their integration, while also pointing towards promising avenues for future research in this rapidly evolving field.

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

Cluster 2, comprising 104 publications, focuses on the intersection of digitization with Circular Economy (CE) and circular business models. This cluster encompasses a wide range of topics, including the role of digitalization in enhancing productive maintenance in manufacturing firms (Samadhiya et al., 2023), circular business models (Salvador et al., 2021), and circular supply chains (Gebhardt et al., 2022; Kayikci et al., 2022). The research in this cluster primarily develops frameworks connecting different constructs, often based on systematic literature reviews. For example, Gebhardt et al. (2022) created a framework for collaboration mechanisms enabled by Industry 4.0 (I4.0) technology, focusing on IoT, Big Data analytics, and cloud computing as enablers of circularity in supply chains. Salvador et al. (2021) investigated how digital technologies enable circular strategies such as design for circularity and their impact on business models. Liu et al. (2019) explored digital technologies facilitating the integration of various circular strategies (Reduce, Reuse, Repair, Repurpose, Remanufacturing, Recycle, and Recover) as outlined by Potting et al. (2017). The cluster highlights I4.0 technologies like IoT and cloud computing as effective enablers of specific CE practices, including product life extension, reuse, and recycling. Some papers in this cluster explored challenges related to policy, technology, and behavioral change, as well as opportunities in implementing CE practices (S. A. R. Khan et al., 2022), while others focused on developing conceptual frameworks or value chain designs to achieve circularity. The complexity of successfully implementing I4.0 technologies due to high costs and financial risks is a recurring theme, with some articles pointing out the potential for a digital divide where only financially robust companies can adopt circular practices using expensive I4.0 technologies (Kamble & Gunasekaran, 2023). The research in this cluster generally adopts a theoretical perspective, leading to calls for more empirical studies. Future research directions identified include investigating the creation of collaborative platforms and systematic collaboration methods to connect different stakeholders in circular supply chains, developing theories to synthesize specific technologies and their interconnections in the CE context

(Gebhardt et al., 2022; Rejeb et al., 2022), and studying various circular business model building blocks (such as consumer segments, value propositions, channels, consumer relationships) in specific manufacturing industries (Rejeb et al., 2022; Salvador et al., 2021). This cluster provides a comprehensive overview of the current theoretical landscape linking CE and I4.0, while also highlighting more empirical studies are often suggested. Further investigation into the creation of collaborative platforms and systematic collaboration methods to connect different stakeholders involved in circular supply chains can be considered as a valuable future research direction in this cluster. Moreover, theories are needed to synthesize specific technologies and their interconnection in the context of CE (Gebhardt M 2022, Rejeb A 2022). Lastly, studying various circular business model building blocks (such as consumer segments, value propositions, channels, consumer relationships, etc.) in specific manufacturing industries would be an intriguing area of research (Salvador R 2021, Rejeb A 2022).

4.3.3 Cluster 3: Industry 4.0 and Big Data analytics for Supply Chain circularity and Sustainability

Cluster 3 (96 publications) focuses on the relationship between I4.0 technologies and sustainable, circular supply chain initiatives. This cluster is more specific than Clusters 1 and 2, focusing on supply chain management and emphasizing the role of Big Data analytics among the wide I4.0 technologies umbrella. The studies explore the intersection of supply chain management, I4.0 technologies (especially Big Data analytics), and Circular Economy (CE) strategies across diverse industries and geographical regions. Notably, this cluster features a mix of empirical methods, both quantitative and qualitative, with several papers utilizing surveys to test hypotheses in different geographical contexts. For instance, Di Maria et al. (2022) investigated the mediating role of supply chain integration in the correlation between I4.0 technologies and CE practices, based on a survey of 1200 Italian firms. Their findings highlight the crucial role of supply chain integration in realizing the potential benefits of I4.0 technologies for achieving circularity in supply chains. Similarly, Akbari & Hopkins (2022) explored how digital technologies enable supply chain sustainability in emerging economies through a survey of 223 Vietnamese supply chain experts. The cluster emphasizes the importance of adopting a holistic and integrated approach to smart sustainable supply chain management, addressing supply chain disruption, capability development, and resource recovery frameworks (Stroumpoulis & Kopanaki, 2022). A recurring theme is the neglect of reverse logistics by manufacturing companies compared to forward supply chains, attributed to operational challenges, knowledge gaps, low return on investment, lack of top management support, and technological barriers (Aldrighetti et al., 2023; Bag et al., 2023). Future research directions identified in this cluster include addressing technological barriers such as data inadequacy, information structure issues, lack of industrial competency, and challenges in implementing innovative devices and information technology (Stroumpoulis & Kopanaki, 2022). The cluster also highlights the need to investigate the government's role in implementing environmental taxation waiver schemes and developing regulations to encourage circular supply chain practices (Kumar et al., 2021). Additionally, researching data-driven approaches to measure and monitor supply chain sustainability performance presents an intriguing area for future study (Hettiarachchi, Seuring, et al., 2022).

4.3.4 Cluster 4: Additive Manufacturing for Circularity and Sustainability

Cluster 4 (140 publications) examines additive manufacturing and 3D printing as technologies that enable the minimization of waste, the optimization of resource utilization, and the promotion of circularity within the manufacturing sector. This cluster explores the relationship between life cycle sustainability and additive manufacturing, providing frameworks for sustainability assessment and strategies for optimizing eco-effective production systems (Dahmani et al., 2021). Key topics include sustainability assessment of additive manufacturing, design of distributed recycling via additive manufacturing (Cruz Sanchez et al., 2020), integration of additive manufacturing and Circular Economy (CE) (Hettiarachchi, Brandenburg, et al., 2022), and the impact on business models (Godina et al., 2020). The cluster features systematic literature reviews and analytical methods to evaluate additive manufacturing parameters, such as Mele & Campana's (2022) adaptive slicing method for liquid crystal display 3D printing to reduce waste and energy consumption. While reuse and recycling are prominent CE strategies (Cruz Sanchez et al., 2020; Dahmani et al., 2021), the 'reduce' strategy is also referenced (Mele & Campana, 2022). The cluster highlights potential benefits of additive manufacturing for circular product design (Dahmani et al., 2021) and sustainable business models (Hernandez Korner et al., 2020), including reduced material waste, lower transportation costs (Kellens et al., 2017), consumer-centric customization (Godina et al., 2020), inventory reduction through on-demand production, and shortened supply chains with improved environmental and social benefits

(Cruz Sanchez et al., 2020). However, the cluster identifies the need for developing reverse logistics frameworks to successfully implement additive manufacturing by connecting different supply chain actors. It also calls for more empirical research on social perceptions of additive manufacturing initiatives and emphasizes the importance of active government participation and supportive policies to increase adoption for sustainability and circularity purposes. Future research directions include investigating innovative additive manufacturing methods and strategies for using recycled materials as input feedstock, developing standardized indicators for assessing environmental impacts of additive manufacturing feedstock production, and optimizing energy and material-efficient production processes through methods like distributed recycling, polymerization, and laser cladding (Cruz Sanchez et al., 2020; Godina et al., 2020). This cluster provides a comprehensive overview of additive manufacturing's role in promoting sustainability and circularity, highlighting both its potential benefits and the challenges that need to be addressed for wider adoption and integration into circular manufacturing systems.

4.3.5 Cluster 5: Urban Sustainability

Cluster 5, comprising 119 publications, centres on the concept of urban sustainability and its intersection with digital technologies. This cluster encompasses research on data-driven approaches to creating smart, sustainable cities, the development and implementation of Information and Communication Technology (ICT) infrastructure to support urban sustainability initiatives, and the application of various digital technologies within the framework of smart city development. The integration of Industry 4.0 technologies such as IoT, Big Data, and cloud computing plays a crucial role in enhancing waste management and environmental sustainability in urban development. Wu et al. (2022) emphasized the collection and analysis of real-time data from digital instruments in urban environments, contributing to data-driven smart cities (Bibri & Krogstie, 2020) and supporting data-driven decision-making for urban sustainability and intelligence. The cluster addresses potential risks, benefits, and ambidexterity capabilities to meet current business demands and future perspectives, while also discussing challenges in adopting and implementing digital technologies. Some papers highlight the importance of citizen engagement in smart city design and implementation (Bibri, 2019a), while others stress the need for balanced innovation and sustainability policies (Kurniawan et al., 2022). The cluster identifies a need for further exploration of government roles in establishing political mechanisms and policy measures for smart cities, exemplified by the Stockholm Royal Seaport prototype using a hybrid Smart Urban Metabolism approach (Bibri, 2019a). The research emphasizes the importance of social acceptability and the impact of urban sustainability strategies. These studies collectively explore how technological advancements can be leveraged to enhance the sustainability, efficiency, and liveability of urban environments, addressing challenges such as resource management, environmental impact, and quality of life for city dwellers. Additionally, greater attention should be given to social acceptability and the impact of adopting urban sustain- ability strategies. To Research should focus on urban intelligence, which encompasses a city's capacity to utilize real-time data to optimize interconnected systems such as energy and water distribution, waste management, and communication networks. Furthermore, there is a need for investigating resilient data-driven decision-making that involves the collection of data from various sources, effective management of data streams, and integration of diverse urban datasets. This comprehensive overview of urban sustainability and smart cities highlights the critical role of digital technologies in shaping future urban environments, emphasizing the need for interdisciplinary approaches to address complex urban challenges and create more efficient, sustainable, and resilient cities.

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

Cluster 6 (87 publications) focuses on the integration of sustainable principles, digital technologies and CE aspects in manufacturing and especially remanufacturing operations. The cluster investigates the role of digital technologies in achieving sustainable and circular (re)manufacturing, with key contributions from various researchers. Chau et al. (2021) explored the prospects of IoT-based technologies in remanufacturing processes, while Kerin & Pham (2019) examined the use of Industry 4.0 (I4.0) technologies in smart remanufacturing environments. Chauhan et al. (2021) proposed a framework integrating I4.0 and CE principles to analyze and optimize resource consumption in manufacturing and Lopes de Sousa Jabbour et al. (2018) developed a research agenda and roadmap for sustainable operations incorporating I4.0 and CE principles. The cluster highlights how digital technologies such as artificial intelligence, machine learning, and IoT can enhance the efficiency and effectiveness of remanufacturing processes, enabling real-time monitoring and optimization of energy consumption. Furthermore, significant resource savings and environmental benefits can be achieved through additive manufactur- ing. Investigating the role of governments in overcoming barriers and fostering new mar- kets for remanufactured goods, along with the development of supportive infrastructure plans, presents an intriguing avenue for future research. From a knowledge perspective, studying data-driven frameworks that integrate smart circular strategies holds promise in providing extensive product and process information, underscoring the need for effective mechanisms for data quality control and data security. Additionally, future research could focus on identifying barriers to I4.0 technology adoption, exploring skill development and trust-building strategies among employees, and advancing the understanding of the relationship between dynamic capabilities and CE practice adoption in response to changing environmental and market conditions. This cluster provides a comprehensive overview of the intersection between digital technologies, sustainability, and circular manufacturing, highlighting both the potential benefits and the challenges that need to be addressed for successful implementation.

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

Cluster 7 (86 publications) focuses on the role of blockchain technology in enabling data integration and supporting sustainability efforts within the circular economy paradigm. The papers in this cluster leverage empirical findings to develop nuanced hypotheses for understanding how blockchain can impact and enhance sustainable operations across the CE value chain. This includes exploring topics such as transparent tracking of material flows, secure data sharing among stakeholders, and the potential for blockchain-based smart contracts to automate and optimize circular business processes. This cluster explores the application of blockchain technology in CE practices, with some papers using empirical findings to develop hypotheses for understanding its impact on sustainable operations. For instance, Rajput & Singh (2019) employed a qualitative methodology, combining literature review and case studies, to examine the role of artificial intelligence, Big Data analytics, Blockchain, and IoT in CE strategies such as waste reduction and design for circularity. Zhang et al. (2020) developed a framework for implementing blockchain-based life cycle assessments through a systematic literature review. Other researchers identified critical success factors for implementing blockchain-based circular supply chains, including a shared vision among stakeholders and adaptability to changing technological and regulatory environments (Varriale et al., 2021). Umar et al. (2022) presented an empirical study on Industry 4.0 technologies and green supply chain practices using a quantitative approach with survey questionnaires. The cluster also explores the potential of integrating blockchain with IoT and RFID to enhance sustainability in distribution and order management. Blockchain's features such as immutability, transparency, reliability, and verifiability make it an ideal solution for facilitating information flows among complex supply chain networks and stakeholders. The papers highlight critical success factors for implementing blockchain-based circular supply chains, including trust, transparency, and data privacy (Rajput & Singh, 2019; Varriale et al., 2021; A. Zhang et al., 2020). Future research directions identified in this cluster include expanding empirical studies on sustainability practices facilitated by blockchain-based solutions, investigating the social impact of Industry 4.0 on human resource management practices, examining the relationship between adoption rates and technical knowledge constraints, and exploring the role of government policies in promoting blockchain and Industry 4.0 technology adoption. The cluster also emphasizes the need for enhancing data traceability, security, and integrity features of blockchain use for smart contracts to build trust between partners and foster collaborative relationships (Varriale et al., 2021; A. Zhang et al., 2020). There is a need for exploring the social impact of I4.0 on human resource management practices and examining the relationship between adoption rates and technical knowledge constraints. Government policies, regulations, and incentives play a pivotal role in fostering the adoption of I4.0 and blockchain technologies across industries, highlighting the need for supportive frameworks to accelerate digital transformation. Furthermore, enhancing blockchain-enabled smart contracts' features, such as data traceability, security, and integrity, is essential to building trust among business partners and promoting collaborative, transparent working relationships. Addressing these aspects through robust frameworks for data standardization and privacy will not only improve operational efficiency but also provide organizations with actionable insights.

4.3.8 Cluster 8: Miscellaneous and Sectorial Applications

Cluster 8, encompassing 31 publications, explores industry-specific applications and miscellaneous topics related to Circular Economy (CE) and sustainability, making it the smallest cluster in the analysis. The papers in this cluster investigate various aspects of Industry 4.0 (I4.0) and CE implementation across different industrial contexts. For example, Abdul-Hamid et al. examined the drivers of I4.0 in Malaysia's palm oil industry, while Piyathanavong et al. (2022) studied the role of project management in sustainable supply chain development within the Thai metals industry. Other papers focus on specific industrial applications of CE and I4.0 technologies, such as Vimal et al.'s (2022) analysis of adoption drivers for I4.0 technologies in circular sharing networks for paper, cement, and sugar industries. This cluster emphasizes the importance of empirical research to assess the impact of I4.0 technologies on CE strategies and identify key factors for successful implementation. It highlights how integrated data management systems can enhance collaboration for optimized procurement and production across industries. This cluster underscores the critical need for empirical studies to investigate and evaluate how Industry 4.0 technologies influence circular economy strategies, identifying crucial factors that enable successful implementation. For example, integrated data management systems can substantially improve cross-industry collaboration, optimizing procurement and production processes. Moreover, examining the role of management systems in addressing employee resistance to technological change presents a compelling direction for future research. Such investigations could provide valuable insights into overcoming barriers to Industry 4.0 adoption and fostering a more circular and sustainable industrial landscape.

4.5 Summary of findings

Despite the growing interest in Industry 4.0 (I4.0) technologies for environmental sustainability and circular economy (CE), research in this domain remains fragmented. This bibliometric review provides a comprehensive analysis of these interconnected fields, identifying key contributors and influential journals. Through network-based analysis, eight major research clusters emerged, revealing both high-level conceptual approaches and technology-specific studies. The findings highlight a dichotomy between broad explorations of sustainability and CE in relation to I4.0, and more focused investigations on specific technologies like Big Data analytics, additive manufacturing, and blockchain. A large amount of literature has adopted a high-level conceptual approach (in particular Cluster 1 addressing the linkage between 'General Sustainability and Industry 4.0'; Cluster 2 discussing the impacts of 'General Circular economy and Industry 4.0') while other studies have a more specific focus on one or few technologies on a more narrow domain (Cluster 3 focusing on the role of Big Data analytics in supply chains; Cluster 4 on 'additive manufacturing' in R&D and production process, Cluster 7 on Blockchain). In conclusion, a structured and comprehensive research agenda is identified. This agenda includes ten promising research directions for scholars in this field. These directions encompass development at the technological level (data integration, security), material level (additive manufacturing), social dimensions, general policy dimensions, and managerial dimensions. The research agenda lays a solid foundation for future investigations in this field.

4.5.1 Contribution of Research

Theoretical implications:

This study provides significant theoretical contributions to the field of Industry 4.0, environmental sustainability, and circular economy. By conducting a comprehensive bibliometric review and network-based analysis, it offers a systematic understanding of the intersections between these three dimensions, addressing the previously fragmented nature of the literature. The identification of eight major research clusters illuminates key themes and areas of focus, ranging from high-level conceptual approaches to specific technological applications. This clustering approach provides a structured framework for understanding the current state of research and highlights gaps in knowledge. The proposed research agenda, encompassing ten promising directions, lays a solid foundation for future investigations, encouraging scholars to explore underdeveloped areas such as data integration, security, social dimensions, and policy implications of Industry 4.0 in the context of sustainability and circular economy.

Managerial implications:

From a practical standpoint, this bibliometric literature review serves as a valuable resource for managers, practitioners, and policymakers seeking to leverage Industry 4.0 technologies for environmental sustainability and circular economy initiatives. The comprehensive overview of research themes and clusters enables stakeholders to gain insights into the potential applications and impacts of various technologies across different domains. Managers can use this knowledge to inform strategic decision-making, identify opportunities for implementing Industry 4.0 solutions in their operations, and anticipate challenges in adoption. The study's findings can help raise awareness about the importance of integrating sustainability and circularity principles into digital transformation efforts. Additionally, the identified research directions provide guidance for organizations looking to invest in research and development or collaborate with academic institutions to address key challenges in the field. By understanding the current state of research and future trends, managers can better position their organizations to capitalize on the synergies between Industry 4.0, sustainability, and circular economy practices.

4.5.2 Research Agenda

The literature review has identified several influential articles through bibliometric analysis, revealing important research gaps that form the basis for a comprehensive research agenda comprising ten main directions. Particularly, this research directions identified from the bibliographic coupling where each research direction linked to a particular cluster with four highly transversal directions appearing in at least five clusters, three common to two clusters, and three suggested by single clusters. The research directions outlined in the Table 4. 10 reveal a complex interplay between Industry 4.0, sustainability, and the circular economy, emphasizing the need for a holistic approach to address these interconnected themes. The importance of dynamic capabilities in sustainable manufacturing underscores the need for organizations to adapt to rapidly evolving technological and market landscapes. This research agenda highlights the need for a systemic approach that considers the intricate relationships between emerging technologies, environmental stewardship, and the transition towards a more sustainable, closed-loop economic model. By addressing these interconnected themes, researchers and practitioners can work towards developing innovative solutions that drive progress in the realms of industrial automation, resource efficiency, and waste reduction.

Table 4. 10 Future research direction on Circular economy, environmental sustainability and Industry 4.0

Research direction	Cluster 1 – General linkages between Sustainability and Industry 4.0	Cluster 2 – General linkages between Circular economy and Industry 4.0	Cluster 3 - Industry 4.0 and Big Data Analytics for supply chain circularity and sustainability	Cluster 4 - Additive Manufacturing for Circularity and Sustainability	Cluster 5 - Urban Sustainability	Cluster 6 - Sustainable, Circular and Digital (Re)Manufacturing	Cluster 7 - Blockchain and Data Integration for Sustainability and Circular Economy	Cluster 8 - Miscellaneous and Sectorial Applications

1. Carrying out Empirical Research at the intersection of I4.0, environmental sustainability, and CE	X	X	X	X		X	X	X
2. Investigating the social impact of Industry 4.0 technologies used for CE and sustainability.	X	X	X	X	X	X	X	
3. Investigating the role of government regulations and policies	X	X	X	X	X	X	X	X
4. Developing Data Management and Data Integration frameworks and Platforms for Sustainability and Circular Economy for companies and smart cities			X		X	X	X	X
5. Addressing Data and Cyber Security issues in the context of I4.0, CE, and Environmental Sustainability	X				X			
6. Exploring the influence of specific I4.0 technologies on CE and environmental sustainability		X				X		
7. Exploring Novel Business Models for advancing CE, environmental sustainability and I4.0		X			X			
8. Investigating Sustainability as a driver for Industry 4.0 adoption	X							
9. Developing Sustainable Additive Manufacturing materials, technologies, and supply chains				X				
10. Exploring the Role of Dynamic Capabilities in the Adoption of CE Practices for Sustainable, Circular, and Digital (Re)Manufacturing.						X		

Research direction #1 Carrying out empirical research at the intersection of Industry 4.0, Sustainability, and Circular Economy.

Empirical research plays a crucial role in gaining a deeper understanding of the relationship between I4.0, sustainability, and CE at both conceptual and practical levels. It is essential to move beyond conceptual papers. Six clusters emphasised the need for empirical research to investigate and quantify the impact on sustainability and CE as well as to unify indicators assessing economic, environmental, and social impacts (Beltrami et al., 2021). Furthermore, empirical studies are necessary to address the development and configuration of effective business models and digital manufacturing ecosystems that foster sustainability (Rejeb et al., 2022). By providing valuable insights into areas such as product design, strategic planning, environmental accounting, public policymaking, marketing, logistics, and supply chain management, empirical evidence would enable a comprehensive understanding of the quantitative and qualitative effects of sustainability and CE within the realm of I4.0. This approach would not only bridge the gap between theory and practice but also offer tangible guidance for organizations navigating the complex intersection of digital transformation and sustainable development.

Research direction #2 Investigating the social impact of Industry 4.0 technologies used for Circular Economy and Sustainability.

The majority of research clusters (seven out of eight) underscored the significance of addressing the social implications associated with the adoption of Industry 4.0 technologies within the context of the circular economy and environmental sustainability. However, there is a notable absence of comprehensive investigations examining the evolving social landscape, including issues such as education, skills, and wealth disparities in consumer markets, which provide a strong impetus for future research in this domain. ne key aspect emphasized is the effect of automation on low- to middle-skilled jobs (Godina et al., 2020) while, on the other hand, the

creation of new opportunities in technology and engineering fields also deserves further investigation (Kamble & Gunasekaran, 2021). The importance of addressing income and employment polarization should also be mentioned (Ghobakhloo, 2020). It is vital to ensure social inclusivity, citizen participation, and equitable access in sustainable urban development. Atif et al., (2021) suggests the exploration of the social acceptability of CE products and services as an area for investigation. Furthermore, the social dimension of sustainability in supply chain management demands increased attention, with the adoption of reliable social performance measurement models like the social return on investment to quantify social impact. Policymakers play a pivotal role in promoting the adoption of emerging technologies and fostering skills development to support these initiatives. Lastly, research should examine the influence of social media on consumer behavior and its potential to enhance sustainable supply chains (Jeble et al., 2018)(Shiris et al., 2018). This multifaceted approach underscores the importance of integrating social considerations into sustainability efforts, ensuring a more holistic and equitable transition towards a circular economy.

Research direction #3 Investigating the role of Government regulations and Policies.

Government regulations and policies are instrumental in advancing sustainability, circular economy

(CE), and Industry 4.0 (I4.0) adoption, influencing various industry aspects from market creation to production and logistics across micro, meso, and macro levels (Chau et al., 2021). Future research should investigate the effectiveness of policy interventions such as subsidies and energy-saving regulations in promoting sustainable practices and minimizing socio-economic inequality related to I4.0 technologies (Chauhan et al., 2021). The environmental impact of I4.0 implementation also requires attention. Given I4.0's reliance on data-driven technologies, policies must address data privacy, security, and governance concerns, including safeguarding data, protecting intellectual property rights, and developing regulations for data sharing (Kayikci et al., 2022). Governments have a critical role in promoting sustainability among urban consumers, necessitating research on innovative policy measures, monitoring policy effectiveness, and understanding stakeholder involvement in urban sustainability policy development and implementation (Bibri, 2019b). To promote CE practices, policymakers can incentivize the adoption of circular supply networks and green products, and support remanufacturing industries (Umar et al., 2022). Lastly, cross-national studies can offer valuable insights into diverse policy-making approaches, enabling policymakers to refine their strategies and cultivate new markets for sustainable products. This research direction emphasizes the need for a comprehensive understanding of the policy landscape to effectively drive the integration of I4.0 technologies with CE and sustainability principles across various sectors and geographical contexts.

Research direction #4 Developing Data Management and Data Integration frameworks and Platforms for Sustainability and Circular economy for companies and Smart cities.

Addressing gaps and challenges in data management and integration emerges as a critical research direction for the future of Industry 4.0 (I4.0), Circular Economy (CE), and sustainability integration. This direction encompasses various aspects, including the integration of new technologies and resolution of compatibility issues within existing systems in circular procurement and supply chain management. Ensuring data accuracy, timeliness, and completeness is crucial for developing data-driven circular strategies in manufacturing. Research should focus on challenges associated with blockchain-based data management systems, such as data manipulation, integration, scalability, and transmission (Bag et al., 2023; Hettiarachchi, Seuring, et al., 2022). Enhancing data traceability, security, and integrity in blockchain utilization is essential for fostering trust and collaborative relationships. Developing data-driven frameworks that promote semantic interoperability between machines and designing efficient interfaces and data networks to encourage stakeholder collaboration are key areas for investigation. Knowledge management within organizations, particularly in collecting, storing, and sharing information generated through I4.0 technologies, could significantly contribute to digital supply chain networks. In urban sustainability, there's a need to integrate diverse data sources and technologies for effective decision-making in smart cities. This involves developing frameworks, protocols, and applications for sensor data collection and analysis, optimizing ICT infrastructure, and exploiting the potential of Big Data and cloud computing (Kurniawan et al., 2022).

Research direction #5 Addressing Data and Cyber Security issues in the context of Industry 4.0, Circular Economy, and Sustainability

Further research attention is needed in the areas of data and cyber security due to the extensive data transactions and sharing involved in Industry 4.0 (I4.0). This is crucial as cyber threats from anonymous users can be challenging to identify yet can significantly impact operations (Ghobakhloo et al., 2021). The research direction also highlights opportunities for more transparent and traceable options using encrypted digital records in manufacturing sustainability. Future studies should focus on leveraging digitization to address security and privacy concerns in smart city and manufacturing environments. This includes investigating security threats across different layers of data technologies and examining the security and safety of digital infrastructure for citizens, vendors, and stakeholders (Rajput & Singh, 2019).

Research direction #6 Exploring the influence of specific Industry 4.0 technologies on Circular Economy and Sustainability

The role of specific Industry 4.0 (I4.0) technologies in decision-making solutions supporting various aspects of business operations within the Circular Economy (CE) paradigm for environmental sustainability requires further investigation. While technologies like IoT and Big Data have been extensively explored, the specific contributions of other I4.0 technologies have been relatively neglected. Given the nascent stage of CE implementation, it is crucial to explore the interconnections between different technologies and their collective role in establishing a CE paradigm (Stroumpoulis & Kopanaki, 2022). This research direction calls for the development of classification frameworks or theories that can elucidate the roles of specific technologies in the CE context. Such frameworks could serve as prescriptive conceptual tools to support practitioners in implementing I4.0 technologies for CE and sustainability purposes. By focusing on the specific contributions of various I4.0 technologies, this research direction aims to provide a more nuanced understanding of how the individual and integration of more than one technology technologies can be leveraged to enhance planning, control, execution, business model innovation, corporate competitiveness, and on-the-job training capabilities within the CE paradigm. The emphasis is on exploring how these technologies transform operations management practices.

Research direction #7 Exploring novel Business Models for advancing Circular Economy, Sustainability, and Industry 4.0.

Cluster 1 highlights a significant gap in current research regarding the relationship between Industry 4.0 (I4.0) and environmental sustainability. While numerous studies have examined I4.0 as an enabler of sustainability and discussed the impacts of adopting I4.0 technologies, there has been a predominant focus on how I4.0 drives sustainability. However, there is a notable lack of research exploring how environmental sustainability can strategically drive the adoption of I4.0 technologies and the digitalization process of companies and supply chains. This research direction calls for investigating how strategic paths towards increasing circularity and achieving goals like "Net zero" could be undertaken by incorporating investments in digital technologies. Beltrami et al. (2021b) identify this as a crucial area for future research, emphasizing the need to understand the bidirectional relationship between sustainability goals and I4.0 adoption, potentially leading to more holistic and integrated approaches in both academic and industrial contexts.

Research direction #8 Investigating Sustainability as a driver for Industry 4.0 adoption

Cluster 2 highlights promising research directions for sustainable additive manufacturing, emphasizing the combined development of eco-friendly and recycled materials with technological advancements in 3D printing processes. This research direction calls for evaluating various recycling and manufacturing methods, as well as assessing the environmental footprint of materials used (Kellens et al., 2017). Potential areas of investigation include designing and developing systems to save resources, reduce energy consumption, and optimize labor and material costs. Future research should focus on how to utilize secondary raw materials as additive manufacturing powders and design reverse supply chains to collect them, connecting various stakeholders in the process (Godina et al., 2020; Kellens et al., 2017).

Research Direction #9 Developing Sustainable Additive Manufacturing materials, technologies, and supply chains.

Cluster 6 emphasizes the need for future research to advance the understanding of relationships between dynamic capabilities and the adoption of Circular Economy (CE) practices. This research direction calls for investigating how firms can develop, acquire, and improve dynamic capabilities and resilience using Industry 4.0 technologies in manufacturing supply chains to adapt to changes and environmental uncertainties. Further exploration is needed to overcome the challenge of developing dynamic capabilities in isolation and to identify the roles of different stakeholders in supporting CE transition for enhanced resilience (Chari et al., 2022). By focusing on these areas, researchers can contribute to a more comprehensive understanding of how organizations can effectively leverage I4.0 technologies to build adaptive capabilities and implement CE practices in increasingly complex and uncertain business environments.

Chapter 5. The adoption of Digital Technologies in Operations Management processes for environmental sustainability and circularity

This chapter narrows its focus to investigate the role of digital technologies (DTs) in operational management (OM) processes, specifically examining their impact on environmental sustainability and circularity in manufacturing industries. Building upon the research direction (#6) suggested in previous chapter exploring the influence of Industry 4.0 technologies on the Circular Economy and environmental sustainability, the chapter presents a theoretical framework that analyses the interplay between DTs and OM processes. Through a rigorous methodology includes a systematic literature review, content analysis, and contingency analysis to elucidate how digital technologies interact with OM processes to activate environmental drivers, ultimately leading to environmental sustainability and circular benefits. Therefore, this study provides a more comprehensive understanding of the synergies between DTs and OM processes to achieve circularity and environmental sustainability and provides implications for future research and industrial practice.

5.1 Literature review design

DTs are also seen as enablers of more environmentally sustainable and circular operations, signalling a major shift in the manufacturing landscape, moving beyond mere technological and economic considerations to embrace goals of environmental sustainability (Barteková & Börkey, 2022). However, companies face barriers to achieve these sustainability outcomes, due to the lack of a strategic roadmap for implementation, or compatibility, scalability, and interoperability issues between existing and new systems, cultural and skills gaps about sustainable practices and digital technologies (Cannas et al., 2024a; Rajput & Singh, 2021), as well as economic barriers, related to high implementation costs for DTs and uncertain economic benefits. More broadly, the synergy between DT and operations management (OM) processes, such as product development, supply chain management, production, distribution, maintenance and reverse logistics offers a promising framework for achieving energy efficiency, waste reduction, resource reuse, and closed material loops (Aldrighetti et al., 2023; Neri, Negri, Cagno, Franzò, et al., 2023).

Operations Management (OM) processes are fundamental to implementing circular economy principles in the industrial practices and achieving sustainability objectives in organizations. OM processes refer to the activities and systems that organizations use to oversee the production and delivery of goods and services. These processes focus on efficiently managing resources, optimizing the production process, and ensuring smooth material and information flows, to achieve either resource efficiency, minimizing waste, reducing the cost or achieving a closed-loop system. In the context of a circular economy, operations management must consider the closed-loop nature of logistics systems and consequently extend their spatial and temporal horizon throughout the product lifecycle, including end-of-life management aspects (Aldrighetti et al., 2023). Managing, planning and executing OM processes is complex and inherently interdisciplinary. OM processes consist of several activities. Based on the literature, OM processes can be grouped into seven classes, as reported in Table 5. 1.

Table 5. 1 Classification of Operations Management (OM) Processes (Based on (Cannas et al., 2024b; Kleindorfer et al., 2005)*)*

OM process	Description
Product development (PD)	It is the process of creating and designing a new product to meet consumer needs.
Procurement, inbound Logistics & Upstream Supply chain management (PLUS)	It is the process of procuring raw materials and components, managing their inventories, ensuring efficient inbound transportation, warehousing and handling of materials, components, and products, and managing relationship with suppliers.
Production (PROD)	It refers to the set of activities, processes and procedures involved in transforming raw materials into finished goods
Distribution, Outbound Logistics & downstream Supply chain management (DOLS)	It is the process of managing the distribution of goods, their inventories, material handling and outbound logistics, and requires coordinating and optimizing all the steps and actors involved towards the final customer.
Maintain, technical assistance & repair (MAINT)	It includes maintenance, which refers to regularly updating and checking the performance of the system/product; technical assistance, which involves offering expert help to resolve issues or enhance the functionality of assets and products; and repair, which pertains to fixing issues or malfunctions.
Reverse Logistics (REVLOG)	It focuses on the return of products from customers back to the manufacturer/seller or end-of-life centers for reasons such as reuse, refurbish, recycling, or disposal. The orchestration or management of the actors involved in such processes is considered.
End of life treatment &	It refers to the end-of-life treatment methods and procedures used to

processing (EOL)	remanufacture or recycle, a product or its components once they have reached the end of its useful life.

Circular economic principles and sustainability objectives influence OM processes (Kleindorfer et al., 2005), such as designing products with consideration for their environmental impact throughout the product lifecycle (Behl et al., 2023); however, designing and implementing closed-loop supply chains, while addressing inherent complexities like managing product returns, sorting, and recycling, presents significant challenges (Guo & Zhong, 2023).

Similarly, Environmental sustainability involves preserving the Earth's life-supporting systems by enhancing their integrity (Moldan et al., 2012). Digital technologies (DTs) can play a pivotal role in achieving sustainability in manufacturing by reducing resource consumption and optimizing the use of existing assets, such as through sharing models that lessen the need for new production (Ferreira et al., 2023). However, the adoption of DTs does not inevitably lead to environmental sustainability: reasons are related to environmental impact inherent to the use of DTs, and the so-called rebound effects (Sorrell & Dimitropoulos, 2008). In fact, environmental benefits are achieved when operating mechanisms are aligned with factors triggering environmental sustainability, such as resource consumption, lifecycle duration, or prevention of CO2 emissions. Saccani et al. (2024)'s comparative study harmonized such factors driving improved environmental performances, named environmental value drivers, in the context of product-service systems. Building on that study, we will focus on investigating five key drivers of environmental sustainability and circularity, relevant for the adoption of DTs in OM processes. For the sake of simplicity, we label them environmental drivers: they are described in Table 5. 2.

Table 5. 2 Categorisation of different environmental drivers that can be triggered by DTs (Adoption from (Saccani et al., 2024))

Environmental Driver	**Description**
Resource Efficiency	Resource efficiency for finished products and assets refers to the ratio of a product's added value to the value of resources used in its production. By considering the product's operation and resource usage, efficiency can be assessed by comparing the benefits obtained to the associated environmental impacts.
Reduced usage of hazardous, toxic or critical materials	Strategies to minimize pollutants, hazardous and critical materials include product redesign, use of clean materials and processes, and implementation of reuse practices.
Lifetime extension	Lifetime extension allows products to remain in use for longer. This can be achieved through regular maintenance, provider ownership, or product redesign. This extends the lifespan of goods and reduces the need for new materials, thereby lowering resource consumption and mitigating resource depletion across the product lifecycle.

Intensified asset usage	Intensifying asset usage aims to maximize the utilization of existing assets/products in terms of time, capacity, or functionality, thereby reducing the number of product units needed to meet usage demands.
Dematerialization and transparency	Dematerialization of assets is achieved by leveraging services that minimize material consumption throughout a product's lifecycle. Additionally, digital technologies enhance transparency by enabling the identification, traceability, and monitoring of product-related data, such as location, composition, condition, maintenance history, and performance, or the virtualization of assets (e.g. thanks to digital twins), increasing visibility across the value chain.
Closing the loop	"Keep products in the loop" through multiple usage cycles, minimizing the need for new resources; "close the loop" between post-use and production enabling recycling, resulting in a circular flow of resources

5.1.1 Research gap and objective

When analysing the role of DTs for environmental sustainability and circularity, the literature has presented a quite fragmented view, overlooking a systemic perspective about the crucial interplay between DT and OM processes to achieve circularity and sustainability (Alcayaga et al., 2019; Birkel & Müller, 2021; Bressanelli et al., 2022; Taddei et al., 2022). Despite widespread claims about the environmental potential of digital technologies (DTs), the specific mechanisms through which DTs interact with OM processes to drive environmental sustainability and circularity remain underexplored. Existing research lacks a comprehensive investigation into the detailed interplay between DTs and OM processes, particularly in terms of specific impact areas and the environmental sustainability drivers they trigger (Das et al., 2024; Schilling & Seuring, 2024). Furthermore, the antecedent-process-outcome patterns that explain how DTs enhance resource efficiency and operational productivity, leading to environmental benefits, have not been fully elucidated (Schilling & Seuring, 2024). This gap in understanding motivates the need for a deeper exploration of the mechanisms by which DTs contribute to environmental sustainability and circularity within OM processes. To fill this gap, this study proposes a comprehensive review of the extant literature addressing the following research question:

"*How Digital Technologies acting on Operations Management processes contribute to foster environmental sustainability and circularity?*"

Drawing on the discussions in the preceding sections, Figure 5. 1 presents the theoretical research framework developed in this study to examine the sustainability and circularity impacts of digital technologies (DTs) through their interaction with OM processes. The framework illustrates how the nine DTs outlined in Background influence the seven OM processes identified in section 5.1, thereby activating specific environmental drivers detailed in section 5.2. This interplay ultimately contributes to achieving environmental sustainability and circularity outcomes.

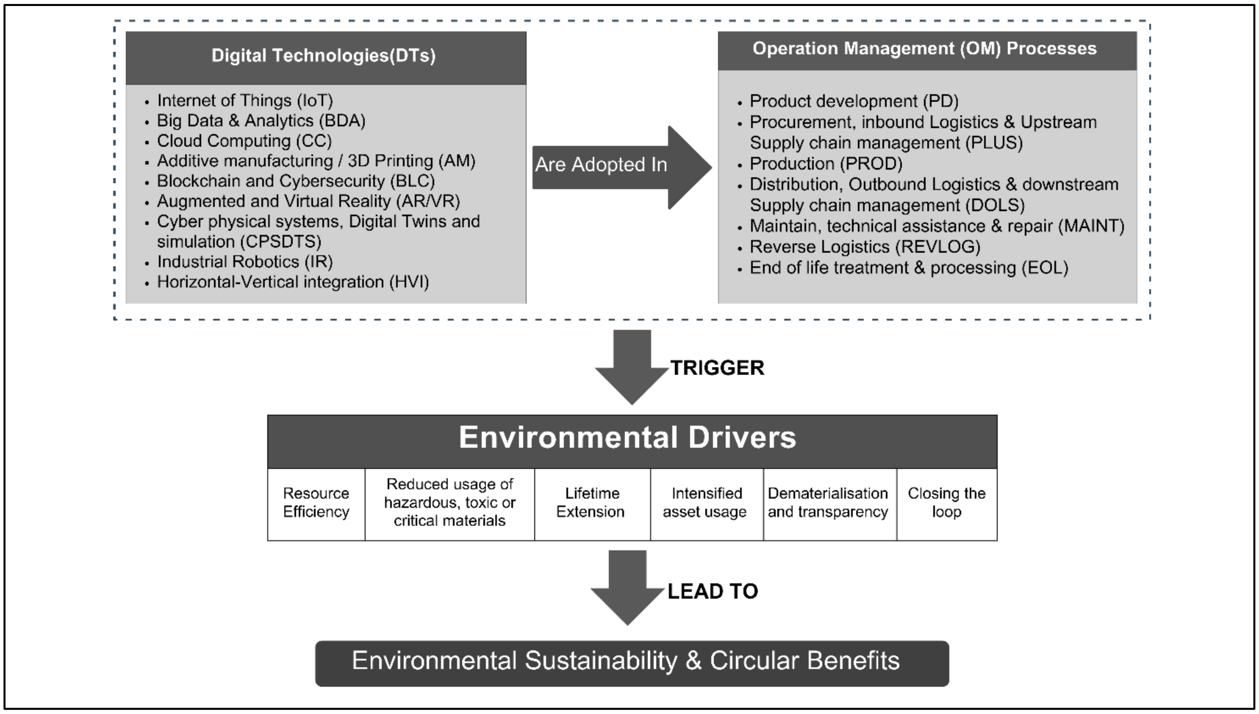


Figure 5. 1 Research framework

5.1.2 Methodology

To address the research question and contribute to the advancement of knowledge in this field, this study conducts a systematic literature review (Seuring et al., 2020) focusing on digital technologies (DTs) and their role in OM processes, as well as their environmental implications. The research employs descriptive, frequency, content-based, and contingency analyses, guided by an original research framework. The findings reveal that the integration of DTs across various OM processes activates distinct environmental drivers, enhancing sustainability and circularity, with resource efficiency emerging as the predominant driver. Additionally, the study assesses the maturity of scientific research on DT-OM process relationships, categorizing them as consolidated, niche, or emerging areas of investigation.

The systematic literature review process began with the development of a comprehensive review protocol and search strategy guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher et al., 2009; Page et al., 2021) to ensure clarity, transparency, and limited bias. The followed steps are depicted in Figure 5. 2.

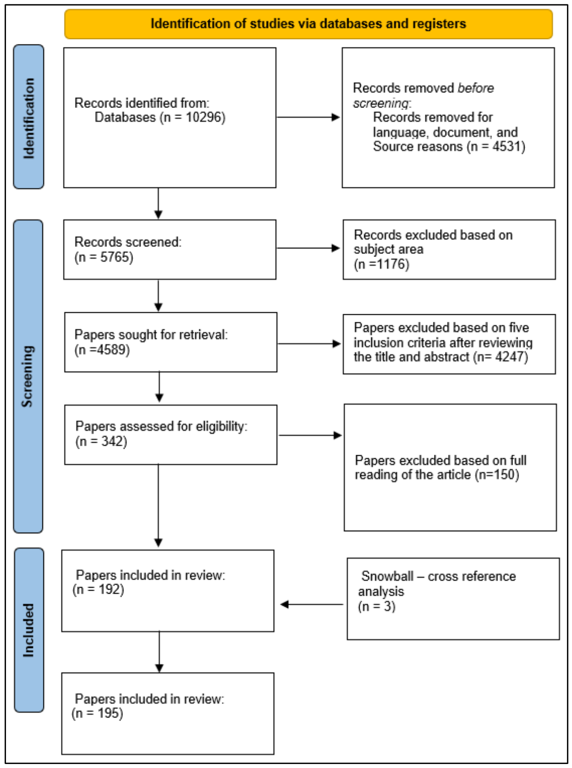


Figure 5. 2 Flow diagram for the selection of the literature based on PRISMA guidelines

Two sets of keywords were carefully selected to capture the relevant literature: one focusing on the **popular digital technologies** and the other on circular economy and sustainability concepts. The search was conducted in January 2024 using a meticulously crafted search string that combined these keyword sets. Specifically, the search string TITLE-ABS-KEY ("Circular Economy" or "Sustainability") AND TITLE-ABS-KEY ("Internet of Things" OR "Cyber-physical systems" OR "Cloud computing" OR "Industrial robotics" OR "Data analytics" OR "Big data" OR "Additive manufacturing" OR "3D printing" OR "Industry 4.0" OR "Digital Technologies") was employed across major academic databases. This rigorous search methodology yielded an initial corpus of 10,296 articles. The second phase of the methodology involved a rigorous screening process to refine the initial pool of articles. Only peer-reviewed journal articles published in English were included, while conference papers, books, and other non-peer-reviewed sources were excluded to ensure the quality and reliability of the analysis. Further filtering focused on subject areas relevant to the study, such as engineering, operations, services, manufacturing, computer and social sciences, and business management. Articles from unrelated fields, including dentistry, nursing, neuroscience, arts and humanities, medicine, agricultural and biological sciences, pharmacology, immunology and microbiology, earth and planetary sciences, chemistry, biochemistry, genetics, materials science, physics, and astronomy, were excluded. This meticulous screening process resulted in a refined selection of 4,589 relevant articles from the original dataset for further analysis.

The subsequent phase of the methodology involved a thorough review of the titles and abstracts of the 4,589 papers based on specific inclusion criteria. These criteria were designed to ensure the relevance and quality of the selected articles:

- The article must specifically address digital technologies or Industry 4.0/5.0, avoiding general or broad discussions of these topics.
- The article must explicitly focus on circular economy or environmental sustainability, rather than treating them as peripheral trends or discussing them in vague terms.
- The article must concentrate on manufacturing or business operations management processes related to the production of goods, aligning with the technical aspects of the Ellen MacArthur Foundation's butterfly diagram (Macarthur, 2013).
- The article should examine the application of digital technologies (DTs) to one or more of the OM processes outlined in Table 2. 4 and Table 5. 1.
- The article should discuss beyond a purely literature-based review and incorporate analytical or conceptual modelling, or empirical analyses such as case studies, surveys, or similar methodologies.

This rigorous screening process resulted in 342 pertinent articles for detailed analysis. A full-text review, reapplying all inclusion criteria, further refined the selection to 192 articles. To address potential keyword limitations in the database search, a cross-reference analysis was conducted, included three additional relevant papers. We carried out a descriptive, content, frequency and contingency analysis. The descriptive analysis classified papers by publication year and journal. The content-based analysis identified patterns within 195 articles, following a structured framework (Figure 5. 1). This analysis included data collection methodology (Bressanelli et al., 2020), digital technologies (DTs) (Table 2. 4), operational management (OM) processes (Table 5. 1), impact domains (qualitative classification of DT influence on OM), environmental drivers (Table 5. 2), and environmental benefits (qualitative classification). Content coding was performed in MS Excel, ensuring validity through multiple reviews. A single researcher executed the coding, with co-authors providing quality checks. Content analysis alone often has limited value when viewed as individual items, since it lacks the ability to establish links between different constructs. A contingency analysis was therefore carried out in order to explore the relationships between constructs within the articles and identify potential dependencies or correlations based on code combinations occurring in the literature sample (de Lima et al., 2024; Fleiss et al., 2003). This method has been applied in prior studies on sustainable supply chains and DTs (de Lima et al., 2024; Hettiarachchi, Brandenburg, et al., 2022b; Schilling & Seuring, 2024). Contingency tables compared observed and expected DT-OM process pairings, assessing statistical significance via SPSS 26.0 crosstabs. A Chi-square test determined the phi coefficient, indicating association strength. Relationships were deemed significant at $p < 0.05$, with a phi coefficient > 0.1 suggesting a strong association (Akoglu, 2018).

5.2 Descriptive Analysis

The temporal analysis of publications, illustrated in Figure 5. 3, reveals a significant evolution in research focus since 2014. While early publications (2014-2017) primarily explored 3D printing within a broad context, with limited discussion on circular economic strategies and general sustainability, a marked shift occurred from 2018 onwards. The field experienced exponential growth, particularly in 2022 and 2023, which accounted for 70% of the sample. This surge reflects an expanding research interest in the role of digital technologies in enabling circular and sustainability benefits across various operations management processes. Hence, starting from 2018, articles began to explore multiple important technologies and their roles in various aspects of operations management processes.

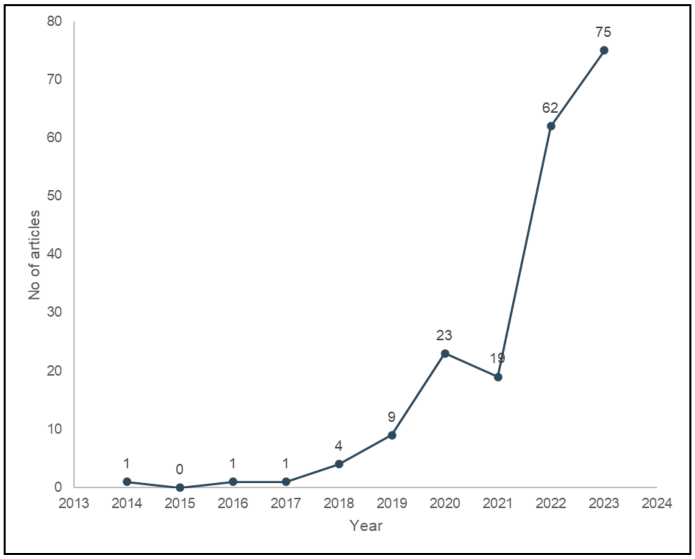


Figure 5. 3 Temporal distribution of the literature sample

Figure 5. 4 represents the journal distribution of the sample. The 195 selected articles are published across 85 different journals, with only 11 journals featuring four or more publications. Notably, 48% of the articles appear in leading journals specializing in circular economy, sustainability, and operations management. These include Business Strategy and the Environment, Computers and Industrial Engineering, Production Planning and Control, International Journal of Advanced Manufacturing Technology, International Journal of Production Economics, Journal of Cleaner Production, and Resources, Conservation and Recycling. Among them, the Journal of Cleaner Production stands out as the most prominent source, accounting for 28 articles (18%) of the total sample.

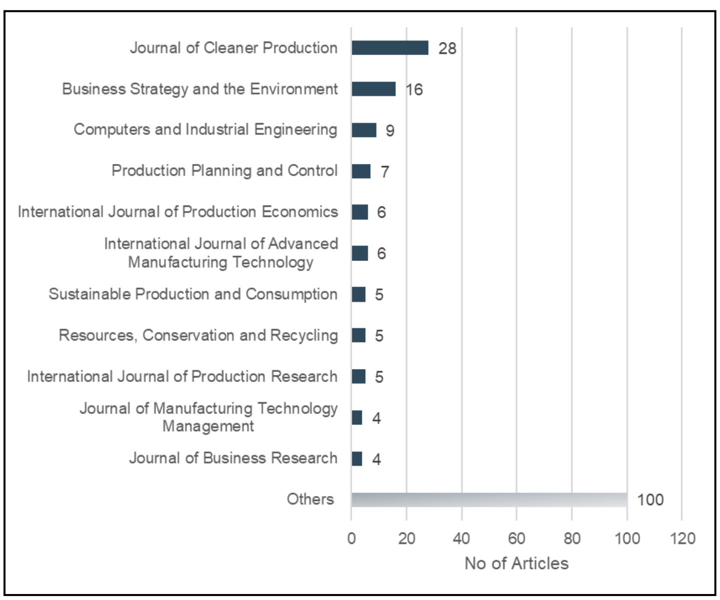


Figure 5. 4 Distribution of articles per Journal

5.3 Content Based Analysis

In this section, a systematic examination of the articles is conducted by thoroughly reading each article and analyzing the tables and visual data provided within them. This framework comprises a defined set of units of dimensions and deductively categorized options (different items within each dimension) to classify the content of the 195 selected articles. This categorization is derived from foundational theoretical constructs and the thematic scope elucidated within the examined articles mentioned by (Bressanelli et al., 2020). The analysis was facilitated by a comprehensive database in MS Excel, which underpinned the entire coding process as per the specified framework. Within this process, patterns, themes, commonalities, and divergences within the data were identified using analytical or thematic codes mentioned in the Excel database. To ensure the codes' validity, the codebook underwent multiple rounds of review, aligning with the framework's description. The coding procedure was meticulously conducted by a single researcher who received support and quality checks from other team members. Nevertheless, it is important to acknowledge the inherent limitations of the coding process, including the potential for subjective interpretation based on the researcher's own knowledge and experience.

5.3.1 Classification based on Methodology

The articles were analysed based on the methodologies adopted for Data Collection and Data Analysis. The classification of the 195 articles based on this methodology along with the inclusion of conceptual frameworks. For data collection, four primary methods were identified, as shown in Figure 4. The majority of studies relied on literature reviews (99 articles) and case study methods (85 articles), highlighting the exploratory nature of research in this domain. These methods often aim to consolidate existing knowledge or derive insights from practical applications, typically through single-case analyses. Fewer studies utilized surveys (76 articles) or laboratory tests and in-house experiments (34 articles), reflecting a limited emphasis on empirical and experimental approaches. Additionally, 55 articles developed conceptual models and frameworks, underscoring ongoing theoretical advancements in understanding critical factors such as drivers, barriers, and capabilities related to circular economy (CE) and sustainability (Bag, Gupta, et al., 2021; Ghadge et al., 2022; Pinheiro et al., 2022; Sharma et al., 2021).

In terms of data analysis methodologies, the studies employed various techniques to interpret and derive insights from the collected data. Statistical analysis emerged as the most frequently used method, appearing in 92 articles, followed by conceptual developments (55 articles) and static simulations (53 articles). Expert-based opinions, including focus group interviews, were utilized in 47 studies, reflecting a reliance on qualitative insights to explore complex topics. However, relatively few studies employed analytical models or dynamic simulations, which use mathematical modelling to explore closed-loop solutions within CE frameworks. This indicates an opportunity for further research employing advanced quantitative techniques to deepen understanding. Overall, the methodological approaches reveal a field that is still maturing, with a strong focus on exploratory and qualitative methods but growing interest in theoretical model development. While conceptual frameworks are being actively refined to address gaps in understanding the interplay between digital technologies and CE practices, there remains significant potential for expanding empirical research through more robust experimental designs and advanced analytical tools to enhance practical applicability.

5.3.2 Classification based on Industry 4.0 technology

Figure 5. 5 illustrates the number of articles addressing the nine DTs. It is observed that IoT (57%, i.e. 110 out of 195), BDA (56%, i.e. 109 out of 195) followed by AM (50%) are the most investigated technologies. IoT and BDA facilitate data acquisition, transfer, and processing, enabling enhanced resource management and improved performance across the value chain through real-time information sharing, collaboration, and coordination among various processes. For instance, IoT and BDA empower organizations to optimize operations by leveraging data-driven insights to enhance decision-making and operational efficiency (Chiarini et al., 2020; Kristoffersen et al., 2020; Rizvi et al., 2023). Additionally, AM enhances production processes, making them suitable for high product complexity and customization, enabling minimal material consumption and greater energy efficiency compared to traditional manufacturing (Kahhal et al., 2024). It disrupts the supply chain by shifting towards the use of recycled materials, promoting local material sourcing to optimize purchasing and upstream supply chain processes. The articles have investigated the sustainability of different AM

production technologies. AM technologies, such as Fused Deposition Modelling (FDM) (Depalma et al., 2020; Khalid & Peng, 2021), Large Scale Additive Manufacturing (LSAM)(Romani et al., 2023), and Fused Filament Fabrication (FFF) (Bossart et al., 2021; Ferreira et al., 2023; Mohammed et al., 2022; Sam-Daliri et al., 2023), have transformative potential in the manufacturing sector, leading to improvements in sustainability, efficiency, and customization compared to traditional manufacturing. (Kahhal et al., 2023).

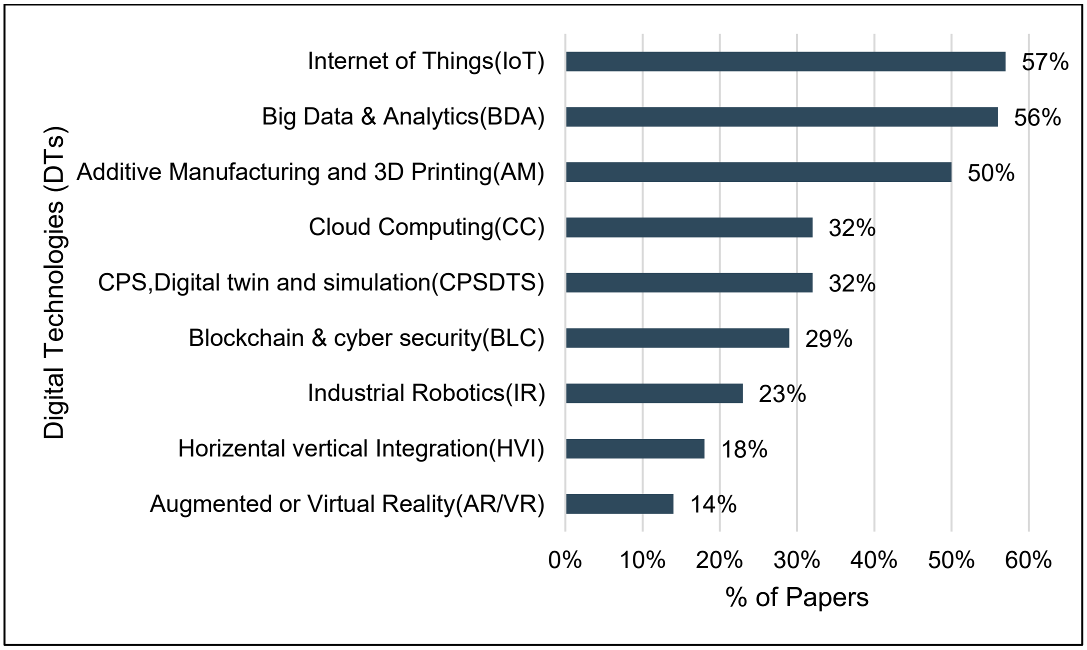


Figure 5. 5 Industry 4.0 technologies discussed by set of papers

Conversely, technologies such as Augmented Reality/Virtual Reality (AR/VR) and Horizontal and Vertical Integration (HVI) are less frequently discussed, appearing in only 15% (28 articles) and 20% of the studies, respectively. This limited focus may be attributed to their relatively recent emergence in operations management processes and the various challenges associated with their adoption. Factors such as technological hurdles, organizational resistance, social barriers, high investment costs, and a lack of standardized data integration protocols hinder the effective implementation of these technologies (Ferreira et al., 2023; Shang et al., 2022; Sharma et al., 2021). Moreover, insufficient knowledge about AR/VR capabilities and unclear in direct economic and environmental benefits further contribute to reluctance among organizations to embrace these innovations. Addressing these challenges will be crucial for unlocking the full potential of AR/VR and HVI in enhancing operational efficiency and sustainability in manufacturing contexts.

5.3.3 Classification based on OM processes

Figure 5. 6 provides an overview of the frequency with which different Operations Management (OM) processes are addressed in the literature sample. Production (PROD) emerges as the most frequently discussed process, appearing in 96 articles (49% of the sample). This is closely followed by Procurement, inbound Logistics & Upstream Supply chain management (PLUS) at 45% and End-of-Life (EOL) treatment and processing at 43%.

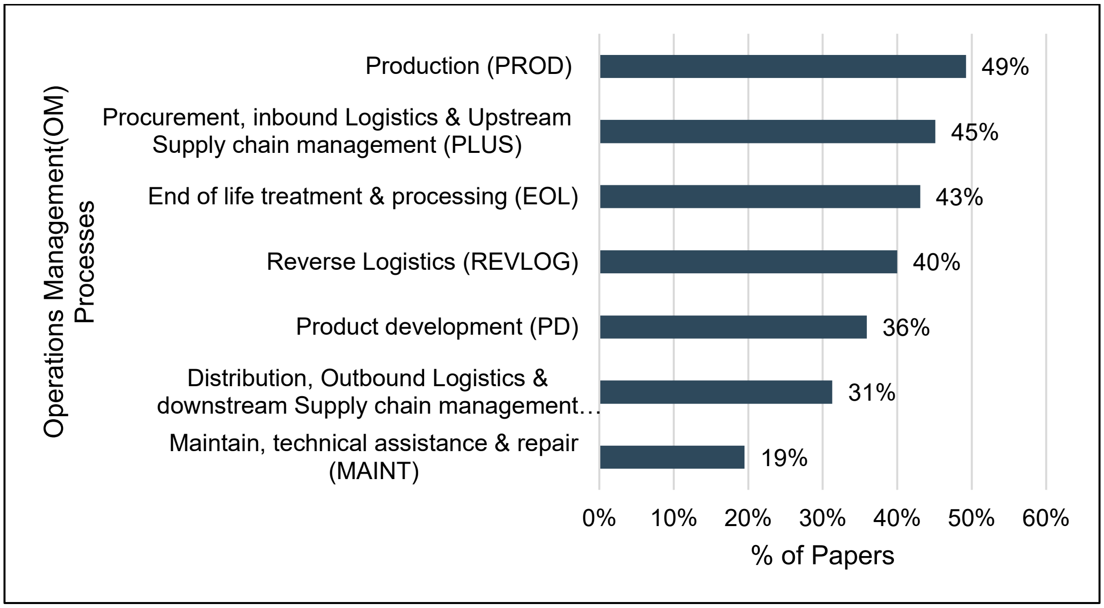


Figure 5. 6 Number of papers touching Operations Management processes

The high frequency of PROD-related discussions centre on how digital technologies (DTs) can reduce environmental impacts by increasing efficiency and optimizing resource and energy consumption. PLUS-focused papers explore themes such as the transformation of traditional supply chains into digital ones, highlighting logistical advantages, enhanced operational efficiency, and improved supplier coordination (Ali et al., 2023; Kusi-Sarpong et al., 2023; Tavana et al., 2023). From a circular economy perspective, EOL processes are critical, with reviewed papers emphasizing the importance of DTs in technically improving or optimizing activities like disassembly, material sorting, recovery, recycling, upcycling, and non-organic material reuse (Delpla et al., 2022; Garrido-Hidalgo et al., 2020; Kumar et al., 2023). Another observation, the evolving landscape of distribution and downstream supply chains is increasingly prioritizing closer manufacturer-consumer relationships. Business models such as servitization and product-service systems (PSS) are emerging as key drivers in this shift, focusing on service aspects alongside product offerings to foster customer loyalty and satisfaction. Additionally, advancements in outdoor delivery, after-sales service platforms streamlining product returns, and route optimization for cost reduction are gaining traction. These developments contribute to a reduction in damaged goods and a more efficient Sales & Distribution (S&D) network, ultimately leading to increased profitability. Among the seven OM processes, Maintenance (MAINT) received the least attention, addressed by only 19% of the sample (38 articles). This limited consideration of DTs' role in maintenance activities highlights a potential area for future research. Samadhiya et al. (2023) explored the relationship between total predictive maintenance and Industry 4.0 (I4.0) within the circular economic context, emphasizing the need to examine the effects of specific I4.0 tools and technologies on different maintenance practices. While I4.0 generally has a positive impact on maintenance practices, it may not universally yield sustainable outcomes, necessitating the identification of specific factors within these practices that influence individual sustainability dimensions. Ma & Mo (2023) highlighted operational challenges in maintenance, including decentralized information systems and non-standardized process flows, while Turner et al. (2022) investigated the digital maintenance framework, emphasizing challenges related to data connectivity and gathering. These findings suggest a need for more focused research on the integration of DTs in maintenance processes to fully leverage their potential in enhancing sustainability and operational efficiency.

5.3.4. Distribution based on 4 CE strategies

The thematic analysis of 195 articles on the Circular Economy's 4Rs strategies reveals a significant imbalance in research focus, with 'Recycle' and 'Reduce' strategies dominating the discourse, while 'Reuse' and 'Remanufacturing' receive comparatively less attention as shown in Figure 5. 7. This disparity highlights a critical area for future research to promote a more holistic approach to circular economy practices.

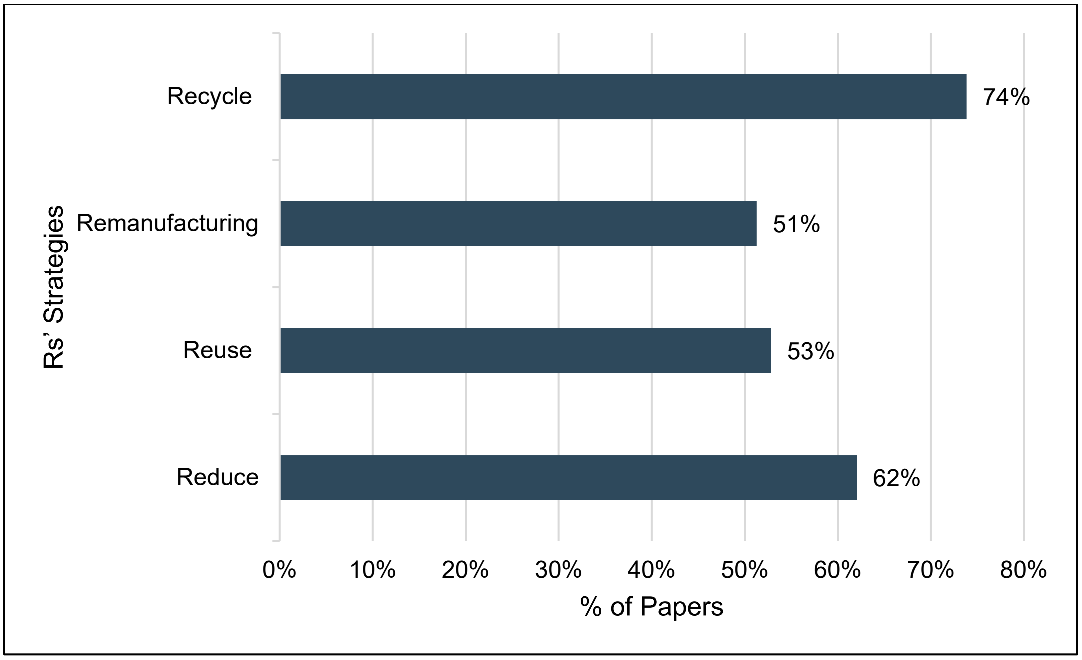


Figure 5. 7 Number of papers touching 4Rs' strategies

The 'Reduce' strategy, which aims to enhance energy and resource efficiency throughout a product's lifecycle, is extensively discussed across multiple studies. It encompasses a wide range of approaches, from optimizing natural resource consumption and enhancing production efficiency to implementing lightweight designs without compromising product quality (Salvador et al., 2021). Advanced technologies play a crucial role in supporting reduction strategies, with supply chain optimization and smart manufacturing technologies like 3D printing at the forefront (Bag, Wood, et al., 2020; Wu, Mehrabi, Naveed, et al., 2022; Gebler et al., 2014). Real-time monitoring and interactive management systems are highlighted as key enablers for improving energy efficiency in manufacturing processes (Rajput & Singh, 2020; Khalid & Peng, 2021). The 'Reuse' strategy, focusing on extending product life and recirculation, emphasizes the importance of understanding a product's condition for informed decision-making (Alcayaga et al., 2019; Dahmani et al., 2021; Turner et al., 2022). Industry 4.0 technologies are identified as catalysts for promoting reuse through innovative business models such as usage-based systems and digital marketplaces (Huynh, 2022; Bressanelli et al., 2021; Kouhizadeh et al., 2020; Beltagui et al., 2020). Remanufacturing emerges as a crucial yet underexplored CE strategy, involving the extraction of functional parts from non-functional products to create new value. This process offers both ecological and economic advantages (Salvador et al., 2021; Caterino et al., 2022; Mantelli et al., 2020). Key factors influencing the success of remanufacturing include the efficiency of reverse supply chains, consumer intentions, and design principles that facilitate easy disassembly and reassembly (Bag, Luthra, et al., 2021; Hartono et al., 2022; Schlesinger et al., 2023; Zacharaki et al., 2021). Future research opportunities in this area include optimizing disassembly procedures, understanding the complex value chain of remanufacturing, and refining part detection techniques (Govindan, 2022; Prajapati et al., 2022). Recycling, while extensively discussed and recognized as an essential method in CE and sustainability principles, is positioned at the end of the CE strategy sequence, serving to close the material loop (Delpla et al., 2022). Its prominence in literature can be attributed to its potential economic benefits and the well-established recycling infrastructure in many countries (Bergonzi & Vettori, 2021; Bossart et al., 2021; A. Dash et al., 2022; Di & Yang, 2022; Lin, 2018). However, it's crucial to note that despite its theoretical importance, current recycling rates remain disappointingly low, with only about 3% of materials being effectively recycled (Gupta et al., 2021). This underscores the need for innovative approaches and technologies to significantly improve recycling efficiency and effectiveness, positioning it as a critical area for future research and development within the circular economy framework.

5.4 Contingency analysis

The literature sample was analysed to explore the contingency relationships, first among DTs, and then between DTs and OM processes. The preliminary contingency analysis among DTs was carried out to identify significant correlations among DTs and to support their grouping, so to simplify and increase the conceptual relevance of the subsequent contingency analysis between DTs and OM processes. This two-dimensional contingency relationship involved a pairwise comparison of factor, using Chi-square test to determine the statistical significance of the relationships. The phi coefficients were calculated to measure the strength of the association between the variables, as described in Methodology section.

5.4.1 Contingency relationship among DTs

Figure 5. 8 shows the contingency relationships between pairs of technologies expressed through the values of phi coefficients. This contingency analysis of digital technologies (DTs) reveals intricate relationships and interdependencies among nine technologies. Only the 20 relationships with phi

coefficients greater than 0.3, indicating strong associations and statistical significance ($p < 0.05$), are presented in Figure 5. 8. Higher significance relationships are specifically highlighted in the figure. The analysis highlights a particularly strong connection between the Internet of Things (IoT) and Big Data Analytics (BDA), with a phi value of 0.636, underscoring their symbiotic relationship in data generation and analysis. Similarly, IoT shows a robust link with Cloud Computing (CC) (phi 0.518), emphasizing CC's crucial role in providing the necessary infrastructure for IoT data management. The strong correlation between BDA and CC (phi 0.427) further reinforces the interdependence of these technologies in modern manufacturing systems. These findings support the grouping of IoT, BDA, and CC into a single macro-technology cluster termed "Data Collection and Processing Technology" (DCPT), aligning with recent literature (Di Maria et al., 2022; Kristoffersen et al., 2020; Prakash & Ambedkar, 2023). The analysis also reveals more complex relationships among other technologies. Cyber-Physical Systems and Digital Twin Systems (CPSDTS), Industrial Robotics (IR), and Augmented/Virtual Reality (AR/VR) are often categorized as automation technologies, but their relationships with other DTs vary significantly. For instance, CPSDTS shows stronger connections with Horizontal and Vertical Integration (HVI) (phi 0.517) and IoT (0.488) than with IR (0.421) or AR/VR (0.427). This suggests that while these technologies contribute to automation, their applications and integrations within manufacturing systems can differ substantially. HVI emerges as a pivotal technology, showing significant connections with five other technologies, considered HVI as a key and foundational technology for integration and information flow and one of the strongest enablers of circularity (Kusi-Sarpong et al., 2023). Interestingly, Blockchain (BLC) and Additive Manufacturing (AM) appear as standalone technologies, showing no significant correlations with other DTs in this analysis. Based on these findings, the study proposes a refined categorization for subsequent analysis, introducing DCPT as a new macro-technology encompassing IoT, BDA, and CC, while retaining BLC, HVI, AM, CPSDTS, IR, and AR/VR as distinct technologies for further investigation.

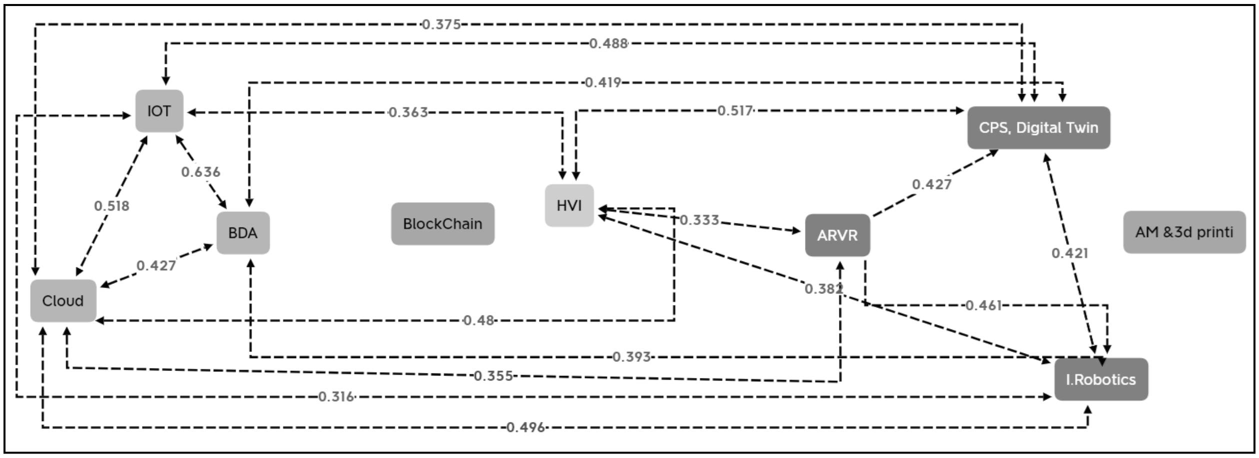


Figure 5. 8 Contingency relationship between DTs

5.4.2 Contingency analysis

The contingency analysis between the seven digital technologies (DTs) identified in Section 5.4.1 and the seven Operations Management (OM) processes examined in this study explored 49 potential relationships. The observed frequencies represent the actual number of studies addressing specific DT-OM process combinations, while the expected frequencies indicate the anticipated counts based on probability (as detailed in section 5.1.2). Among these relationships, 21 were found to be statistically significant, with p-values below 0.05 and phi coefficients exceeding 0.1, signifying meaningful connections. These significant relationships, outlined in **Table 5. 3**, highlight key intersections where DTs play a critical role in enhancing OM processes. The following subsections present a detailed analysis of the 21 significant relationships identified between digital technologies (DTs) and Operations Management (OM) processes. Organized around the seven DTs, each subsection includes a table summarizing the impact domains within the connected OM processes, the activated environmental drivers, and the resulting sustainability benefits. These tables, aligned with the research framework outlined in section 5.1.1, provide a comprehensive overview of how each DT influences specific OM processes to drive environmental sustainability. Additionally, key references from the literature sample are cited to support the findings, offering a robust foundation for understanding the interplay between DTs and OM processes in promoting sustainability and circularity.

Table 5. 3 Contingency relationships between different DTs and OM processes

#	Technology	OM Process	Observed freq.	Expected freq.	p-value	Phi coeff.
1	Data Collection and Processing Technology (DCPT)	Procurement, inbound Logistics & Upstream Supply chain management (PLUS)	70	52.8	0.0001	0.362
2	Horizontal-Vertical integration (HVI)	Procurement, inbound Logistics & Upstream Supply chain management (PLUS)	28	16.2	0.0001	0.312
3	Cyber physical systems, Digital Twins and simulation (CPSDTS)	Procurement, inbound Logistics & Upstream Supply chain management (PLUS)	41	28	0.0001	0.288
4	Augmented and Virtual Reality (AR/VR)	Maintain, technical assistance & repair (MAINT)	12	5.5	0.001	0.242
5	Additive manufacturing / 3D Printing (AM)	Production (PROD)	59	47.3	0.001	0.241
6	Industrial Robotics (IR)	Maintain, technical assistance & repair (MAINT)	16	8.6	0.001	0.23
7	Industrial Robotics (IR)	Procurement, inbound Logistics & Upstream Supply chain management (PLUS)	29	19.9	0.002	0.225
8	Blockchain and Cybersecurity (BLC)	Reverse Logistics (REVLOG)	32	22	0.001	0.223
9	Horizontal-Vertical integration (HVI)	Distribution, Outbound Logistics & downstream Supply chain management (DOLS)	19	11.3	0.002	0.221
10	Additive manufacturing / 3D Printing (AM)	End of life treatment & processing (EOL)	52	41.4	0.002	0.221
11	Data Collection and Processing Technology (DCPT)	Reverse Logistics (REVLOG)	57	46.8	0.002	0.218
12	Data Collection and Processing Technology (DCPT)	Distribution, Outbound Logistics & downstream Supply chain management (DOLS)	46	36.6	0.003	0.212
13	Blockchain and Cybersecurity (BLC)	Procurement, inbound Logistics & Upstream Supply chain management (PLUS)	34	24.8	0.003	0.21
14	Horizontal-Vertical integration (HVI)	Maintain, technical assistance & repair (MAINT)	13	7	0.005	0.20
15	Industrial Robotics (IR)	Distribution, Outbound Logistics & downstream Supply chain management (DOLS)	21	13.8	0.008	0.191
16	Industrial Robotics (IR)	Product development (PD)	23	15.8	0.01	0.184
17	Horizontal-Vertical integration	Reverse Logistics (REVLOG)	21	14.4	0.013	0.178

	(HVI)					
18	Augmented and Virtual Reality (AR/VR)	Procurement, inbound Logistics & Upstream Supply chain management (PLUS)	18	12.6	0.028	0.158
19	Cyber physical systems, Digital Twins and simulation (CPSDTS)	Distribution, Outbound Logistics & downstream Supply chain management (DOLS)	26	19.4	0.028	0.157
20	Industrial Robotics (IR)	Production (PROD)	28	21.7	0.03	0.156
21	Cyber physical systems, Digital Twins and simulation (CPSDTS)	Production (PROD)	37	30.5	0.046	0.143

5.4.2.1 DCPT and OM processes (Procurement, inbound Logistics & Upstream Supply chain management (PLUS), Distribution, Outbound Logistics & downstream Supply chain management (DOLS), and Reverse Logistics (REVLOG))

The analysis reveals strong connections between Data Collection and Processing Technologies (DCPT) and several Operations Management processes. The most robust link is with Procurement, Inbound Logistics & Upstream Supply Chain Management (PLUS), where DCPT operates in four key domains: supplier coordination, inventory optimization, sustainability tracking, and risk management. DCPT also significantly impacts Reverse Logistics (REVLOG) by enhancing communication systems and route optimization, and Distribution, Outbound Logistics & Downstream Supply Chain Management (DOLS) through improved transportation and warehouse operations. These relationships, detailed in Table 5. 4 (relationships #1, #11, and #12), demonstrate how DCPT activates various environmental drivers across the supply chain. It provides a comprehensive overview of the processes, impact areas, environmental drivers, and sustainability benefits associated with DCPT implementation in these OM processes.

Data Collection and Processing Technologies (DCPT) play a pivotal role in enhancing visibility and information sharing across the supply chain, significantly improving coordination and fostering collaborative relationships between companies and their suppliers.

Table 5. 4 Summary of relationships between DCPT and OM Processes

OM process	Impact domains	Environmental Driver						Sustainability / CE benefits	Ref.
		Resource Efficiency	hazardous/toxic/critical substances reduction	Lifetime extension	Intensified asset usage	Dematerialisation and transparency	Closing the loop		
PLUS	Information sharing and coordination, leading to flexibility, greater operational efficiency and effectiveness	X				X		Resource sharing, material consumption and waste reduction	(Bag et al., 2023; Edwin Cheng et al., 2022; Yadav et al., 2020)
PLUS	Inventory management optimization (e.g. through real-time data and improved demand forecasting)	X			X	X		Reduced waste Reduced obsolescence of inventories	(Agarwal et al., 2022; Bag et al., 2023; Garrido-Hidalgo et al., 2020; Mishra & Singh, 2022)
PLUS	Raw material information and traceability	X	X		X		X	waste reduction, circular flows of materials	(Mastos et al., 2021; Pinheiro et al., 2022; Schöggl et al., 2023)
PLUS	Risk management		X			X		Environmental risk reduction, greater environmental compliance	(Bag et al., 2023; Lopes de Sousa Jabbour et al., 2023; Patil et al., 2023; Yadav et al., 2020)
DOLS	Logistic route optimization	X				X		Reducing operational costs, minimizing waste, optimizing resource utilization, and reducing carbon emissions	(Cannas et al., 2024; Rajput & Singh, 2019)
DOLS	Warehouse management optimization	X			X			Energy consumption reduction	(AL-Khatib, 2023; Cannas et al., 2024; Nantee & Sureeyatanapas, 2021)
REVLOG	Optimization of reverse logistic information management systems	X	X			X	X	Lowering costs and energy consumption, waste reduction	(Dev et al., 2020b; Edwin Cheng et al., 2022; Garrido-Hidalgo et al., 2019; Yadav et al., 2020)

REVLOG	Route optimization	**X**						Reduce transportation and related emissions	(Bag et al., 2021; Dev et al., 2020b; Mishra & Singh, 2022; Pourmehdi et al., 2022)
REVLOG	Enhance tactical and strategic Reverse Logistics (REVLOG) decisions	**X**	**X**	**X**		**X**	**X**	Circular flows. Increased material efficiency	(Bag et al., 2021; Krstić et al., 2022; Pourmehdi et al., 2022)

By providing data-driven decision-making platforms, DCPT optimizes purchasing and upstream supply chain management processes (Bag et al., 2023; Edwin Cheng et al., 2022), leading to increased operational efficiency and effectiveness while minimizing unnecessary resource utilization and waste. Real-time visibility into demand and inventory levels enables more accurate forecasting, reducing excess purchases and stock misallocation (Pinheiro et al., 2022). This optimization of inventories allows for early detection of potential stockouts and lead time deviations, mitigating material shortages (Bag et al., 2023; Garrido-Hidalgo et al., 2019). Furthermore, innovative data structures like the Digital Product Passport facilitate green purchasing practices and real-time tracking of material characteristics, enhancing supplier commitment to sustainability standards (Schöggl et al., 2023). The integration of DCPT also improves the orchestration of information flows regarding supplier and material origins, geographical and climatic data, and operational and financial information, enabling better identification and management of environmental risks and supply discontinuities (Bag et al., 2023).

In Distribution, Outbound Logistics & Downstream Supply Chain Management (DOLS), DCPT enables the tracking of smart objects throughout logistics processes, generating valuable data for route optimization and reducing uncertainties in transportation parameters (K. Ali & Johl, 2023; Cannas et al., 2024). This leads to reduced logistic and operational costs, decreased resource consumption, and a minimized carbon footprint in distribution activities. Within warehouse operations, DCPT optimizes layout design, storage methods, and product picking processes, enhancing overall order fulfilment service levels (AL-Khatib, 2023). These improvements result in optimized space utilization, reduced energy consumption, and overall cost reductions in warehouse management.

Reverse Logistics (REVLOG) benefits significantly from DCPT through improved communication infrastructure and enhanced decision-making capabilities. DCPT supports the optimization of reverse logistics management systems, facilitating both tactical and strategic decisions regarding end-of-life product repurposing. By providing comprehensive visibility and tracking of products throughout the reverse logistics and recovery processes, DCPT enhances information flows crucial for effective decision-making (Krstić et al., 2022; Pourmehdi et al., 2022). This improved visibility aids in critical processes such as collecting returned products, assessing their condition, and determining appropriate recovery options (S. Mishra & Singh, 2022). Additionally, DCPT supports tactical decisions, such as more effective sorting at facility centres. Ultimately, these enhancements lead to increased recovery value from returned products and contribute to closing the loop in circular economy models by improving product return and recovery rates.

5.4.2.2 Blockchain-Cybersecurity and OM processes (Procurement, inbound Logistics & Upstream Supply chain management (PLUS) and Reverse Logistics (REVLOG))

The integration of Blockchain (BLC) technology significantly enhances Operations Management processes, particularly in Procurement, Inbound Logistics & Upstream Supply Chain Management (PLUS) and Reverse Logistics (REVLOG). As shown in Table 5. 5, BLC plays a crucial role in addressing various information challenges within PLUS, such as improving traceability, transparency, accountability, and data integration while mitigating risks associated with cyber-attacks (Kayikci, Gozacan-Chase, et al., 2022; Rehman Khan et al., 2022). By providing richer and up-to-date information, BLC fosters collaborative and decentralized decision-making, enhancing responsiveness to upstream supply chain risks. For instance, IBM's application of blockchain technology allows for rapid identification of alternative suppliers during unforeseen circumstances, demonstrating the agility that BLC brings to procurement processes.

Table 5. 5 : Summary of relationships between Blockchain & Cybersecurity and OM Processes

OM process	**Impact domains**	**Environmental Driver**						**Sustainability / CE benefit**	**Ref.**
		Resource Efficiency	**Hazardous/toxic/critical substances reduction**	**Lifetime extension**	**Intensified product usage**	**Dematerialisation and transparency**	**Closing the loop**		
PLUS	Supporting collaborative relationships and information sharing with suppliers	X	X			X		Green procurement, increased circularity of material flows	(Bag et al., 2021; Chaudhari et al., 2022; Govindan, 2022; Kouhizadeh et al., 2020;

									Saxena et al., 2021)
PLUS	Mitigating uncertainties and risk in supply chain		X			X		Reduced environmental risk, waste reduction	(Chaouni Benabdellah et al., 2023; Chaudhari et al., 2022; Kouhizadeh et al., 2020; Rane et al., 2023)
REVLOG	Tracking product lifecycle data to support effective reverse logistics planning and decision-making.	X	X		X	X	X	Waste reduction, disassembly optimization, circular flow of resources, improved decision-making about recovery options, and developing trusted markets for recycled materials	(Gupta et al., 2021b; Kumar et al., 2023; Rizvi et al., 2022; Tri et al., 2022)
REVLOG	Increasing the participation of customers and supply chain stakeholder in reverse logistics		X	X	X	X		Circular flow of resources, improving green customer practice	(Govindan, 2022; Prajapati et al., 2022)

Furthermore, BLC ensures certified information and greater traceability regarding purchased materials and components, facilitating circular procurement practices and the development of digital product passports (Ghadge et al., 2022). Additionally, the technology enables transparent tracking of transportation emissions, supporting regulatory compliance through penalties or incentives for suppliers adopting sustainable practices (Kouhizadeh et al., 2020).

In the context of REVLOG, BLC enhances product lifecycle tracking and return mechanisms while promoting customer involvement. By providing secure and transparent records of product lifecycle data, organizations gain insights into a product's journey from raw materials to finished goods. This includes crucial information about material origins, production energy usage, manufacturing dates, ownership history, and usage patterns. Such visibility is essential for effective REVLOG planning and decision-making. For example, Toyota's implementation of blockchain technology to monitor the condition and history of returned or recalled vehicles exemplifies how organizations can make informed repurposing decisions (Rizvi et al., 2022). Moreover, blockchain-based tokens can incentivize customer engagement in REVLOG by rewarding product returns through cryptographic tokens or micropayments upon receipt by reverse logistics partners (Kayikci et al., 2022; Kouhizadeh et al., 2020). Additionally, BLC enhances trust in product returns by safeguarding consumer data and enabling secure deletion during product disassembly. Ultimately, blockchain-enabled transparency can facilitate the emergence of a new market for trading and pricing recycled materials by providing reliable information about environmental impacts and recyclability (Chaouni Benabdellah et al., 2023). This comprehensive integration of blockchain technology into PLUS and REVLOG processes not only streamlines operations but also supports sustainability initiatives across the supply chain.

5.4.2.3 HVI and OM processes (Procurement, inbound Logistics & Upstream Supply chain management (PLUS), Distribution, Outbound Logistics & downstream Supply chain management (DOLS), Maintain, technical assistance & repair (MAINT), and Reverse Logistics (REVLOG))

The adoption of HVI supports PLUS (relationship #2 in Table 5. 3), DOLS (relationship #9), MAINT (#14), and REVLOG (#17). The main impact domains, environmental drivers triggered, and sustainability benefits are shown in Table 5. 6. This integration enables centralized data management with clear lines of authority and responsibility. HVI facilitates the digitalization of logistics and inventory management, allowing for optimization of transportation routes, material flows, and packaging material reutilization, ultimately leading to more efficient resource use throughout the supply chain. In production and maintenance, HVI integrates asset maintenance with production processes, enabling faster responses to equipment failures and providing valuable insights. By integrating production management with manufacturing execution systems, HVI optimizes resource consumption, reduces waste, and lowers maintenance costs.

Table 5. 6 Summary of relationships between HVI and OM Processes

OM process	**Impact domains**	**Environmental Driver**							**Sustainability / CE benefit**	**Ref.**
		Resource Efficiency	**Hazardous/toxic/critical substances reduction**	**Lifetime extension**	**Intensified product usage**	**Dematerialisation and transparency**	**Closing the loop**			
PLUS	Improving buyer -supplier information sharing and trust	X				X			Reduction of material consumption and waste	(Aldrighetti et al., 2023; Ghobakhloo et al., 2022; Kayikci, Kazancoglu, et al., 2022; Neri, Negri, Cagno,

									Kumar, et al., 2023)
DOLS	Improving planning and downstream supply chain coordination through information sharing increasing operations and transportation efficiency	X			X	X		Material efficiency and waste reduction through optimized inventories, energy consumption and transportation emissions reduction	(Behl et al., 2023a; Ghobakhloo et al., 2022; Neri, Negri, Cagno, Kumar, et al., 2023)
MAINT	Real-time monitoring of production shopfloor for early detection of breakdowns and preventive maintenance	X		X				Energy and material efficiency, reduced downtime and under-optimal usage of assets	(Chen et al., 2023; Samadhiya et al., 2023)
REVLOG	Optimization of material flows and industrial symbiosis	X	X			X	X	Closing the loop, transforming waste into resources	(Neri, Negri, Cagno, Kumar, et al., 2023; Skalli et al., 2024)

This holistic approach enhances overall operational efficiency and sustainability. HVI's application extends to Reverse Logistics (REVLOG) by supporting the development of collaborative and efficient return programs through supply chain partner integration. Furthermore, it promotes industrial symbiosis by facilitating a collective approach to exchanging materials, energy, water, and byproducts among different industries. This collaborative ecosystem fosters resource efficiency and circular economy principles, contributing to more sustainable and resilient supply chains.

5.4.2.4 AR/VR and OM processes (Maintain, technical assistance & repair (MAINT) and Procurement, inbound Logistics & Upstream Supply chain management (PLUS))

The adoption of AR/VR supports MAINT (relationship #4 in Table 5. 3), and PLUS (relationship #18), as reported in Table 5. 7. AR/VR assists warehousing and material handling of purchased goods. It enables more efficient and effective warehousing operations, e.g. avoiding mis-picks, enhancing reliability of picking operations. In Maintenance (MAINT), AR/VR delivers an immersive and interactive experience that revolutionizes machine inspection and repair processes. By overlaying computer-generated images onto physical objects, these technologies provide real-time instructions and visual guidance for maintenance tasks (Aldrighetti et al., 2023; Kayikci, Kazancoglu, et al., 2022;

Neri et al., 2023). Virtual 3D models coupled with motion capture systems facilitate precise identification of defective parts and enhance operators' repair and disassembly abilities (Kerin et al., 2023). Moreover, AR/VR supports immersive training experiences and enables remote assistance, allowing experts to guide technicians from afar, thereby increasing productivity and reducing maintenance and travel costs (Agarwal et al., 2022).

Table 5. 7 Summary of relationships between AR/VR and OM Processes.

OM process	Impact domains	Environmental Driver						Sustainability / CE benefit	Ref.
		Resource Efficiency	Hazardous/toxic/critical substances reduction	Lifetime extension	Intensified product usage	Dematerialisation and transparency	Closing the loop		
PLUS	Increasing efficiency, effectiveness and safety of warehouse operations	X						Reduced waste and energy consumption	(Chen et al., 2023; Laskurain-Iturbe et al., 2021; Lopes de Sousa Jabbour et al., 2022; Ramirez-Peña et al., 2020)
MAINT	Enhanced machine inspection, Improved training	X	X	X				Improved reparability, downtime reduction, reduced need for substituting sub-assemblies (since single parts can be repaired or substituted)	(Aldrighetti et al., 2023; Di Maria et al., 2022; Kayikci, Kazancoglu, et al., 2022; Krstić et al., 2022; Neri, Negri, Cagno, Kumar, et al., 2023)
MAINT	Remote assistance, guidance to the remote technicians	X		X		X		Reduced downtime, reduction of environmental impact of maintenance. Reduced need for repair manuals	(Agarwal et al., 2022)

5.4.2.5 Cyber-physical system, Digital Twin & Simulation (CPSDTS) and OM processes (Procurement, inbound Logistics & Upstream Supply chain management (PLUS), Distribution, Outbound Logistics & downstream Supply chain management (DOLS), and Production (PROD))

CPSDTS support PLUS (relationship #3 in Table 5. 3), DOLS (relationship #19), and PROD (relationship #21), as summarized in Table 5. 8. Cyber-Physical Systems and Digital Twin Systems (CPSDTS) are revolutionizing supply chain management by enabling adaptive control that aligns purchasing with fluctuating demand and changing consumer preferences. These systems leverage real-time data and predictive models to provide detailed analysis of supply chain processes, resulting in improved control, reduced lead times, and enhanced efficiency in managing upstream impacts of demand fluctuations (Liang et al., 2018). CPSDTS interact with digital platforms containing comprehensive information about suppliers' sustainability practices, certifications, and performance metrics. They also serve as repositories for data on renewable, alternative, and environmentally friendly raw materials, facilitating what-if scenario analyses (Agarwal et al., 2022; H. Ali et al., 2023; Elhazmiri et al., 2022; Kusi-Sarpong et al., 2023). This integration enables data-driven decision support for "green" supplier selection and optimization of the downstream supply chain, addressing factors such as transportation costs and environmental footprint. At the production level, CPSDTS enable virtual modeling that offers unprecedented flexibility and adaptability throughout the manufacturing process. This capability allows for the prediction and mitigation of potential waste and inefficiencies before physical production begins. Cyber-physical systems support various data acquisition and handling techniques, feeding information to digital twins for the simulation of real-world production scenarios. These simulations predict equipment performance, optimize production scheduling, and evaluate the effects of deploying new manufacturing procedures or machinery upgrades (Zacharaki et al., 2021). Daneshmand et al., (2023) highlighted the application of this technology in monitoring and controlling complex production environments with extreme conditions, such as high pressure, temperature, and acidity. The ability of CPSDTS to analyze material flows and lifecycle data facilitates continuous improvement by identifying even minor instances of waste generation or energy leakage (Liang et al., 2018). This granular level of analysis enables manufacturers to fine-tune their processes for maximum efficiency and sustainability. By providing a comprehensive, real-time view of the entire production ecosystem, CPSDTS empower decision-makers to make informed choices that optimize resource utilization, minimize environmental impact, and enhance overall operational performance. As these systems continue to evolve, they promise to drive significant advancements in sustainable manufacturing practices and circular economy initiatives across various industries.

Table 5. 8 Summary of relationships between CPS, Digital Twin & Simulation and OM Processes

OM process	Impact domains	Environmental Driver: Resource Efficiency	Hazardous/toxic/critical substances reduction	Lifetime extension	Intensified product usage	Dematerialisation and transparency	Closing the loop	Sustainability / CE benefit	Ref.
PLUS	Handling supply chain uncertainties and the upstream impacts of demand fluctuations	X				X		Environmental risk reduction Optimization of raw material consumption	(Chang, 2022; Liang et al., 2018; Ma et al., 2022; Ojha, 2023)
PLUS	Green supplier selection	X	X			X		Green purchasing, waste reduction, supporting circular flows of materials	(Agarwal et al., 2022; H. Ali et al., 2023; Behl et al., 2023a; Kusi-Sarpong et al., 2023)
DOLS	Enhancing the product delivery and distribution systems	X				X		Reducing environmental impact of downstream transportation and inventory	(Abdul-Hamid et al., 2024; Tao et al., 2018)
PROD	Optimizing the production parameters using simulation		X	X				Minimize the downtime, resource consumption and energy consumption	(Bag et al., 2023; Chen et al., 2023; Liang et al., 2018; Ma et al., 2022)
PROD	Evaluating production process, technology and scheduling alternatives	X			X	X		Optimize energy consumption, reduce idle time, tooling consumption	(Liu et al., 2019; Nascimento et al., 2019; M. Sharma et al., 2021; Tao et al., 2018)

5.4.2.6 Industrial Robotics and OM processes (Product development (PD), Procurement, inbound Logistics & Upstream Supply chain management (PLUS), Production (PROD), Maintain, technical assistance & repair (MAINT), and Distribution, Outbound Logistics & downstream Supply chain management (DOLS))

IR shows significant relationships with five OM processes: MAINT (relationship 16 in Table 5. 3), PLUS (relationship #7), DOLS (#15), Product development (#16), and PROD (#20). The main impact domains, environmental drivers triggered, and sustainability benefits are listed in Table 5. 9.

Industrial Robotics (IR) plays a pivotal role in enhancing productivity, quality, and safety in manufacturing environments. By automating repetitive tasks at higher speeds and with greater efficiency, robots significantly reduce energy consumption of machinery and equipment (Agarwal et al., 2022). This automation extends to executing multiple tasks sequentially without lengthy setups or tool changes, thereby minimizing material waste and scrap during production. The collaboration between robots and human operators further optimizes workflows, with robots handling heavy-duty, dangerous, or repetitive tasks, thus enhancing workplace safety and reducing human exposure to hazardous substances (Laskurain-Iturbe et al., 2021). In maintenance operations, IR facilitates inspection and automated disassembly, even in challenging conditions unsuitable for human operators, such as shipyard maintenance activities. This capability not only reduces workplace accidents and ensures worker safety but also optimizes disassembly processes and reduces energy consumption (Kerin et al., 2023; Strandhagen et al., 2022). The integration of robotic technologies like Automated Guided Vehicles (AGVs) and Automated Storage and Retrieval Systems further enhances material handling operations, leading to increased efficiency and optimized energy consumption. AGVs and autonomous mobile robots streamline the movement of goods and packaging within warehouses, significantly improving logistic efficiency. This automation results in more efficient energy use and a decreased carbon footprint associated with handling both raw materials and finished products (Karmaker et al., 2023; Nantee & Sureeyatanapas, 2021). The implementation of these technologies represents a significant step towards more sustainable and environmentally friendly manufacturing and logistics processes. In product development, IR supports automated prototyping by adhering to exact design specifications, thereby enhancing precision and eliminating human errors. This capability facilitates the exploration of complex geometries for customization, integrating seamlessly with various digital technologies such as Additive Manufacturing (AM) and Cyber-Physical Systems and Digital Twin Systems (CPSDTS) (Daneshmand et al., 2023; Hartono et al., 2022; Liu et al., 2023; Thao, 2023). This integration accelerates the product development cycle and enables more innovative and efficient design processes. The comprehensive impact of IR on manufacturing processes extends beyond mere automation. By enhancing safety, optimizing energy use, reducing waste, and enabling more sophisticated product development, industrial robotics is driving a paradigm shift towards more sustainable, efficient, and innovative manufacturing practices. As these technologies continue to evolve, their role in shaping the future of industry and contributing to environmental sustainability will undoubtedly expand.

Table 5. 9 Summary of relationships between Industrial Robotics and OM Processes

OM process	Impact domains	Environmental Driver						Sustainability / CE benefit	Ref.
		Resource Efficiency	Hazardous/toxic/critical substances reduction	Lifetime extension	Intensified product usage	Dematerialisation and transparency	Closing the loop		
PROD	Streamlined production process, reducing human error, and support in higher precision and accuracy in quality control	X						Increased efficiency, reduction waste, resource optimisation, worker safety and protection	(Agarwal et al., 2022; J. J. Ferreira et al., 2023; Laskurain-Iturbe et al., 2021)
MAINT	Facilitate maintenance activities (e.g. more efficient inspection, disassembly and serviceability, addressing challenging environmental conditions…)	X	X	X			X	Improve repairability and reduce errors, increased disassembly effectiveness	(Hartono et al., 2022; Neri, Negri, Cagno, Kumar, et al., 2023; Yang et al., 2023)
PLUS	Automation in inbound and internal handling	X						Reduced energy consumption and waste	(Bag et al., 2020; Chiarini et al., 2020b; Nantee & Sureeyatanapas, 2021)
DOLS	Streamlined warehouse activity	X						Energy consumption optimization	(Nantee & Sureeyatanapas, 2021)
PD	Improved and more efficient prototyping	X	X	X				Waste and hazardous substance reduction, circular product development and	(Agarwal et al., 2022; Findik et al., 2023; Prakash & Ambedkar, 2023)

5.4.2.7 Additive Manufacturing/3D Printing (AM) and OM processes (Production (PROD) and End of life treatment & processing (EOL))

AM supports PROD (relationship #5 in Table 5. 3) and EOL (relationship #10), as reported in Table 5. 10. AM employs a layer-by-layer fabrication approach, enabling the realization of complex geometries leading to enhanced functionality, facilitating easy customization and cost-effectiveness in the design-to-manufacturing process (Agrawal, 2022). A number of studies suggests that the elimination of tooling and additional fixture configurations of AM diminish waste and lead time, thereby enhancing operational efficiency and optimizing the overall production process (Chaudhuri et al., 2022; Tang et al., 2016; Zheng et al., 2020). Gebler et al. noted that 3D printing can avoid 40%

of raw material-related waste, with 95-98% of unfused raw material being repurposable. AM's versatility extends to the use of sustainable materials, including biobased options, which enable waste reuse or biodegradation. Furthermore, AM supports local manufacturing by incorporating locally sourced recycled materials, decentralizing supply chains and reducing transportation-related costs and emissions (Dash et al., 2022; Sauerwein & Doubrovski, 2018; H. Wu, 2022; H. Wu et al., 2022). AM aligns seamlessly with circular economy principles, offering potential to decrease environmental footprints through enhanced material recovery and recycling practices. The technology allows for the design of products that are easier to disassemble and recycle at the end of their lifecycle, facilitating material recovery without altering production processes (Faveto et al., 2024). Recent studies have explored recycling waste into 3D printing filament to produce high-quality, strong, and lightweight components, presenting a promising alternative to virgin materials. This approach not only reduces the demand for new raw materials but also addresses the growing concern of plastic waste. By enabling the use of recycled materials and supporting the principles of a circular economy, AM contributes significantly to sustainable manufacturing practices. The ability to recycle and reuse materials within the AM process itself further enhances its sustainability credentials, with some systems allowing for the immediate reuse of excess powder in subsequent prints (Bossart et al., 2021; Giani et al., 2022).

Table 5. 10 Summary of relationships between AM and OM Processes

OM process	**Impact domains**	**Environmental Driver**						**Sustainability / CE benefit**	**Ref.**
		Resource Efficiency	**Hazardous/toxic/critical substances reduction**	**Lifetime extension**	**Intensified product usage**	**Dematerialisation and transparency**	**Closing the loop**		
PROD	Supporting design and production flexibility and customization (on demand)	**X**		**X**	**X**			Reduce tools production and material waste, increase the overall sustainability (e.g. greater performance in field of customized parts)	(Agrawal, 2022; Faveto et al., 2024; Mantelli et al., 2020; Schlesinger et al., 2022; Tang et al., 2016)
PROD	Supporting local and on-demand manufacturing	**X**			**X**		**X**	Reduced inventories and transportation needs, facilitated end-of-life collection	(Dash et al., 2022; Faveto et al., 2024; Mohammed et al., 2022; Pinheiro et al., 2022; Sauerwein & Doubrovski, 2018; Wu, Mehrabi,

									Karagiannidis, et al., 2022; Wu, Mehrabi, Naveed, et al., 2022)
EOL	Reusing waste as secondary raw materials		X				X	Increased recycling and circularity of material flows	(Caceres-Mendoza et al., 2023; Giani et al., 2022; Reffat et al., 2024; Sauerwein & Doubrovski, 2018; Stefaniak et al., 2022; Tri et al., 2022)

5.5 Clustering of contingency relationship

Additionally, Figure 5. 10 presents a visual representation of the 21 significant relationships previously outlined in **Table 5. 3**. The X-axis depicts the observed frequency of the pairs, while the Y-axis displays the phi coefficient, reflecting the strength of each relationship.

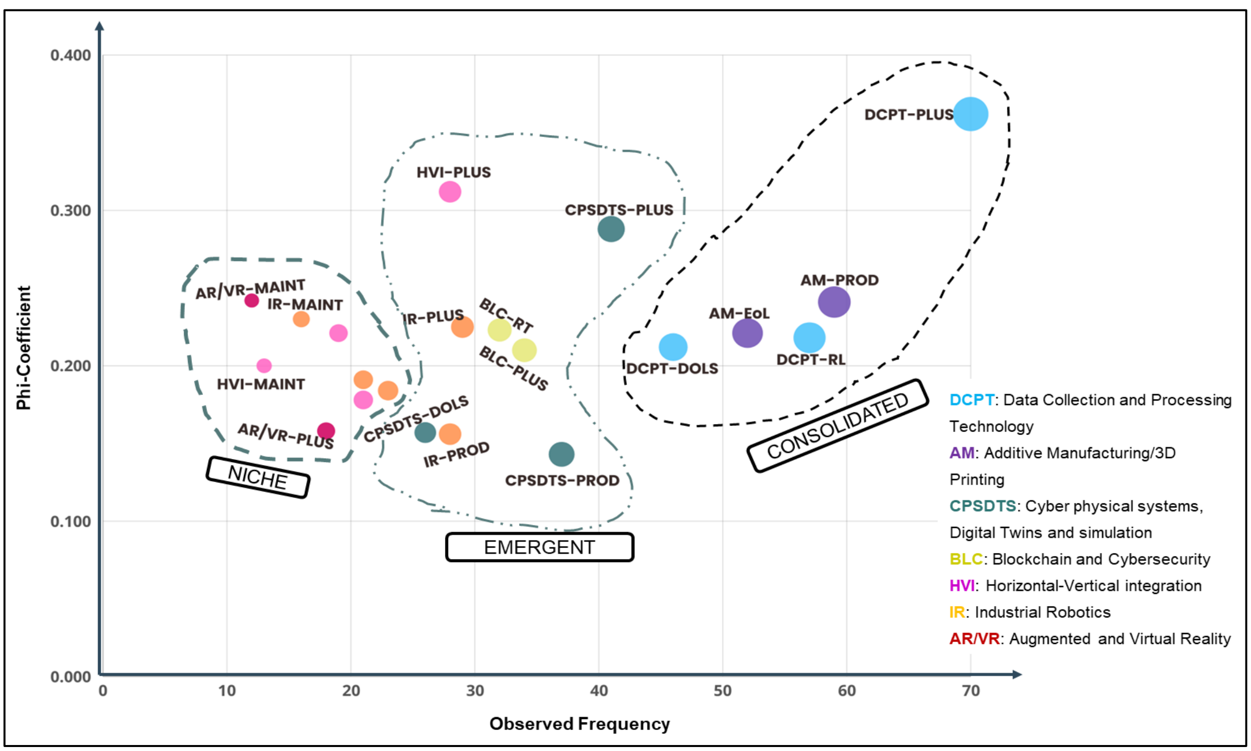


Figure 5. 9 Visualization of the contingency relationships for the 21 DTs-OM process couples based on the observed frequency and phi coefficient

This visualization facilitates the classification of relationships into three categories based on frequency:

Consolidated, Emerging, and Niche. Building on these **two figures** (Figure 5. 8 and Figure 5. 9), the following sections conceptualize and analyze the findings from the systematic literature review. By integrating frequency and contingency analysis, it becomes evident that two technologies DCPT and CPSDTS exhibit both extensive coverage in the literature and significant contingency relationships with multiple operational management processes, each associated with three such processes. DCPT encompasses three fundamental technologies IoT, CC, and BDA and serves as a core data collection and sharing system (Di Maria et al., 2022). It facilitates and enhances the functionality of other DTs, including CPSDTS, HVI, AR/VR, and IR, as evidenced by the contingency analysis of DTs in Section 4.3.1 (Marković & Jemović, 2024). Additionally, both contingency and content analysis indicate that adopting DCPT in the three interface OM processes engaging upstream and downstream (both forward and reverse) supply chain partners supports sustainability outcomes, aligning with prior research (Gholami et al., 2022). By enabling real-time information sharing, improving visibility, and enhancing data-driven decision-making (Yadav et al., 2020), DCPT contributes to sustainability primarily through resource efficiency, particularly in material and energy usage, and dematerialization substituting material flows with information flows (Bressanelli et al., 2022). However, its influence on other environmental drivers remains comparatively limited. Cyber-Physical Systems, Digital Twin, and Simulation (CPSDTS) have been extensively explored in the literature. Unlike DCPT, CPSDTS primarily operate within internal processes such as production, inbound and outbound logistics, and warehousing, facilitating execution and planning optimization through virtualization and simulation. The key environmental drivers for sustainability remain resource and energy efficiency, along with dematerialization. While CPSDTS benefit from DCPT adoption, they serve as a complementary approach, contributing to reduced resource consumption and waste across various internal operations management activities within manufacturing firms. AM emerges as the second most frequently discussed technology in the literature, playing a distinct role in manufacturing transformation processes and end-of-life treatment. It is widely recognized for its potential to reduce waste and energy consumption while facilitating localized, closed-loop supply chains that enhance the utilization of secondary raw materials (Walachowicz et al., 2017). Beyond improving resource efficiency, AM also drives the "closing the loop" principle, reinforcing circularity. However, existing research primarily highlights technical gaps, particularly in the comprehensive sustainability assessment of recycling and manufacturing processes. Further studies are needed to evaluate the feasibility of using secondary raw materials as AM feedstock and to develop reverse supply chain designs for their efficient collection (Das et al., 2024; Ferreira et al., 2023). BLC (Blockchain and Cybersecurity) has also garnered significant attention in the literature. This technology fosters environmental sustainability by leveraging drivers like dematerialization and virtualization, such as enabling the tracking and securing of materials and product history data, facilitating upstream traceability, and supporting digital product passports (Schilling & Seuring, 2024). Additionally, smart contracts incentivize circular consumer behaviors (Chaouni Benabdellah et al., 2023). These capabilities contribute to the reduction of hazardous, toxic, and critical raw material usage and waste throughout the product lifecycle, particularly through enhanced lifecycle data visibility and green procurement. However, further research and practical applications are required to fully unlock the potential of these emerging technologies, as the existing literature lacks comprehensive empirical studies (Ghobakhloo et al., 2022). Additionally, challenges remain in their adoption, including the absence of specialized tools and applications for BLC in remanufacturing processes (Govindan, 2022).

This analysis emphasizes the intricate relationship between digital technologies (DT) and operations management (OM) processes in promoting sustainability and circularity. While technologies such as DCPT and CPSDTS demonstrate wide applicability and impact, others, including AM and BLC, offer more specialized yet potentially transformative advantages. The emerging and niche connections, especially those involving IR, HVI, and AR/VR, suggest promising directions for future research and development within sustainable operations management. The findings suggest that a strategic approach is essential for the implementation of DT in OM processes, balancing both the broad impact (as seen with DCPT) and the depth of specific applications (such as AM in production and end-of-life management). Future research should focus on addressing gaps, particularly through empirical studies of BLC applications and exploring the potential of emerging technologies like AR/VR in maintenance and service operations. Moreover, investigating the integration of these technologies to generate synergistic effects on sustainability outcomes represents an exciting avenue for both academic research and practical application.

5.6 Summary of findings

This research provides a multifaceted contribution to the understanding of how digital technologies can drive environmental sustainability and circularity in manufacturing and supply chain operations. By offering a systemic view, elucidating specific mechanisms, highlighting areas for future investigation, and employing robust methodological approaches, the study lays a foundation for more targeted and effective integration of digital technologies in pursuit of sustainable and circular manufacturing practices. By exploring these underutilized drivers in greater depth, future research can unlock new pathways for leveraging digital technologies to achieve transformative sustainability outcomes across manufacturing and supply chain operations.

5.6.1 Contribution of research

This study offers a comprehensive understanding of the synergies between digital technologies (DTs) and operations management (OM) processes in achieving circularity and environmental sustainability, while also providing valuable implications for future research and industrial practices. The revised research framework in Figure 5. 10 underscores the critical role of environmental drivers in attaining these benefits. Among these drivers, resource efficiency emerges as the most dominant, consistently triggered by DTs across various OM processes.By enabling the monitoring and optimization of physical activities, DTs reduce energy and fuel consumption, while process optimization minimizes material usage and waste. Informed decision-making further enhances recovery rates and optimizes scheduling for transportation and production activities. This alignment of operational efficiency with environmental benefits reflects the dual impact of DTs: cost savings through improved productivity that simultaneously translate into sustainability gains (Gupta et al., 2021b; Nascimento et al., 2019). While previous studies, such as Schilling & Seuring (2024), focused on generic DTs in supply chain management, this research provides deeper insights into the specific roles of individual DTs and their impact mechanisms on distinct OM processes. Blockchain (BLC) stands out as an exception to the resource efficiency focus, as it primarily triggers dematerialization, transparency, and the reduction of hazardous, toxic, or critical materials.

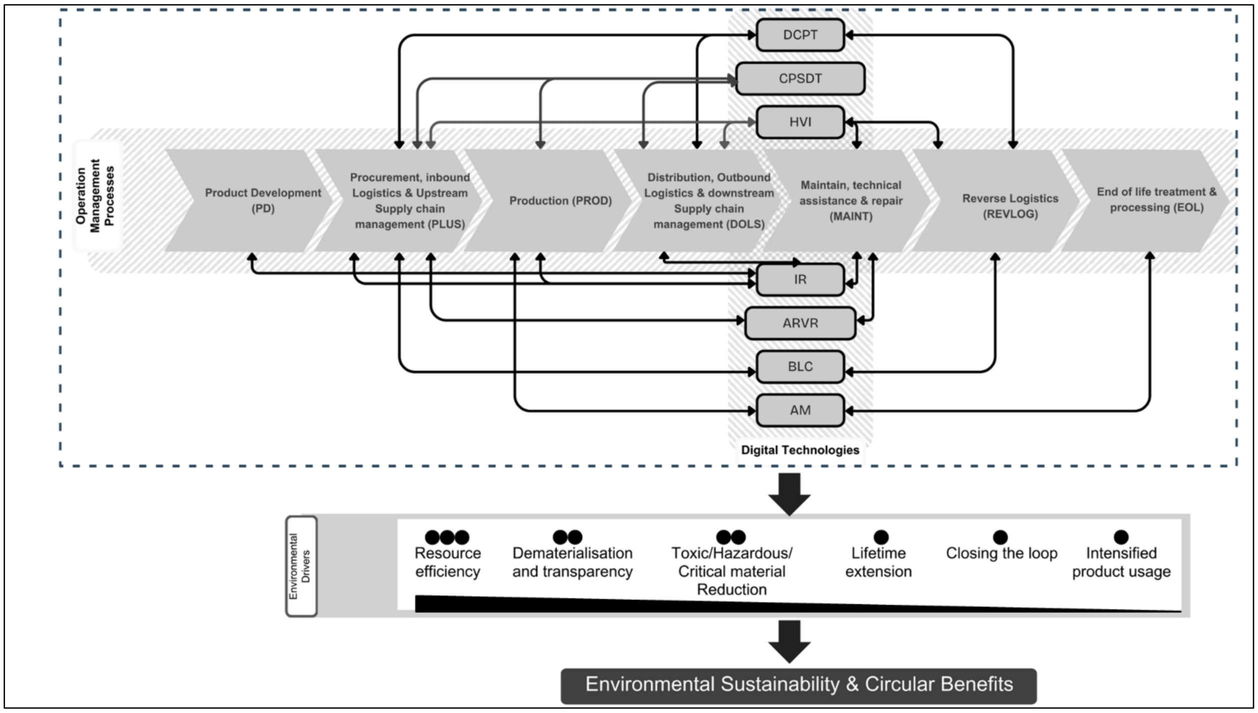


Figure 5. 10 A framework for the role of Digital Technologies applied to OM processes in activating environmental sustainability and circularity drivers

BLC's unique role lies in ensuring reliable and secure information flows that support material-related decision-making. For example, BLC facilitates traceability and green purchasing practices in procurement and enables informed decisions in reverse logistics about repurposing products or materials. Beyond BLC, other frequently activated sustainability drivers include dematerialization and transparency, which are inherent to most DTs due to their ability to virtualize physical activities. This reduces material flows and associated environmental impacts while enhancing operational effectiveness through better information visibility. Additionally, reduced usage of hazardous materials is often observed in PLUS activities due to traceability initiatives and green procurement practices, as well as in REVLOG processes where improved decision-making supports strategies like reuse, remanufacturing, or recycling. However, the findings reveal that other environmental drivers such as closing the loop, lifetime extension, and intensified asset usage are less frequently addressed in the literature but hold significant potential when DTs are applied to specific OM processes. For instance, reverse logistics benefits from DTs not only through reduced reliance on virgin critical materials but also by enabling effective “closing the loop” strategies. Similarly, end-of-life processes leverage DTs to recover materials efficiently for reuse within circular systems. Lifetime extension is predominantly supported by technologies like AR/VR, HVI, and IR within maintenance activities. These technologies enhance decision-making capabilities while augmenting the workforce's technical skills for servicing assets, thereby improving repairability and extending asset lifetimes. This highlights an opportunity for further research into how DTs can activate these underexplored drivers to move beyond sustainability gains achieved solely through efficiency improvements toward a more holistic circular economy approach.

5.6.2 Theoretical Contribution

The comprehensive analysis of the literature has led to a refined framework, as illustrated in Figure 5. 10, which builds upon the initial conceptualization presented in Figure 5. 1. This revised framework visually represents the significant relationships between digital technologies (DTs) and Operations Management (OM) processes, while also reorganizing the environmental drivers based on their activation frequency across the 21 contingency relationships identified. This study makes four key conceptual contributions to the evolving research domain of digital technologies' role in fostering environmental sustainability and circularity within manufacturing and supply chains.

Firstly, this research adopts a novel systemic approach to interpreting the literature on DTs and sustainability. By explicitly analysing the interplay between DTs and OM processes, and identifying the environmental drivers activated, the study provides a comprehensive view of how these technologies contribute to improved environmental sustainability and circularity. This holistic perspective, encapsulated in the final research frameworks Figure 5. 10, represents a significant advancement in understanding the complex relationships between technology, operations, and sustainability outcomes.

Secondly, the study illuminates the mechanisms through which DTs, when applied to specific OM processes, lead to enhanced environmental sustainability and circularity. By unveiling these antecedent-process-outcome patterns, the research offers valuable insights for both academic understanding and managerial practice. The findings underscore that the environmental benefits of digital technologies are contingent upon the OM processes to which they are applied and the specific environmental drivers they activate. Table 5. 11 summarizes these findings, detailing the maturity of investigation for each DT, their interrelations with other DTs and OM processes, the primary environmental drivers activated, and areas ripe for future research.

Thirdly, a critical insight emerging from this analysis is that DTs predominantly lead to environmental benefits through increased operational efficiency, primarily triggering the resource efficiency driver as a consequence of productivity and cost reduction effects. Dematerialization and, to a lesser extent, reduced usage of hazardous, toxic, or critical materials are also frequently activated drivers. However, the study reveals that other environmental drivers, particularly those related to intensified asset usage, lifetime extension, and closing the loop, have been under-investigated. This finding highlights the need for future research to explore how DTs can more comprehensively contribute to sustainability gains by enhancing effectiveness and realizing the full potential of circular supply chains.

Table 5. 11 Summary of the findings about the role of DTs for environmental sustainability and circularity

Digital Technology	**Characteristics***	**Impacted processes/activities****	**Investigation maturity****	**Environmental drivers triggered*****	**Research gaps*****
Data collection and processing technology (DCPT)	Foundational for other DTs	Several interface supply chain activities (Upstream, Downstream, Reverse Logistics)	Consolidated	++ Resource Efficiency + Dematerialization + Others	Relationship with circular drivers (lifetime extension, intensified asset usage, closing the loop)
Horizontal-Vertical integration (HVI)	Foundational for other DTs	Several interface supply chain activities (Upstream, Downstream, Maintenance, Reverse Logistics)	Niche	++ Resource Efficiency + Dematerialization	Deeper investigation on significant relationships; Challenges in data management and integration
Cyber physical systems, Digital Twins and simulation (CPSDTS)	Connected to several other DTs, empowered by DCPT	Several internal activities (production, inbound and outbound, material handling warehousing and logistics)	Emerging	++ Resource Efficiency ++ Dematerialization	Complementary role with DCPT and benefits of joint adoption
Industrial Robotics (IR)	Connected to several other DTs	Several physical activities (production, material handling, product development, Maintenance)	Niche - Emerging	++ Resource Efficiency + Others	Deeper investigation on significant relationships with OM processes
Augmented and Virtual Reality (AR/VR)	Connected to several other DTs	Focused – physical activities (maintenance, warehousing)	Niche	++ Resource Efficiency + Dematerialization + Lifetime Extension	Deeper investigation on significant relationships with OM processes; Empirical/quantitative research on practical implementation, obstacles and outcomes
Additive manufacturing / 3D printing (AM)	Standalone	Focused – physical activities (production, end-of-life treatment)	Consolidated	++ Closing the loop ++ Resource Efficiency	Technical developments to expand the adoption of AM and achieve the promised benefits on a large scale
Blockchain and Cybersecurity (BLC)	Standalone	Focused – interface activities (tracking in procurement and reverse logistics)	Emerging	++ Dematerialization ++ Hazardous/toxic/critical mat reduction	Empirical/quantitative research on practical implementation, obstacles and outcomes

Lastly, from a methodological standpoint, this study employs a structured content analysis using statistical methods to examine contingency relationships. While not novel in itself, this approach contributes to the broader adoption of such methodologies in OM research, responding to calls from previous studies for more rigorous analytical techniques in the field. By demonstrating the effectiveness of this approach in uncovering nuanced relationships between DTs, OM processes, and sustainability outcomes, the study sets a precedent for future research methodologies in this domain.

5.6.3 Managerial Implication

The fine-grained yet systemic analysis of the relationships among digital technologies (DTs), operations management (OM) processes, and environmental drivers provides valuable managerial implications for fostering sustainability and circularity. Managers are often focused on implementing DTs to achieve operational efficiency or cost advantages, with environmental outcomes considered secondary. However, this study highlights the importance of proactively incorporating environmental considerations into managerial decisions regarding DT implementation and OM process redesign (Das et al., 2024). The relationships visualized in Figure 5. 9 and the detailed impact mechanisms analysed in Section 4 offer practical guidance for leveraging DTs to achieve environmental benefits. For managers already committed to specific DTs, these insights can help identify how best to deploy these technologies to maximize their environmental potential. Conversely, for those planning investments in DT adoption, the findings provide a strategic framework to determine where (which OM processes and impact domains) to apply DTs to activate specific environmental drivers, such as resource efficiency or dematerialization. By aligning technological investments with sustainability goals, managers can make informed decisions that not only enhance operational performance but also contribute to long-term circularity and environmental sustainability improvements.

5.6.3 Research direction

This study emphasizes the need for increased investigation into how DTs can trigger broader environmental drivers such as closing the loop, lifetime extension, and intensified asset usage. These drivers represent a shift from traditional efficiency-based sustainability gains toward a fully circular approach that maximizes resource recovery and minimizes environmental impact throughout the product lifecycle. This study highlights the need for further exploration into the roles of Industrial Robotics (IR), Horizontal and Vertical Integration (HVI), and Augmented/Virtual Reality (AR/VR) in advancing environmental sustainability. IR offers considerable potential for enhancing resource efficiency in various physical operations such as warehousing, handling, and maintenance. Its capacity to reduce waste and energy consumption while prolonging asset lifecycles through improved service is particularly noteworthy. Connected to five operational management (OM) processes, IR proves to be a versatile technology that can contribute to sustainability by minimizing material waste and optimizing energy usage across multiple applications. HVI, similar to DCPT, emerges as a key technology facilitating integration and data flow across supply chains. It connects different stages of production and distribution, enabling centralized data management and more efficient resource use. By promoting closed-loop material flows, HVI supports circular economy principles, reduces waste, and encourages resource reuse. However, despite its promising potential, HVI has received comparatively less attention in existing literature than DCPT. Its role in driving resource efficiency and dematerialization in interface activities remains under-explored and warrants further investigation to fully understand its influence on sustainability outcomes. AR/VR technologies are highly relevant to maintenance, repair, and technical support functions. These technologies enable immersive training, real-time remote guidance, and improved visualization of complex systems, contributing to extended asset lifespans and resource efficiency through dematerialization. However, challenges such as high implementation costs, technical complexities, and connectivity issues have hindered widespread adoption of AR/VR, especially in after-sales services and other operational contexts. Despite these barriers, the transformative potential of AR/VR in improving maintenance practices and reducing environmental impacts through better resource management underscores its significance for future research. The analysis categorizes the relationships between digital technologies (DT) and OM processes into three groups: Consolidated, Emerging, and Niche. Consolidated relationships, such as those involving DCPT and AM, span five OM processes, demonstrating their broad applicability. Emerging relationships focus on PLUS processes enabled by CPSDTS, BLC, IR, and HVI. Niche relationships, which are more specific and less explored, involve HVI, IR, and AR/VR across four OM processes (PD, PLUS, DOLS, and REVLOG). Notably, MAINT is present in the Niche group three times but has not been as thoroughly studied as other OM processes. This categorization highlights the need for strategic research on emerging technologies like HVI and AR/VR, as well as leveraging established technologies such as DCPT and AM to advance sustainability efforts. Future research should address the gaps in empirical evidence for BLC applications and explore synergies between these technologies to optimize their contribution to circular economy objectives.

Chapter 6. Circular Readiness Assessment of Indian Manufacturing Industries

From the previous chapter, it is clear that the adoption of Digital Technologies (DTs) may have a significant role in achieving environmental sustainability and circularity in operations management processes. However, before implementing Industry 4.0 technologies to achieve Circular Economy (CE) objectives, organizations should consider several foundational aspects related to the circular paradigm. Successful implementation requires organizations to develop a profound understanding of circular economy strategies and their nuanced implementation mechanisms. For this reason, conducting a comprehensive assessment of current manufacturing practices in the company is necessary. It involves meticulously mapping circularity across existing production flows, material flows, waste generation patterns, organizational mindset, and potential opportunities to understand and optimize circular economic implementation strategies. By conducting such comprehensive assessments, organizations can identify where Industry 4.0 technologies can optimize resource use, minimize waste, and establish closed-loop systems that generate economic and environmental value. Methodologically, this research aims to offer a comprehensive understanding of circular economy implementation that considers organizational strategic alignment. This holistic perspective ensures that technological interventions are not isolated technical exercises, but rather deeply integrated strategic transformations aimed at achieving environmental sustainability and circularity. For this reason, this chapter presents an empirical study conducted to assess the circular readiness of Indian manufacturing industries. The investigation aims to provide the current state of circularity adoption and readiness within different Indian manufacturing sectors.

6.1 India: the long path towards a Circular Economy

India's increasing population, urbanization, and industrialization are projected to substantially elevate the nation's resource consumption in the coming decades, creating considerable strain on both domestic resources and the environment. This challenge is further exacerbated by India's lack of domestic reserves for critical materials such as rare earth elements, which results in a heavy reliance on imports. Due to rising resource consumption, India's demand for metals is expected to triple, while the demand for non-metallic minerals is set to double in the future (A. Kumar et al., 2020). This growth presents a formidable challenge to sustained development, as it is hindered by limited domestic resource availability and escalating international import costs, potentially leading to significant economic, environmental, and social consequences. Consequently, Indian manufacturing firms face a pivotal decision: they must choose between adopting a circular economy model, which allows for decoupling economic growth from resource dependency while integrating environmental concerns into business strategies or continuing with a linear production model that carries substantial risks. Adhering to a linear development model represents a conservative approach that exposes to severe negative consequences, including resource scarcity, critical raw material shortages, waste generation, and environmental pollution. This model exacerbates global warming, climate change, habitat destruction, deforestation, and socio-economic inequality. Traditional industrial practices rely on linear supply chains, where resources are extracted, processed into products, and eventually discarded as waste. This "cradle-to-grave" approach ties economic growth to unsustainable levels of resource consumption and waste generation. In this model, corporate profits and national GDP growth depend on the continuous extraction and depletion of natural resources. India is committed to achieving responsible consumption and production, as outlined in the United Nations Sustainable Development Goals (UNSDGs). The G20 summit held in New Delhi on September 9-10, 2023, highlighted the critical role of the Circular Economy (CE), extended producer responsibility, and resource efficiency in advancing sustainable development. Aligned with Prime Minister Modi's vision of Aatmanirbhar Bharat (Self-Reliant India), the CE has become a cornerstone of urban development and a key pillar of the Lifestyle for Environment (LiFE) initiative. LiFE promotes eco-friendly and sustainable lifestyles to support global net-zero goals. Additionally, the Make in India initiative has spurred growth in the small and medium enterprise (SME) sector, which comprises 48 million enterprises, employs 106 million people, and contributes 6.11% to manufacturing GDP and 24.63% to the service sector GDP (Chhimwal et al., 2022; Nudurupati et al., 2022). Despite these advancements, India's resource extraction rate stands at 1,580 tonnes per acre, 251% above the global average of 450 tonnes per acre (Sarma et al., 2023). SMEs account for 25% of industrial energy consumption, and India is the third-largest emitter of greenhouse gases, contributing 9.2% of global emissions (Varun Boralkar, 2023). These factors underscore the critical need for environmental sustainability, with SMEs playing a pivotal role in addressing these challenges. India is increasingly adopting CE principles to meet its Nationally Determined Contribution (NDC) targets (Ellen MacArthur Foundation, 2016; Gedam et al., 2021; Varun Boralkar, 2023). This involves optimizing resource flows across value chains, integrating forward and reverse logistics, fostering design innovation, building collaborative ecosystems, and developing new business models. Despite initiatives like the Swachh Bharat Mission and Mission LiFE, which reflect India's commitment to sustainability and CE practices, widespread adoption by SMEs remains limited (Varun Boralkar, 2023). Key barriers include technological gaps, insufficient data for decision-making, unclear regulatory frameworks, and a lack of cross-sector collaboration involving education, policy support, technological innovation, and consumer awareness (Das et al., 2024). Consequently, the CE has become imperative for India. The focus shifts from selling products with increasingly shorter lifecycles to maximizing the utility of existing products, components, and materials through reuse, remanufacturing, and recycling. Despite numerous government initiatives, policies, and transnational partnerships, Indian SMEs face significant challenges in implementing CE practices (R. Mishra et al., 2022; Virmani et al., 2022). These challenges stem from the absence of a clear framework to measure the current state of CE adoption and address implementation barriers. Transitioning to a CE requires a fundamental shift in mindset, along with the development of new processes, resources, and skills. Key strategies to facilitate this transition include regulatory support, business incentives, industrial symbiosis, and public awareness campaigns. However, a successful transition necessitates a clear understanding of current practices and capabilities. Manufacturers must assess their position on the path to circularity to prioritize actionable CE strategies effectively.

6.2 Research design

Despite growing interest in the circular economy (CE), there is a notable lack of comprehensive empirical research specifically evaluating CE adoption levels and practices within Indian manufacturing companies. Existing studies are predominantly theoretical or focus on broader developing country contexts, leaving a gap in sector-specific insights. There is a pressing need for in-depth analysis of CE implementation across various manufacturing sectors in India, as adoption levels and associated challenges may vary significantly. Small and medium enterprises (SMEs), which form the backbone of Indian manufacturing, have received limited attention in CE research (Sohal et al., 2022). While SMEs constitute the majority of the sector, there is insufficient empirical evidence on CE practices and challenges specific to Indian manufacturing SMEs. Additionally, there is a lack of quantitative metrics and indicators to assess the degree of circularity in Indian manufacturing companies. Measuring circularity in the Indian context could offer valuable insights for assessing progress and benchmarking performance. Another critical gap lies in understanding how Indian manufacturing companies integrate CE principles across their supply chains, particularly in areas such as reverse logistics. Finally, comprehensive studies are required to identify and analyse key factors influencing CE implementation in the Indian manufacturing context.

So, the research question:

1) What is the degree for circularity of Indian manufacturing companies?

6.3 Methodology

To address this research question, the RISE Laboratory has developed C-Readiness, a model and tool designed to evaluate the current level of circularity within enterprises, identify their strengths, and pinpoint areas for improvement (Bressanelli & Saccani, 2025). The tool also determines the optimal starting configuration for initiating the transition to a circular economy and building the necessary capacities. It is primarily targeted at manufacturing companies seeking to adopt circular economy principles. The tool allows for analysis at both the company and product levels. It can be utilized in two modes: a self-assessment mode, accessible via a web-based platform, or an assisted mode, which involves training sessions and workshops to discuss and interpret the results. The tool comprises 33 multiple-choice questions, organized into six assessment areas that align with the lifecycle of a product and its value chain Table 3. 1:

1. Product Structure: This area evaluates the circularity of a company during the initial phase of the product lifecycle. It focuses on strategies for circular product redesign, including the use of recyclable, recycled, or biodegradable materials, as well as design principles such as standardization and modularity in the product Bill of Materials (BOM).

2. Production Processes: The second area assesses circularity during the production phase, examining the potential for reducing resource consumption and emissions throughout the manufacturing process.

3. Business Model: This area evaluates how the company creates and delivers value to customers, including innovative solutions such as product-as-a-service models (e.g., leasing, pay-per-use, or product sharing).

4. Supply Chain: The fourth area focuses on the procurement and distribution phases, assessing factors such as material and component traceability, packaging sustainability, and the level of collaboration with supply chain stakeholders.

5. Regeneration and End-of-Life: This area examines the company's actions when products reach the end of their lifecycle, including reverse logistics, product recovery, reuse, remanufacturing, recycling, and waste management.

6. Green Culture and Company Practices: The final area evaluates cross-company sustainable practices, with a particular emphasis on environmentally friendly behaviors and initiatives, such as transitioning to plastic-free operations.

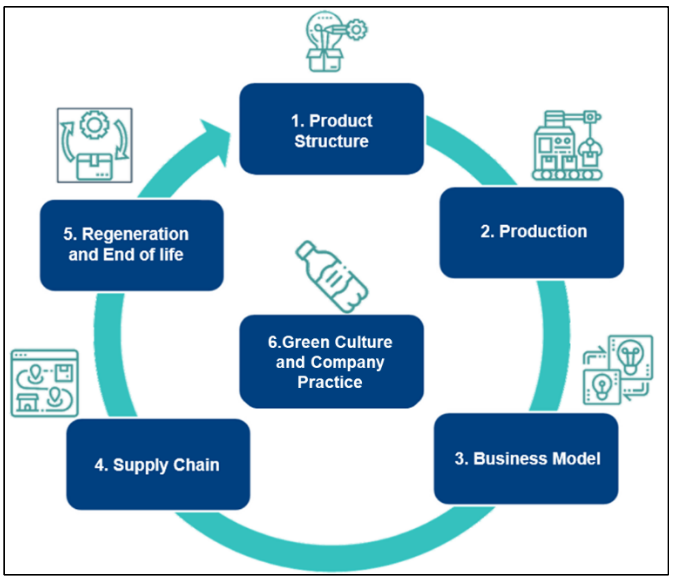


Figure 6. 1 Assessment areas of the C-Readiness tool

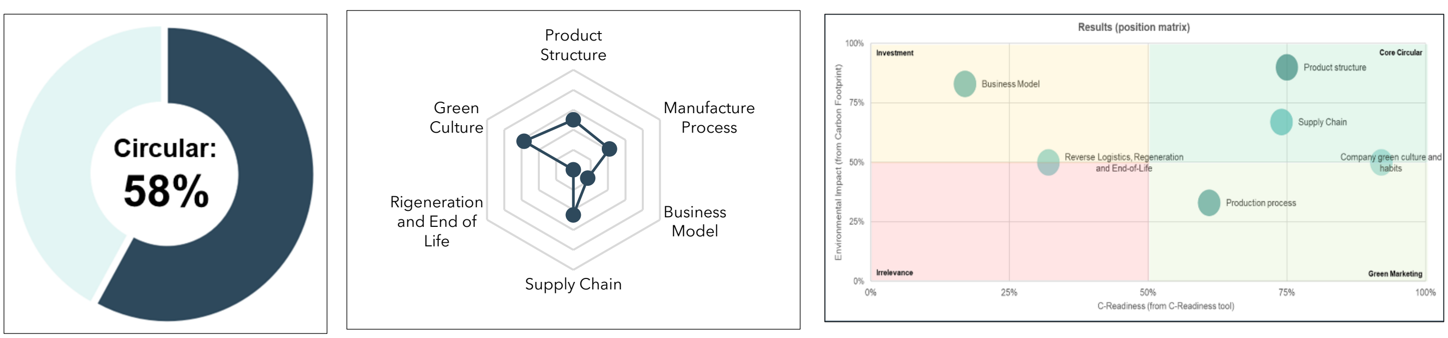
By addressing these six areas, C-Readiness provides a comprehensive framework for assessing and enhancing the circularity of manufacturing companies, supporting their transition to sustainable and circular business practices. The C-Readiness tool employs a sophisticated scoring system to quantify a company's circularity. For each assessment area, the tool calculates a circularity value as the arithmetic mean of the ratings obtained for individual elements within that area:

$$C_{R_{j-esima\ Area}}[Pt] = \frac{\sum_i P_i}{|i|}$$

where j represents the evaluation area, i represents the individual evaluation element of the j-th area, and Pi represents the score obtained in the evaluation of the i-th element. The overall result of Circularity (Figure 6. 2) is calculated as the weighted average of the scores recorded in the six assessment areas, where WRj is the weight given to the j-th area:

$$C_{Readiness}[Pt] = \sum_j C_{R_j} \times W_{R_j}$$

This evaluation is supported by a radar chart (Figure 6. 2b) highlighting the results achieved in each assessment area, and a positioning matrix (Figure 6. 2c), highlighting the areas to invest in or that can be considered as negligible, depending on their relative environmental impact.



(a) overall assessment (b) segmentation by area (c) positioning and development matrix

Figure 6. 2 Results obtained through the application of the C-Readiness tool.

More precisely, a cross-analysis of the circular readiness (C-Readiness) and environmental impact (from Life Cycle Assessment or Product Carbon Footprint analysis) result can provide interesting indications for development, such as the identification of areas in which it is necessary to invest in, in order to increase corporate circularity (areas with high environmental impact but low circular readiness score), negligible areas (low circular readiness score but low environmental impact), which are potentially exploitable for communication and reporting purposes (low environmental impact but high circular readiness) and core areas (high environmental impact and high circular readiness).

6.4 Result

The C-Readiness tool was deployed to assess Indian manufacturing companies. The survey and data collection process began by identifying a list of Indian companies from official government sources, including the Micro, Small & Medium Enterprises (MSME) registry of the Government of India, the Confederation of Indian Industry (CII), the Open Government Data (OGD) Platform India, and the Indian Industry Association. Based on this list, a database was compiled, from which over 10,000 email addresses were collected. A random sampling method was employed to select 1,000 email addresses for survey distribution. The survey was administered via a web-based platform with over 670 companies initially accessing the platform. Partial responses were addressed through structured follow-up calls, where participants were reminded of the survey's timeline to encourage completion. After the follow-ups, 380 fully completed and validated responses were retained for analysis. To ensure data integrity and meaningful analysis, the study focused on these 380 companies that provided complete and reliable responses. This rigorous selection process ensures that the insights derived from the assessment accurately reflect the current state of circular readiness in the Indian manufacturing sector, providing a solid foundation for identifying trends, challenges, and opportunities in the transition towards a more circular economy.

6.4.1 Descriptive Result

The descriptive statistics of the study provide valuable insights into the composition of the sample of Indian manufacturing companies assessed using the C-Readiness tool. The analysis encompasses a diverse range of company sizes (classification based on Micro, Small and Medium Enterprises Development Act of India, 2006) and industrial sectors. Only 3% of the sample is made of micro companies (turnover less than 5 Crore INR/ 0.5 million euro). Most (52%) can be classified as small-sized companies, with a turnover between 5 and 50 Crore INR (0.5 – 5 million euro) (Figure 6. 3). Medium-sized companies (turnover between 50 and 250 Crore INR/ 5-25 million euro) account for 37% of the sample. By contrast, only 8% represent large companies (turnover more than 250 Crore INR/ 25 million euro). The analysis focuses more on small and medium-sized companies compared to the overall Indian business landscape. This is a potential indication that the research might be biased towards small and medium-sized companies; either they are already more interested in or actively implementing circular practices, or larger companies are less inclined to participate in such research.

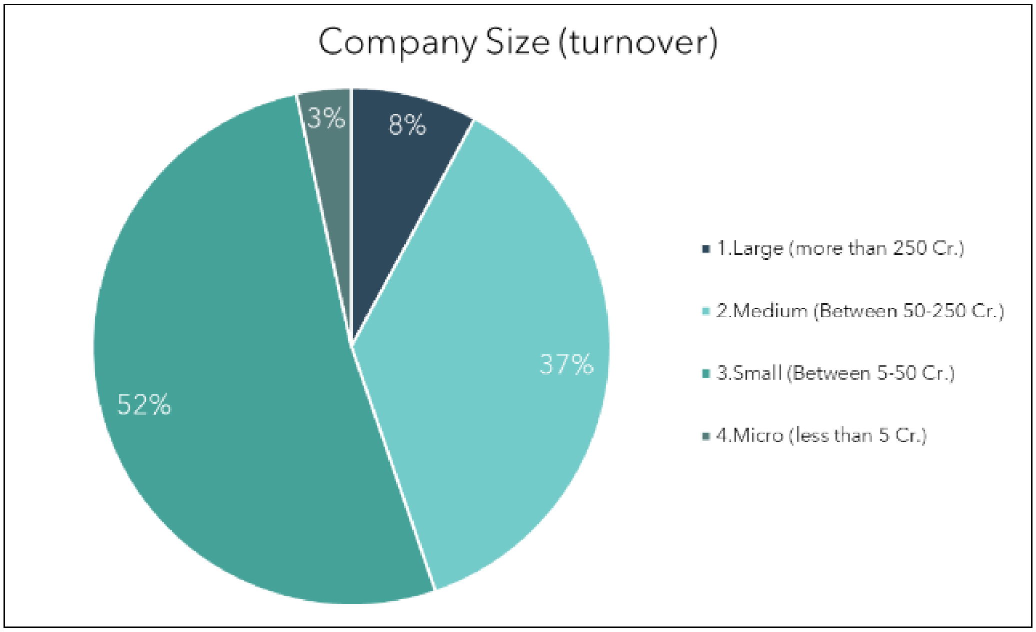


Figure 6. 3 Distribution of companies by size

The 380 companies analysed in this study were categorized into homogeneous industrial sectors, as illustrated in Figure 6. 4. Specifically, 13 industrial sectors were covered according to the National Industrial Classification (NIC), which aligns with the United Nations International Standard Industrial Classification, ensuring data comparability across countries. The primary objective of this research is to gather comprehensive and detailed insights from India's manufacturing sector, with a focus on key industries such as textiles, electronics, paper and paper products, coke and refined petroleum products, and metallurgy. The textile and fashion sectors are the most prominently represented in the research sample, comprising 93 companies (24.5%). These companies primarily engage in weaving, textile finishing, garment manufacturing, and the production of fur and knitted apparel. This sector is witnessing increased investment as global brands reassess their sourcing strategies and expand their presence in Indian manufacturing units. The electrical and electronic equipment sector follows, with 86 companies (22.6%) involved in manufacturing electrical motors, generators, electronic components (such as computers, communication equipment, and magnetics), batteries, and other electrical equipment. This sector has experienced significant growth in recent years, likely driven by government initiatives such as the "Vocal for Local" campaign and Production Linked Incentive (PLI) schemes, which encourage the production and sale of domestically manufactured goods. The metallurgical industry is the fourth largest in the sample, with 73 companies (19.2%) producing basic precious metals, non-ferrous metals, steel, and non-metallic mineral products. The petroleum derivatives, chemicals, and pharmaceuticals sector also includes 73 companies (19.2%), with a focus on petroleum products and other chemical derivatives. In contrast, the rubber and plastics industry is represented by only 19 companies (5%). Similarly, the components sector, which manufactures general-purpose machinery, fabricated metal products, and special-purpose machinery, comprises 14 companies (3.7%). The food and beverage sector follows with 11 companies, accounting for 2.9% of the sample. The automotive sector, which focuses on motor vehicles, parts, and accessories, is represented by just 4 companies (1.1%). Finally, the "other" sector, which includes mining, ceramic products, and paper-related products, consists of 7 companies (1.8%).

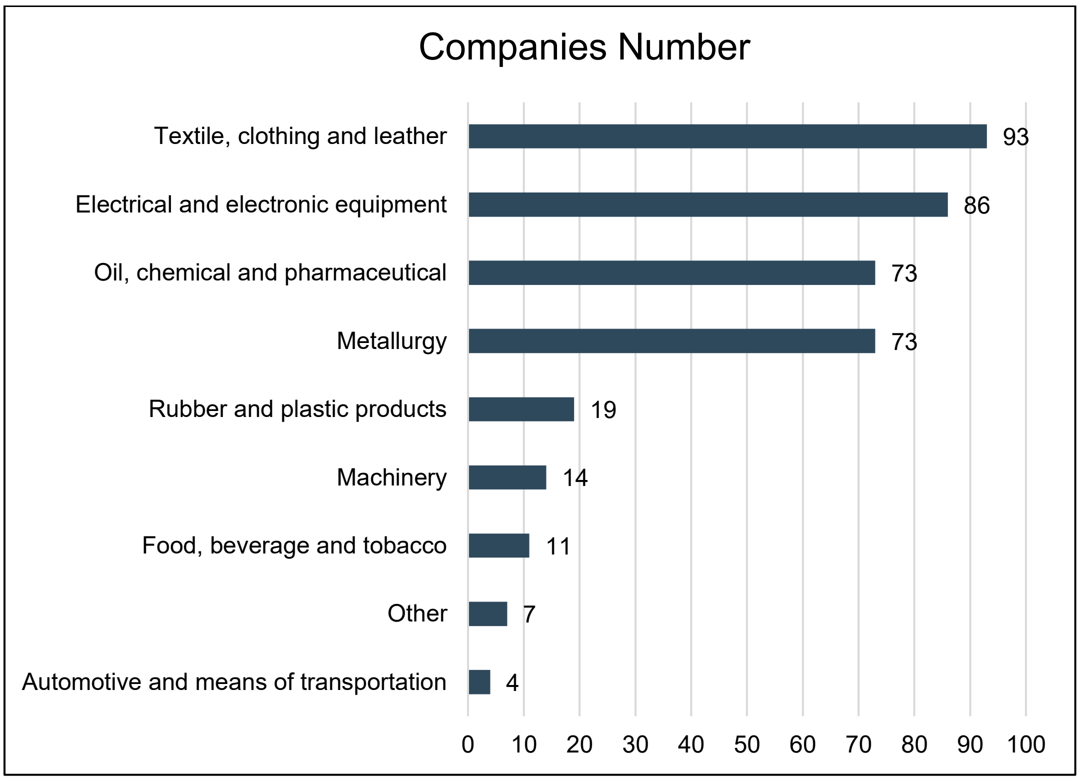


Figure 6. 4 Distribution of companies per sector

6.4.2 Circularity of manufacturing companies

The application of the C-Readiness tool enabled the calculation of the overall circularity score (C-Score) and the scores for individual domains (product structure, production processes, business model, supply chain, regeneration, corporate culture, and best practices) across the sample of 380 companies. The findings reveal that Indian manufacturing companies, on average, exhibit limited readiness for the Circular Economy (CE) paradigm, with an average C-Score of 47 out of 100. Notably, 60% of the companies scored below 50 points (Figure 6. 5), indicating that the CE paradigm remains in its early stages of implementation within industrial practices.

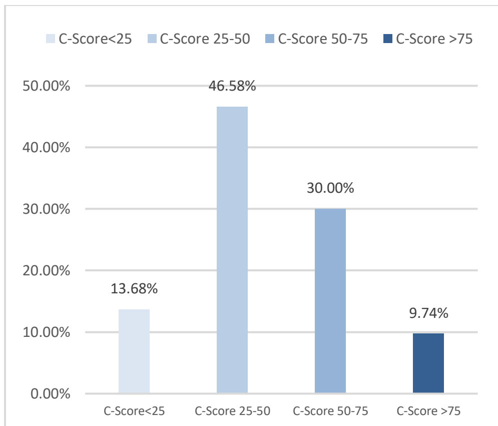


Figure 6. 5 C-Readiness Result

Furthermore, companies were categorized into four classes based on their C-Scores: Class I (score < 25), Class II (score 25–50), Class III (score 50–75), and Class IV (score > 75). A significant proportion of companies—177 (46.58%)—fall within Class II (C-Score range of 25–50), underscoring the considerable progress still required for India's production ecosystem to fully embrace and operationalize CE principles. This outcome is further elaborated in Figure 6. 6 and Figure 6. 7, which evaluates the six domains of CE implementation: the scores achieved in each domain are commented hereafter. The analysis highlights that companies demonstrate higher adoption of circularity principles in the domains of **green organizational culture** and **supply chain management**. The companies analysed showed strong performance in green culture and best practices, achieving an average score of 58 points. This trend is reinforced by the fact that 31% of the companies attained a C-Score exceeding 75 points, reflecting the rapid diffusion of green culture within Indian industries. This is particularly evident in the adoption of sustainable transportation solutions, which represents a proactive response to India's significant carbon emissions from transportation. Initiatives such as the

Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India (FAME I), led by the Department of Heavy Industries (DHI), have encouraged the adoption of electric vehicles for both inter- and intra-city mobility. Additionally, Indian manufacturers are offering services such as on-demand transportation, shared mobility, and carpooling, which contribute to more efficient and sustainable mobility systems by reducing carbon emissions, alleviating traffic congestion, and minimizing parking demands. Large manufacturing industries are also making strides by eliminating single-use plastics and implementing segregated waste collection practices, signalling a positive shift toward sustainability. However, small and medium-sized enterprises (SMEs) often lack structured tools, such as sustainability reports, to effectively communicate their sustainability progress to stakeholders. Moreover, the role of a sustainability manager, who can steer companies toward CE adoption, remains underrepresented, particularly among SMEs.

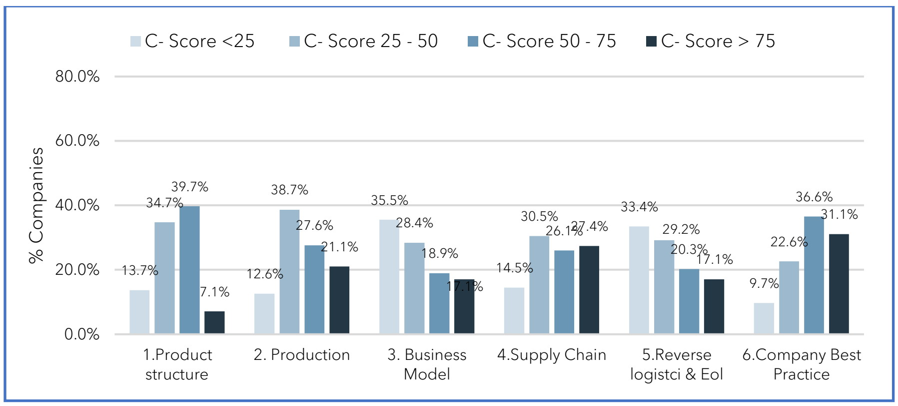


Figure 6. 6 C-Readiness result segmented by assessment area

The analysis also reveals that the companies examined demonstrate a moderate performance in terms of **supply chain circularity**, with an average circularity score of 52 points. Notably, 27% of the companies achieved a circularity score exceeding 75 points, indicating significant progress in certain areas. A key finding is that Indian manufacturing companies are increasingly adopting transport management software to optimize logistics operations systematically. This software reduces reliance on paper-based systems, such as e-way bills, and automates trip management, providing real-time visibility into transportation processes. Leading software solutions like SAP, Bharat Software Solutions, RAMCO, GREEN TRANS, and TMS Hub enable companies to manage logistical complexities effectively, enhancing efficiency and reducing emissions. Additionally, the Indian manufacturing sector heavily utilizes the Indian railway network, which spans approximately 68,000 kilometers, as a cost-effective and energy-efficient transportation mode. Railways generate up to 80%

less CO_2 and consume 75-90% less energy compared to road transport for freight movement. Despite these advancements, smaller companies have made limited progress in sustainable packaging, particularly in adopting recyclable materials. Significant gaps persist in evaluating supply networks against circularity and environmental sustainability criteria. Furthermore, only a few companies have established traceability systems for purchased materials and products across their supply chains, highlighting the need for pilot projects in this domain.

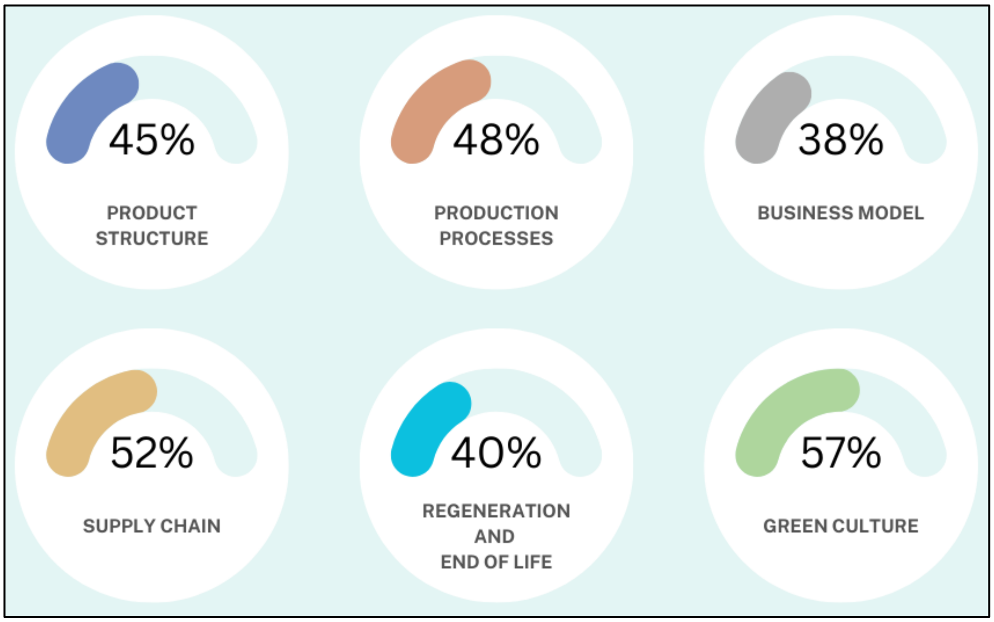


Figure 6. 7 The circularity Score of the companies in the sample in different dimesnions

In the area of **production processes**, the average circularity score is 48 points. Companies have shown a strong commitment to reducing production waste and scrap, as well as implementing systems to monitor resource consumption. However, industrial symbiosis models remain underutilized, and the adoption of renewable energy sources and energy efficiency measures in production plants is still limited. Product structure, regeneration and end-of-life practices, and business models emerged as the three lowest-scoring areas in the survey, with average circularity scores of 45, 40, and 38 points, respectively. These areas require careful investigation for further development to improve the overall circularity score.

Moreover, the average circularity score for **product structure** is 45 points, with only 7% of companies scoring above 75 points. This suggests that Indian companies are not adequately prepared for circular product design, likely due to a focus on short-term profitability and a lack of awareness about circular design principles. Moreover, over 80% of companies lack environmental product certifications, missing opportunities to communicate their sustainability efforts effectively. The results also indicate that Indian companies need to improve **remanufacturing and end-of-life** management practices, with 33% of the analysed companies scoring below 25 points. Despite the importance of reuse, regeneration, and recycling in the Circular Economy, companies are far from fully integrating these practices. The lowest performance is observed in the domain of business models, where 36% of companies scored below 25 points. Most companies do not offer reconditioned product lines or utilize platforms for buying and selling production scraps, reflecting a significant knowledge gap. Collaboration with suppliers and partners for circularity is also minimal, though increased awareness and supportive platforms could facilitate this transition. Furthermore, the adoption of circular-as-a-service business models, such as leasing, pay-per-use, and sharing, remains limited. These models are crucial for decoupling economic growth from material consumption and waste generation. Consequently, greater efforts are needed to experiment with as-a-service models and recover end-of-life products to create circular product lines.

Finally, based on the survey results, it is noted that there are varying scores for the supply chain (52%), production process (48%), product structure (45%), and business model (38%), which are considered the four major levers/endogenous characteristics that companies directly act on or invest in to improve CE practices. Despite their interconnected nature, the supply chain lever scored significantly higher than the business model lever. This difference suggests the importance of additional investigation into the underlying reasons for these deviations. Understanding the factors contributing to the high readiness score of the supply chain and the low score of the business model could provide valuable knowledge about their interrelated dynamics and effectiveness. This will help identify inefficiencies and areas for improvement, leading to better overall implementation of circular economy practices.

6.5 Analysis by company size

The results of the analysis were segmented on the basis of company size (Figure 6. 8), with respect to the 4 turnover classes, as discussed in 6.3.1. The results show that the circularity score generally increases with increasing company size in a statistically significant manner ($p < 0.001$), However, we observed a deviation between small and micro companies, with small companies having a slightly lower circularity score than micro enterprise.

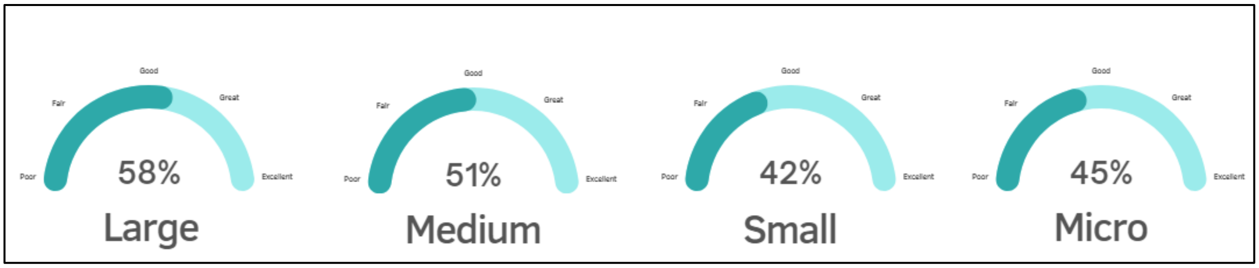


Figure 6. 8 Average score based on company size

On average, micro-enterprises achieve a circularity score of 45 points, while small companies record the lowest score of 42 points. In contrast, medium-sized and large enterprises demonstrate higher scores of 51 and 58 points, respectively. This indicates that large companies are, on average, **16%** points more circular than small enterprises. This disparity can be attributed to the fact that large companies are often under greater scrutiny regarding environmental practices and are more likely to be subject to regulatory obligations. Additionally, their greater investment capacity and easier access to capital enable them to invest more in efficiency measures and supply chain control processes. This is reflected in their higher scores in areas related to production processes, such as energy efficiency initiatives and investments in renewable energy sources, as well as supply chain management.

Indian companies are increasingly adopting green initiatives to foster sustainable workplaces, driven by leadership support and the identification of cost-saving opportunities in energy, water, and waste management. Employee engagement in sustainability programs not only enhances organizational reputation and consumer loyalty but also improves compliance with environmental regulations (Figure 6. 7). The increase in circularity scores is observed across all areas except product structure, where no significant differences are noted between small, medium, and large companies. Interestingly, micro-companies appear to exhibit higher circularity in terms of product structure. However, given the very small number of micro-companies in our sample (only 3%), this finding remains inconclusive. Potential explanations for this observation include the smaller production setups of micro-companies, which may facilitate the adoption of circular design practices. Additionally, micro-industries, often constrained by limited resources, may rely heavily on reusing and repurposing scrap materials to create new products, inherently aligning with circular design principles.

6.6 Analysis by sector

The findings, derived from 380 responding companies, reveal variations in circularity readiness across different industrial sectors. Although the data exhibit limited statistical significance, the analysis indicates that the sectors most advanced in adopting Circular Economy (CE) practices are the chemical industry (including petroleum, chemical, and pharmaceutical), the automotive sector, and the electrical and electronic equipment sector, with average C-Scores of 63, 64, and 46 points, respectively (shown in Figure 6. 9). These sectors, characterized by high environmental impact, have implemented sustainability initiatives for decades, often driven by regulatory frameworks such as Minimum Environmental Criteria in construction, end-of-life vehicle directives in the automotive sector, and CO2 regulations in the steel industry. Other sectors, including textiles and fashion, packaging, ceramics, rubber and plastics, and food, achieved circularity readiness scores aligned with the overall sample average, ranging between 40 and 45 points. This suggests that companies in these sectors have initiated their transition toward circularity, albeit later than the more mature sectors mentioned earlier. At the lower end of the sectorial ranking are metallurgy, metal processing, and machining industries, with average C-Scores below 40 points. This highlights a significant gap in circularity readiness compared to more advanced sectors. Typically, these companies operate in business-to-business (B2B) markets and lack direct engagement with end consumers, resulting in limited awareness of consumer demand for sustainable products. However, the potential for circular value creation in these sectors is substantial, such as offering reconditioned machine tools through "as-a-service" models. Addressing this gap through targeted investments and initiatives is critical to unlocking this potential and advancing circularity in these industries.

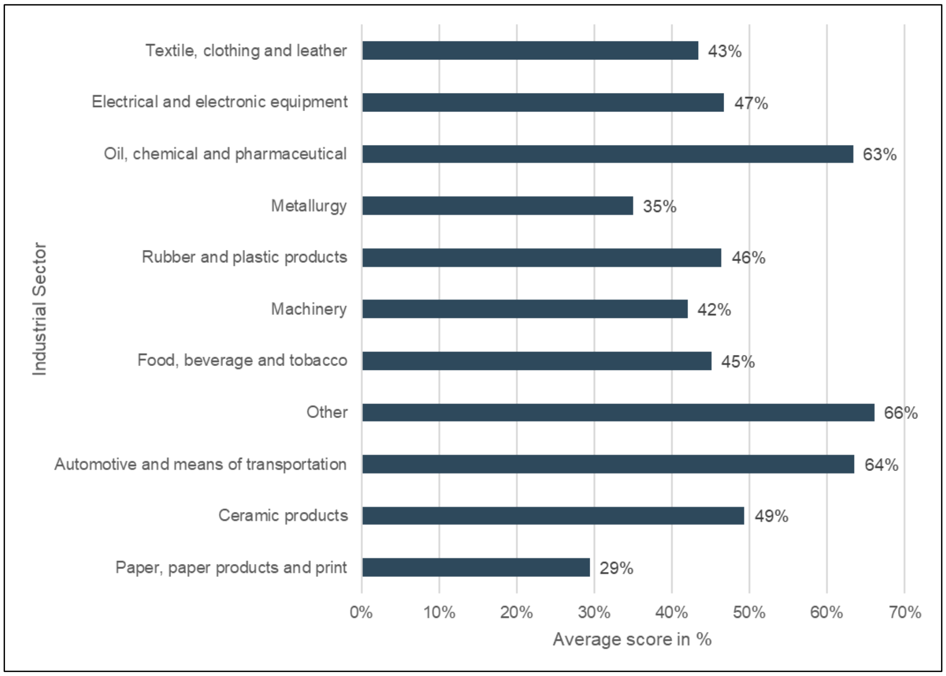


Figure 6. 9 The average C-scores of each sector

6.5.1 Textile Sector

India's textile sector has experienced remarkable growth over the past 15 years, doubling its apparel production and establishing itself as the 6th largest global exporter of textiles and apparel. This growth trajectory positions India as a key player in the global textile market, with promising prospects for further expansion. The industry's success is deeply rooted in regional specialization, with each state contributing unique strengths to the national textile landscape. From Karnataka's renowned silk sarees and cotton textiles to Tamil Nadu's expertise in handloom and knitwear, and Gujarat's dominance in cotton production, the sector showcases a diverse and rich tapestry of textile traditions and modern manufacturing capabilities.

The textile industry's significance to India's economy is underscored by ambitious projections, with expectations to reach $250 billion in textile production and $100 billion in exports by 2030 (CII, 2023). This growth is supported by a network of regional clusters across the northern, southern, and western belts of the country, where traditional craftsmanship seamlessly blends with modern production techniques to meet global demand. The industry's structure, characterized by a mix of small-scale, traditional sectors and large, modern mill sectors, reflects India's unique position in balancing heritage with innovation in textile manufacturing. For this study, the research focused on the western industrial belt, acknowledging the challenges of encompassing India's vast industrial landscape in a single survey (Dwivedi et al., 2023). The application of the C-Readiness tool to 93 textile companies in the sample provided a nuanced assessment of the sector's circularity readiness. Notably, 96% of the surveyed companies fall within the SME category, with only 3% representing large industries. This distribution highlights the critical role of small and medium enterprises in India's textile sector and underscores the importance of understanding and supporting these businesses in their transition towards more circular and sustainable practices. The analysis offers valuable insights into the textile industry's current state of circularity adoption, identifying strengths and improvement areas across various dimensions of circular economy readiness. The survey data depicted in Table 6. 1 represents the job roles of the respondents.

Table 6. 1 Distribution of Respondents by Job Role in Textile sector

Company Size	Job Role	No
Large	Management	2
	Purchasing	1
Medium	Other (Owner)	6
	Production	5
	Management	4
	Purchasing	4
	Sales / Commercial / Marketing department	4
	Administration, Finance and Control	2
	After Sales and Customer Care	1
	Supply Chain Management / Logistics	1
Small	Other (Owner)	51
	Management	4
	Production	4
	Administration, Finance and Control	2
	Purchasing	1
Micro	Other	1

The majority were owners or senior-level managers, suggesting that the data reflects the perspectives and insights of the leadership responsible for key strategic and operational decisions within these organizations. To clarify the responses and analysis, we conducted an hour-long discussion with the participants, who were primarily owners or top managers of the companies. This allowed us to better understand their perspective on the circular economy. The average circularity score of the analysed sample is 43%, highlighting that Indian textile companies exhibit a relatively low level of 'readiness' for the CE paradigm, and significant potential for improvement in aligning with CE principles as shown in Figure 6. 9. The analysis shows that 39% of the companies have circularity scores below 25, indicating that the Indian textile production ecosystem still has significant progress to make in fully adopting and applying CE principles and practices. The analysis further examines the six key areas of CE implementation in Figure 6. 10.

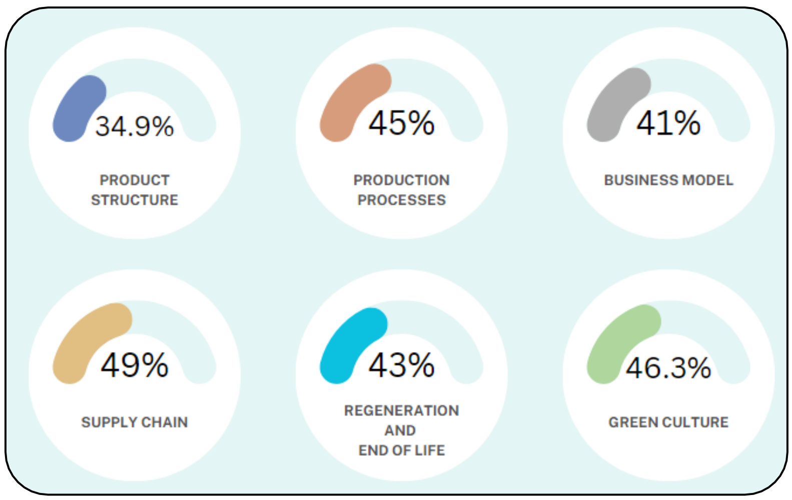


Figure 6. 10 The circularity Score of the respondent companies in textile sector

The sub-dimensions of the six dimensions are presented in APPENDIX A1-A6. The analysis indicates that companies show the highest adoption of circularity principles in the supply chain domain, with a score of 49%. This suggests that companies in India have implemented innovative practices to support a closed-loop supply chain for textile recycling. Most of the industry in India has a semi-organized process for recycling cutting waste, which presents both challenges and opportunities (Dwivedi et al., 2023; Ponnambalam et al., 2023). For instance, the Re-Start Alliance initiative aims to commercialize advanced textile recycling technologies and establish a sustainable supply chain for textile waste feedstock. This allows for the effective collection, sorting, and processing of post-consumer textile waste, enabling the reintroduction of recycled materials back into the manufacturing process (Nickerson, 2024). In terms of product structure, the average circularity score is 34.9%, revealing significant gaps in sustainable practices. Notably, 40% of companies do not utilize biodegradable, recycled, or recyclable materials. A key challenge, as highlighted by Dwivedi et al. (2023), is the production of coloured selvage waste during the weaving of dyed yarns, which diminishes material recyclability. Furthermore, 52% of companies incorporate critical materials into their products, underscoring a critical gap in the adoption of sustainable materials. This gap points to the need for increased awareness and education regarding the benefits of circular materials and their potential for long-term cost savings. Additionally, 40% of companies lack environmental product certifications, despite expressing intentions to obtain them. The absence of such certifications may erode consumer trust and restrict access to markets that increasingly prioritize sustainability (Zaidi & Chandra, 2024). Dwivedi et al. (2023) emphasize the importance of certifications like OEKO-TEX, GOTS, BSCI, SLCP, GRS, Bluesign, and ZDHC in promoting circularity. However, it is observed that textile industries, ranging from small to large scales, often prioritize vendor specifications and economic value over environmental regulations and standards.

Regarding toxic materials, 52% of companies acknowledge the need to eliminate their use but continue to rely on them. While recognizing the importance of phasing out toxic materials is a critical step toward improving product safety and reducing environmental harm, companies must develop and implement actionable strategies to achieve this goal effectively.

In the context of business models, the average score is the second lowest at 41%. The data reveals that only 9% of companies are aware of platforms for buying and selling production scrap and rejects, indicating a significant lack of awareness about tools that could facilitate such exchanges. This gap presents an opportunity for innovative solutions, such as scrap trading platforms, to help companies manage waste more effectively. Additionally, 38% of companies recognize the need to collaborate with suppliers and partners across the value chain to co-design products and processes with a circular approach. Such collaboration, involving transparent information sharing, joint innovation, risk management, and alignment on shared goals, can significantly enhance sustainability initiatives and advance the transition to a circular economy (Nudurupati et al., 2022).

Concerning end-of-life (EoL) management, only 7% of companies encourage consumers to participate in structured processes for recovering EoL products, components, and materials. This highlights a systemic challenge in the industry, as companies lack organized initiatives for EoL product recovery. To address this, companies should invest in developing structured recovery programs that clearly outline processes for collecting and processing EoL products (Molla et al., 2022). Increasing consumer participation in EoL recovery can be achieved through awareness campaigns that emphasize the benefits of returning products at the end of their lifecycle. Leveraging technology, such as blockchain for tracking recycling efforts or streamlining product returns, can enhance user experience. Additionally, offering incentives like instant loyalty points for returning EoL products can boost consumer engagement.

In the production domain, the Indian textile sector demonstrates significant gaps in resource consumption monitoring. Only 3% of companies continuously monitor and take periodic action on their consumption of energy, water, and air, indicating a lack of robust monitoring systems (Saccani et al., 2023). While companies recognize the importance of renewable energy, 53% have yet to adopt it. Another critical finding is that 24% of companies are unaware of industrial symbiosis, a key strategy within the circular economy framework. Industrial symbiosis involves the collaborative exchange of materials, energy, and services, enabling one company's waste to become another's resource. Companies unaware of this concept miss opportunities for cost savings, innovation, and enhanced sustainability. This lack of awareness underscores the need for education and awareness-building initiatives to foster the adoption of circular economy principles across the textile industry.

6.5.2 Electronic and Electrical Equipment (EEE) Sector

As the nature of the study was exploratory, the data was first subjected to a descriptive analysis. The findings of the descriptive analysis are presented below. The application of the C-Readiness tool enabled a detailed assessment of the overall circularity score and performance across individual areas for each of the 83 companies in the sample. The results of this analysis are discussed in the following sections. The results begin with an analysis of the distribution of companies, showing that most belong to the SME sector, while very few have participated from the large and micro industries.

The survey data depicted in Table 6. 2 represents the job roles of the respondents.

Table 6. 2 Distribution of Respondents by Job Role in Textile sector

Company Size	Job Role	No
Large	Technical department	1
Medium	Other (Owner)	2
	Production	3
	Management	4
	Purchasing	4

	Sales / Commercial / Marketing department	2
	Administration, Finance and Control	3
	Technical department	6
Small	Other (Owner)	4
	Production	4
	Management	15
	Purchasing	2
	Sales / Commercial / Marketing department	5
	Administration, Finance and Control	10
	Technical department	20
	Supply Chain Management / Logistics	3
Micro	Purchasing	1

The survey was distributed to key stakeholders in the selected SMEs, including owners, managers, and sustainability officers actively involved in circular economy decision-making. As the majority of respondents were owners or senior-level managers, the data captures the perspectives and insights of the leadership responsible for making key strategic and operational decisions within these organizations. This suggests that the findings of the study reflect the views and priorities of the SME leadership.

The average circularity score of the analysed sample stands at 47%, indicating that Indian electrical and electronics companies exhibit a relatively low level of 'readiness' for the circular economy paradigm. This finding underscores the significant potential for these firms to enhance their alignment with CE principles, as illustrated in Figure 6. 9. Furthermore, the analysis reveals that 65% of the companies have circularity scores ranging between 25-50, suggesting that the Indian electrical and electronics industry still has substantial progress to make in fully adopting and applying CE principles and practices. While some companies have begun to embrace circular approaches, the majority remain in the early stages of transitioning towards a more sustainable, circular model of operations.

The analysis further examines the six key areas of CE implementation in Figure 6. 11; this descriptive analysis offers significant insights into the current state of circularity readiness within the Indian E&E industry. The sub-dimensions of the six dimensions are presented in APPENDIX A7-A12. The analysis indicates that companies show the highest adoption of circularity principles in the green culture and product structure. The analysis of the six dimensions of circularity readiness in the Indian electrical and electronics (E&E) industry reveals a complex landscape of progress and challenges. The highest score of 60% in Green Culture indicates a strong organizational commitment to sustainability, suggesting that companies are successfully fostering eco-friendly practices and employee engagement in sustainability initiatives. This strong foundation in sustainability culture, as emphasized by Bressanelli et al. (2020), can significantly enhance the implementation of circular economy strategies by encouraging employees to adopt sustainable practices in their daily operations. The Product Structure dimension, scoring 52%, further demonstrates the industry's progress in adopting sustainable design principles. This focus on designing for longevity, recyclability, and ease of disassembly indicates a growing recognition of the importance of product lifecycle considerations in achieving circularity (Mesa, 2023; Wang et al., 2022).

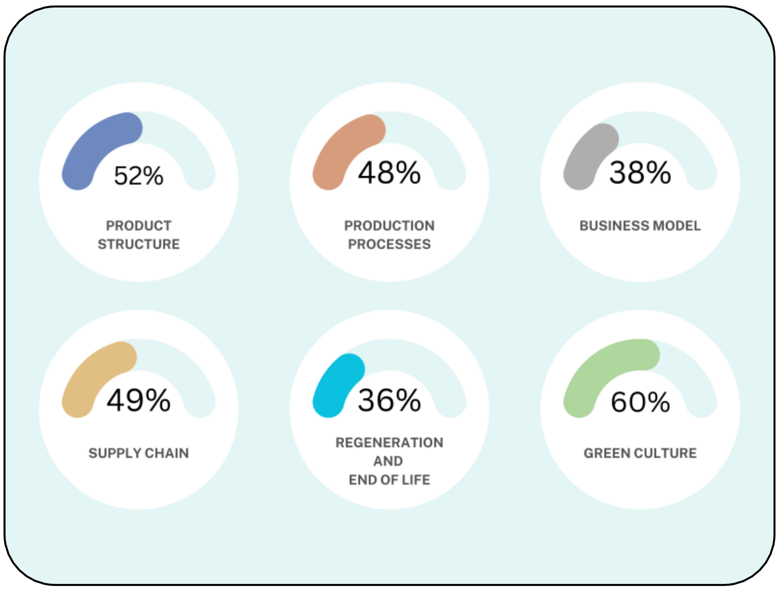


Figure 6. 11 The circularity Score of the respondent companies in EEE sector

The Supply Chain and Production dimensions, scoring 49% and 48% respectively, highlight both efforts and challenges in integrating circular practices into core operational areas. The complexity of supply chain management in the E&E sector, particularly in collaborating with suppliers and stakeholders to improve resource efficiency and minimize waste, is reflected in these moderate scores (Schöggl et al., 2024). Similarly, the Production score indicates some adoption of sustainable techniques but also underscores the significant investments and operational changes required to fully transition to circular production processes (Aldrighetti et al., 2023; Kamble & Gunasekaran, 2023). These interrelated challenges in managing supply chains and production systems exemplify the multifaceted nature of the sector's transition to circularity.

The Business Model dimension's low score of 38% reveals a critical area for improvement, indicating that many companies still rely on linear business models that are misaligned with circular economy principles. This score underscores the need for innovation in areas such as product-as-a-service and take-back schemes (Bressanelli et al., 2021; Negri et al., 2021). The challenges in adopting circular business models, as noted by I. S. Khan et al. (2021), stem from the required shifts in value propositions, customer relationships, and revenue streams. Companies may hesitate to invest due to limited resources, lack of understanding of benefits, or fear of disrupting established operations (S. S. Khan et al., 2015). Choudhary et al., (2022) further highlight the lack of expertise and resources in many organizations to effectively transition to circular strategies, emphasizing the need for investments in R&D and marketing.

The lowest score of 36% in Reverse Logistics and Regeneration underscores major challenges in developing effective systems for the collection, refurbishment, and recycling of end-of-life products. This poor performance is largely attributed to the significant market share held by informal recycling sectors, coupled with insufficient regulatory frameworks for e-waste management and product returns (S. S. Khan et al., 2015; A. Kumar et al., 2022; Wath et al., 2010). The lack of awareness regarding the strategic importance of reverse logistics in achieving circularity often leads companies to overlook its potential for recovering value from returned products and minimizing waste. This dimension represents a critical area for improvement, requiring concerted efforts in policy development, infrastructure investment, and awareness-raising to enhance the E&E industry's circularity performance.

6.7 Summary of findings

CE presents significant business potential for the Indian manufacturing sector. However, manufacturing companies are still far from fully embracing CE principles. To assist companies in evaluating their level of circularity and identifying areas for CE implementation, the C-Readiness tool was developed to assess their readiness for transitioning to a CE. The application of this tool to a sample of 380 companies provided an initial overview of their positioning toward the CE.

The analysis revealed that, despite recent efforts, the average circularity level of the companies remains relatively low, with a C-Score of 47 out of 100. Notably, over 60% of the companies scored below 50 points, highlighting the complexity of achieving a full transition to the CE within the manufacturing sector. This underscores the systematic and transversal nature of the transformation required, as well as the need for medium- to long-term efforts to achieve significant results.

A detailed analysis of circularity across the assessment areas of the tool - product structure, production processes, business models, supply chain, regeneration, and green culture - revealed varying levels of readiness. Companies demonstrated higher readiness in the supply chain (average score of 52 points), where Make in India initative plays a critical role, and in transversal green practices (average score of 57 points). Conversely, significant gaps were identified in business models (average score of 38 points), such as the adoption of product-as-a-service models, and in end-of-life management and remanufacturing (average score of 40 points), both of which are crucial for achieving a fully functional CE.

When analyzed by company size, larger firms exhibited higher readiness for the CE, achieving higher average C-Scores compared to medium and small-sized enterprises. This is attributed to their greater resource availability and stricter regulatory compliance requirements. Sector-wise analysis revealed a varied landscape, with industries such as chemicals, metallurgy, construction, and automotive—sectors historically subject to stringent environmental regulations - achieving higher circularity scores. In contrast, sectors like plant and machine tools, third-party machining, and mechanical, electrical, and electronic components, which face fewer regulatory pressures and less end-customer demand for sustainability, lagged behind.

In our investigation, we explored two key sectors represented in our sample textile and EEE sector. Notably, we found that the EEE sector exhibits a higher level of circularity than the textile sector. Furthermore, the EEE sector has adopted more effective circular practices regarding product structure and green culture, achieving a score of over 50%. However, it is essential to note that the findings are somewhat generalized due to the small sample size, which limits drawing more profound conclusions.

This raises the critical question: How can companies enhance their circularity? The first step involves redesigning products to prioritize mono-materiality, standardization, modularity, dis-assemblability, and the use of durable and recyclable materials. Next, production processes must be reconverted to improve efficiency, reduce waste, and leverage industrial symbiosis, alongside increasing the use of self-generated or renewable energy. Business models should be reimagined toward as-a-service models, where ownership remains with the supplier. For instance, companies could experiment with offering remanufactured product lines through rental, leasing, or pay-per-use models, incorporating sharing mechanisms to maximize product utilization. Additionally, supply chains must be reconfigured to optimize material procurement and product distribution, emphasizing low-emission transportation, sustainable packaging, and supplier evaluation criteria that include environmental and social considerations. Finally, improving end-of-life management requires initiatives to recover products, components, and materials for reuse and regeneration.

From the survey, it is evident that there are differences in the readiness scores of the circular economy levers. Investigating the factors behind these varying scores can reveal the underlying dynamics and interdependencies that affect the implementation of circular economy practices. Additionally, it is interesting to explore the linkage between the supply chain and business model levers, as they have the highest and lowest scores, respectively. Understanding how these two levers are linked, can provide insights into their influence on CE practices. Therefore, chapter 7 examines the potential linkages and relationships between these levers to enhance the overall implementation of CE practices in companies.

While numerous actionable areas exist, companies often face constraints related to time, budget, and resources. Therefore, prioritizing actions is essential, and the C-Readiness tool serves as a valuable instrument for conducting initial assessments and guiding strategic decisions. For future research, conducting a comparative analysis of cross-national studies, such as in India and Italy, would be interesting. The variations in their economies, cultural contexts, industrial practices, and policy frameworks present a valuable opportunity to examine the differing perceptions and implementations of the circular economy within these two contexts.

Chapter 7. Relationship between Supply chain Supply chain management & collaboration, Servitized business model and Circular economy & End-of-life practice

Building on the empirical findings from Chapter 6, which analysed survey results from the Indian manufacturing industry and found that circular economy levers influence the overall C-Readiness score. Among the levers assessed, the supply chain lever achieved the highest score, whereas the business model lever received the lowest score. This observed discrepancy indicates a correlation between these two factors. This chapter discusses the linkage between the supply chain and business model levers and how they drive the effective implementation of circular economy and end-of-life practices.

In this context, CE approach underscores the critical role of effective supply chain management in shaping production and consumption to extend resource lifespans and minimize waste (Geissdoerfer et al., 2018; Ghisellini et al., 2016; Iacovidou et al., 2017). While existing literature also highlights business models, product design, and production processes as essential levers for the successful implementation of CE practices (Bressanelli et al., 2021). However, our findings highlighted an asymmetry in their practical adoption in the manufacturing industry. Kühl et al., (2020) argue that effective integration of these elements requires a fundamental re-evaluation of business operations. This shift demands a systemic transformation that involves collaboration among multiple stakeholders (Berlin et al., 2022; Herczeg et al., 2018; Pinto & Diemer, 2020; Sudusinghe & Seuring, 2022). Therefore, establishing a well-structured and collaborative approach that involves all actors in the supply chain, including suppliers, manufacturers, distributors, and customers, is essential for the successful implementation of a circular economy model (Calzolari et al., 2024). The literature on CE has extensively explored the positive aspects of circular supply chain (CSC) and its integration, which can be examined through both upstream and downstream integration (Di Maria et al., 2022). Additionally, CE requires stronger cooperation with suppliers to ensure the supply of recycled or recyclable materials and reduce waste along the entire chain (supplier integration) (Berlin et al., 2022). It integrates the supply chain and the surrounding business ecosystem to slow, close, and narrow resource flows to ultimately create economic and environmental value (Batista et al., 2018;

Geissdoerfer et al., 2018). Because circular supply chain management cannot be achieved by a single firm, as it requires collaboration between the organisations across the supply chains and other stakeholders across similar and/or different sectors (M. Yang et al., 2018). Empirical studies, such as Calzolari et al. (2024), have shown that manufacturers engage differently with suppliers or upstream supply chain partners compared to consumers and downstream supply chain partners. Moreover, closing the loops requires firms to modify their supply chain collaboration systems by pooling knowledge and competences spanning across departments (internal integration). Additionally, to extend product lifecycles through end-of-life recovery, refurbishing, or remanufacturing, manufacturers must further engage with customers (customer integration) (Bimpizas-Pinis et al., 2022). Building on this, circular economy emphasizes a practice-oriented approach to business model innovation enhance competitiveness by integrating environmental responsibility and economic profitability, through incorporating elements to slow, narrow, and close resource loops (Geissdoerfer et al., 2018). However, switching a company's business model to circular one can be challenging. Moving into product-service systems (PSS) can contribute to resource efficiency by reducing the cost of and need for materials (Tukker, 2015) and building strong relationships between providers and consumers through digital integration (Elhazmiri et al., 2022). In servitized business model (SBM), PSS can be delivered to the customer in three options such as product-oriented, use-oriented, and result-oriented, allowing products to be maintained, upgraded, rented or shared (Tukker, 2004). In terms of value creation and delivery systems for servitized business models, it is critical to develop collaborative supply chain networks with different stakeholders motivated by and contributing to economic viability and environmental benefits. This collaboration also addresses long-term challenges manufacturers encounter in sustaining circular transitions. Implementing a circular business model requires simplifying complex organizational systems and clarifying interrelationships across supply chain elements (Kühl et al., 2022). As discussed in the following section, emphasis is placed on the linkage between SBMs and circular supply chain management to operationalize resource loops - closing, slowing, narrowing, and dematerializing material flows.

Despite the critical role of Supply Chain management & Collaboration (SCMC) and Circular Supply Chain Management (CSCM), along with Servitized business models (SBMs), in advancing the Circular Economy & End of life practice (CEP), their interconnections remain underexplored in research, and practical implementation is limited (Bressanelli et al., 2021; Homrich et al., 2018).

However, a systematic search was conducted on the Scopus database to identify existing studies related to supply chain management and collaboration, circular supply chain management, servitized business models, and circular economy practices. Three distinct keyword combinations were employed to locate relevant studies. For servitized business models, the search included terms such as "servitisation", "servitized business model", "PSS", "Product Service System", "Product as Service", etc. Similarly, the supply chain management and collaboration search focused on phrases like "supply chain coordination", "supply chain collaboration", "supply chain integration", and "circular supply chain". The circular economy search utilized commonly recognized terms such as "circular economy", "CE", and "circular economy practices". We systematically reviewed and selected articles that aligned with survey-based studies employing structural equation modelling to test hypotheses.

However, there are very few previous survey-base studies that investigate the role of servitization business models and supply chain management & collaboration, or circular supply chains, and their impact on circular economy practices shown in Table 7. 1.

Table 7. 1 List of earlier empirical articles on Supply chain management & collaboration, Servitized business model and Circular economy practice

Article	Model	Country or region surveyed	Sample size	Area Investigated		Overview	
				Servitized Business Model	Supply chain Management and Collaboration	Aim/Objective of the study	Key Findings
(Zhu et al., 2011)	SEM	China	396		X	To examine how Environmental Supply Chain Cooperation (ESCC) influences Circular Economy (CE) practice adoption and its economic/environmental performance in manufacturing, focusing on collaboration between green suppliers (GP) and customers (CC).	The study found that CE practices positively influence ESCC, such as green purchasing and customer cooperation. ESCC exerts both moderating and mediating effects between CE practices and CE-targeted performance. As manufacturers require close relationships with GP and CC to adopt CE practices, higher ESCC implementation correlates with enhanced CE adoption and greater performance improvements.
(Di Maria et al., 2022)	SEM	Italy	189		X	To explore the relationship between Industry 4.0 technologies and the circular economy, specifically focusing on how supply chain integration plays a mediating role in this relationship. The study investigates how these technologies can enhance collaboration and integration	The study highlighted that the integration of supply chain partners enhances information sharing, improving responsiveness to environmental challenges. This data-driven approach enables firms to better manage material flows, waste, and resource optimization. This suggests that firms with advanced

						across supply chains to support circular economy initiatives.	Supply Chain Integration (SCI) achieve superior CE outcomes, underscoring the necessity of cross-supply-chain collaboration.
(Hassan et al., 2023)	PLS SEM	Pakistan	475		**X**	To explore the role of Blockchain Technology (BT) in enhancing Supply Chain Integration (SCI) dimensions and achieving Sustainable Supply Chain Performance (SSCP) outcomes, specifically considering the mediating effect of SCI dimensions and the moderating role of Circular Economy (CE) principles.	The study found that Supply Chain Integration (SCI) mediates, and CE moderates the relationship between blockchain technologies (BTs) and Sustainable Supply Chain Performance (SSCP). Additionally, BTs adoption by SMEs enables system-wide integration to achieve sustainable outcomes, with SCI and CE dimensions jointly influencing performance.
(Kühl et al., 2022)	PLS SEM	U.K.	114	**X**	**(X) as end result**	To explore the impact of product-service systems (PSSs) on the implementation of circular supply chain (CSC) practices in small and medium-sized enterprises (SMEs).	The study demonstrated that different type of PSSs positively facilitates the transition from linear to Circular Supply Chains (CSCs). However, internal environmental orientation does not moderate the PSS-CSC relationship. Manufacturers typically begin with product-oriented PSSs to build service capabilities before advancing to complex offerings (e.g., use- and result-oriented PSSs).
(Rijal et al., 2024)	PLS SEM	Nepal	152		**X**	To analyse shirking behaviours in SME supply chain collaborations in Nepal and their impact on CE performance, moderated by CE entrepreneurship (CEE) and technical capability.	The study found that CE entrepreneurship and technical capabilities mitigate shirking impacts and amplify the effect of Supply Chain Collaboration (SCC) on CE performance. Shrinkage directly improves SCC and indirectly enhances CE performance, positioning SCC as a critical strategy for SMEs in emerging economies.
(Calzolari et al., 2024)	SEM	Asia and Europe	150		**X**	To explore the interplay between institutional pressures and supply chain integration in facilitating the adoption of circular economy (CE) practices among multinational enterprises (MNEs)	The study revealed that Supply Chain Integration (SCI) drives Circular Economy (CE) adoption by overcoming institutional distance and coordinating multi-partner activities. SCI support

							technological, logistical, and relational integration, thereby enhancing internal capabilities, lowering transaction costs, reducing uncertainty and resource dependency
(Le et al., 2024)	PLS SEM	Vietnam	457		**X**	To determine how Circular Economy Entrepreneurship (CEE) enables Circular Economy Practices to achieve sustainable supply chain management (SSCM).	The study found that Sustainable Supply Chain Management (SSCM) mediates the relationship between CE Practices and Sustainable Performance (SP). For instance, closer collaboration with suppliers and customers reduces disruption risks, while sustainable operations (e.g., lean processes, circular design) require close coordination among upstream and downstream partners to retain resource value.
(Johl et al., 2024)	SEM ANN	Malaysia and Japan	251	**X**		To explore how green servitization can enhance circular economy practices and promote sustainability in Malaysian and Japanese manufacturing firms.	The study identified that specific green servitization constructs (e.g., internal competencies, maintenance) significantly improve sustainable performance, whereas product-focused strategies and digital technologies show no significant impact. CE Practices (CEPs) mediate in the relationship between green servitization and sustainable performance, as resource efficiency gains from product ownership retention reduce overproduction and extend product lifespans.
(Chowdhury et al., 2025)	PLS SEM	U.K.	248	**X**		To explore AI"s role in advancing green servitization through resource orchestration and re-institutionalization practices.	The study found that the circular economy (CE) impacts green servitisation because cost savings achieved through CE practices provide businesses with additional resources to invest in green services. Furthermore, AI-driven decision support systems (ADSS), supply chain alertness, resource orchestration, and re-institutionalization catalyse circular economy practices. ADSS

							improves supply chain alertness, enabling resource reconfiguration, waste reduction, and optimized efficiency.

From previous studies, it is evident that these concepts have not been systematically and holistically investigated. While empirical studies predominantly employ structural modelling techniques like PLS-SEM, they often adopt a fragmented lens, isolating factors such as supply chain collaboration or SBMs rather than examining their interconnected roles in CE transitions. This approach is particularly evident in regional biases: the majority of studies focus on Asian and Southeast Asian contexts, with only six papers addressing supply chain management (SCM) and three exploring Servitise Business Models (SBMs) in relation to CE. While theoretical research supports the direct impact Supply Chain management & Collaboration (SCMC) practices and SBM on CE, they often overlook the mutual effects of adopting SCMC and SBM on CE implementation. Recent studies have also highlighted this notable gap Le (2024). Furthermore, the above table shows that empirical research on the correlation between CE and SSCMC, as well as between CE and SBM, is relatively low. However, Kuhl reflected both aspects in its analysis, but CSC viewed as final outcome rather than resulting effect which limits our understanding of their combined significance in manufacturing industries for effective CE implementation in real-world contexts. Notably, no study to date holistically integrates both SCM and SBMs, despite their complementary potential in advancing CE. Further, three studies on SBMs and CE have different focuses: Kühl et al., (2022) study product-service systems (PSS) from an internal environmental perspective, Chowdhury et al., (2025) show how CE drives green servitization, In contrast Johl et al., (2024) link green servitization with CE implementation. This inconsistency highlights the ambiguity concerning the relationship between sustainable business models and the circular economy. Although past studies such as Geissdoerfer et al., (2018) provided a solid theoretical foundation in the synergetic relationship, significant gaps remain in investigating the connection between SBM and SCMC in the implementation of CEP. This gap underscores the need for comprehensive empirical research that addresses the integrated impact of SBM and SCMC on CE performance in manufacturing contexts.

This significant research gap drives research questions to unlock a more comprehensive understanding of how CE practices can be effectively implemented in complex manufacturing environments. The integration of these concepts creates a critical synergy that can potentially enhance their individual impact on CE outcomes. Hence this research tries to answer the research question:

RQ: What factors influence the adoption of Circular Economy & End of life practices (CEP) in Indian manufacturing firms, and how can a theoretical model link Supply Chain Management and Collaboration (SCMC) with Servitized Business Models (SBMs)?

To advance the nascent understanding, this research proposes a framework integrating circular business models and circular supply chain management to advance the circular economy, analysing empirically 380 manufacturing industries. This understanding can benefit a manufacturing firm operating within a complex ecosystem, where circular supply chains and servitization business models often intertwined. Thus, this empirical study can provide more actionable insights for practitioners seeking to implement CE principles. From a theoretical perspective, this integration can lead to the development of new theoretical frameworks that support the academic understanding of CE implementation.

7.1 Literature review and Hypotheses

In the context of circular supply chain management, three main aspects are typically discussed. The first involves traditional supply chain management practices, such as managing forward logistics, including upstream and downstream relationships with suppliers and customers (Farooque et al., 2019). The second considers reverse supply chain activities, which are crucial in a CE model that creates value through purposeful business ecosystem integration by leveraging product/service life cycles and closing the loop (P. Kumar et al., 2023). The third focuses on mechanisms for collaborating closely with stakeholders in the operational aspects of circular supply chains (Di Maria et al., 2022). Literature predominantly emphasizes the critical role of both internal and external collaboration in the successful implementation of circular supply chain practices (Aarikka-Stenroos et al., 2022; Farooque et al., 2019; Ratsimandresy & Miemczyk, 2023). Internal integration requires cross-functional coordination integrating departments like R&D, operations, reverse logistics, and marketing. This collaboration enables seamless cross departmental coordination through shared information, joint decision making, and team building efforts, enabling circular product design, implementing take-back systems, and optimized resource use by aligning operational activities, user expectations and behaviours, and business models. External collaboration involves strategic coordination with external stakeholders among upstream and downstream supply chain partners, improving relationships between a firm, its suppliers, consumers, and logistics providers (Bimpizas-Pinis et al., 2022). This includes co-designing products with suppliers, selecting and monitoring green suppliers based on environmental performance for circular purchasing, and tracking materials/components to support future returns and identify cost savings (Zhu et al., 2011). Information sharing with suppliers/customers through IoT, big data analytics, and cloud computing enhances supply chain visibility via transparent data exchange (Lin & Chu, 2024). Within collaborative supply chain management frameworks, real-time data exchange and integration via shared platforms, support cross-functional interaction and end-to-end visibility of components, materials and products. This visibility allows suppliers and manufacturers to optimize operations, coordinate recycling and repurpose initiatives, and dynamically modify resource flows to reduce waste and enhance sustainability. Supplier integration further supports environmental planning by participating in sustainability initiatives, defining joint environmental goals, and implementing shared purchasing policies and practices. Furthermore, green purchasing supports strategic alignment between manufacturers and suppliers to reinforce eco-design initiatives by selecting eco-friendly suppliers (Berlin et al., 2022). By prioritizing environmentally compliant suppliers, manufacturers institutionalize circularity as a shared goal. Collective knowledge and collaboration between manufacturers and suppliers enable more effective solutions to sustainability and circularity challenges, that improved decision-making and innovation through shared insights. Hence, supply chain management & collaboration, supports circularity by optimizing resource usage, promoting sustainable product design, enabling closed-loop systems, and fostering innovation for sustainable practices. This positively influences CE & End of life practices.

H1: SCMC has a positive influence on the adoption of CEP.

The Ellen MacArthur Foundation (2013) identified four sources of value creation within circular economy: business models for circularity could create value from the inner circle, circling longer, cascading use and the pure circles. To some degree, every business model is both linear and circular (Lewandowski, 2016). Planing (2014) regarded business model innovation as one of the fundamental building blocks for the transition to circular economy. So, the transition from traditional product-centric models to SBMs represents a paradigm shift that inherently aligns with CE principles, offering significant potential for enhancing environmental sustainability. As manufacturers progress through the servitization journey, SBMs encompasses both tangible product features and intangible characteristics such as service offerings and contractual elements, integrated offerings that effectively bridge the gap between linear and circular models. SBMs, such as leasing, pay-per-use, or result-based models, incentivize manufacturers to design for durability, repairability, and recyclability. By retaining product ownership, firms are motivated to maximize the value extracted from each unit over multiple usage cycles. Further, during the usage phase, SBMs facilitate optimized resource utilization, extending service life as product and components (Reim et al., 2015; Stahel, 2010; Tukker, 2015) as providers are incentivized to minimize inputs while maximizing performance outcomes. So SBM, servitization promotes providing services that extend product lifecycle, such as maintenance, repairs, improvements, and ultimately reuse. This decreases the necessity for manufacturing of new goods, reducing resource extraction and decreasing the environmental impact of prevalent manufacturing processes. Several case studies highlight successful transitions to the CE to reduce waste and extend resource utility, with prominent examples including Patagonia and Rolex, which prioritize product longevity through repair services; Xerox and Philips, which offer performance-based solutions like subscription models for printing and lighting services; and H&M, known for initiatives promoting clothing returns and reuse (Hofmann, 2019). These models enable the systematic return of resources, preserving or restoring their quality levels, thereby contributing directly to CE goals of dematerialization and closed-loop systems (Geissdoerfer et al., 2018). Hence, empirical evidence supports the role of SBMs as strong levers for CE objectives. Bressanelli et al. (2018) demonstrate how these models foster collaborative ecosystems, enable reverse logistics, and promote resource-sharing initiatives. Leasing and rental models, in particular, facilitate product recovery and recycling at end-of-life. Furthermore, SBM offers strong commercial and financial benefits, including a long-term competitive advantage, by providing added value and exploring market trends. This is a key motivation for manufacturers to drive and support initiatives linked to the dematerialization of consumption. Legislative measures, including Extended Producer Responsibility (EPR) regulations, support SBM by incentivizing circular practices, while digital technologies cloud platforms, trading systems (Gu et al., 2017), and IoT-enabled tracking streamline resource redistribution (Pactwa et al., 2020), waste monitoring, and product recovery (Konietzko et al., 2020). These digital ecosystems can enable cooperative product return mechanisms, ensuring the efficient reintegration of materials into production cycles. While the potential benefits of SBMs for CE are well discussed from a theoretical point of view, there is a scarcity of empirically verified results. Nevertheless, the cumulative discussion suggests that SBMs can significantly enhance both economic and environmental performance through effective resource management. Therefore, based on the strong theoretical background, it can be hypothesized that SBMs positively influence CE performance.

H2: SBM has a positive influence on the adoption of CEP.

Supply chain management & collaboration closely influences SBMs to deliver comprehensive, sustainable, and flexible service offerings. Kuhl 2020 discussed the positive link between SCMC and SBM that leads to circular objective. For example, SCMC supports the monitoring of user behaviour to promote efficient and sustainable product usage, which directly influences consumption patterns and enables firms to identify innovative, resource-efficient methods for service delivery (Yang et al., 2018). This adaptability is reinforced by data-driven decision-making, as integrated supplier networks provide insights into consumer usage patterns, performance metrics, and customer feedback. Such data empowers manufacturers refine service offerings, strengthen customer relationships, and identify opportunities for continuous improvement. These capabilities underpin agile service models, enabling firms to rapidly adapt their service portfolios in response to evolving market conditions or shifting customer preferences. Further it enhances supplier-consumer Integration which facilitates the co-creation of tailored solutions that align with customer demands for customized services or leverages to design innovative service solutions that address dynamic market requirements. In result manufacturing companies support in offering highly customized products to prevent waste and over-production. This optimization extends to inventory management and waste reduction, while also improving forecasting accuracy based on service contracts, ensuring effective resource allocation and ensuring efficient utilization of assets as well as to reduced lead times and enhanced responsiveness to customer demands. This necessitates a greater emphasis on product reliability and maintainability (Colen and Lambrecht, 2013; Reim et al., 2016) This leads to increased information and control over product flows relative to traditional sales business models (Sundin & Bras, 2005; M. Yang et al., 2018). This is exemplified by sharing materials and information between manufacturer and customer to minimize product failure (Fargnoli et al., 2022; Smith et al., 2014). Further, the retention of product ownership incentivizes manufacturers to maximize value capture throughout the product life cycle (Gebauer et al., 2017; Yang et al., 2018). However, there were significantly fewer identified practices around SCMC and SBMs, which offers a promising foundation for exploring the mechanism that enhance circularity. Nevertheless, the above discussion supports the notion that SCMC positively contribute to the transition of SBMs. Thus, SCMC positively influences the adoption of Servitized Business Models, fostering sustainable value creation across the service lifecycle.

H3: SCMC has a positive influence on the adoption of SBM.

Collaborative partnerships with suppliers in sustainable practices enable firms to incorporate circular design principles into products and services, thus extending product life cycles and reducing environmental impacts. This collaborative innovation is further supported by the establishment of long-term partnerships, where a shared commitment to sustainability aligns the objectives of firms and their upstream partners, promoting continuous improvement and coordinated decision-making. Collaborative innovation with suppliers can embed circularity into service offerings (e.g., modular designs for easy disassembly). This servitized approach catalyses innovation in service design through the co-creation of circular services, such as product-as-a-service or maintenance-as-a-service models. For example, Philips' "Lighting-as-a-Service" demonstrates how SBMs can support circular economy practice through structured collaboration, aligning supplier incentives with performance-based contracts to offer a pay per lux business model (Lacy et al., 2020). Furthermore, closer collaboration with suppliers and customers can enhance markets for secondary products and materials while promoting servitization, thereby facilitating the implementation of CE principles. This integrated approach not only optimizes resource utilization but also creates new value streams within the circular ecosystem, fostering a more sustainable and resilient supply chain network.

H4: SBM mediates the relationship between SCMC and CEP

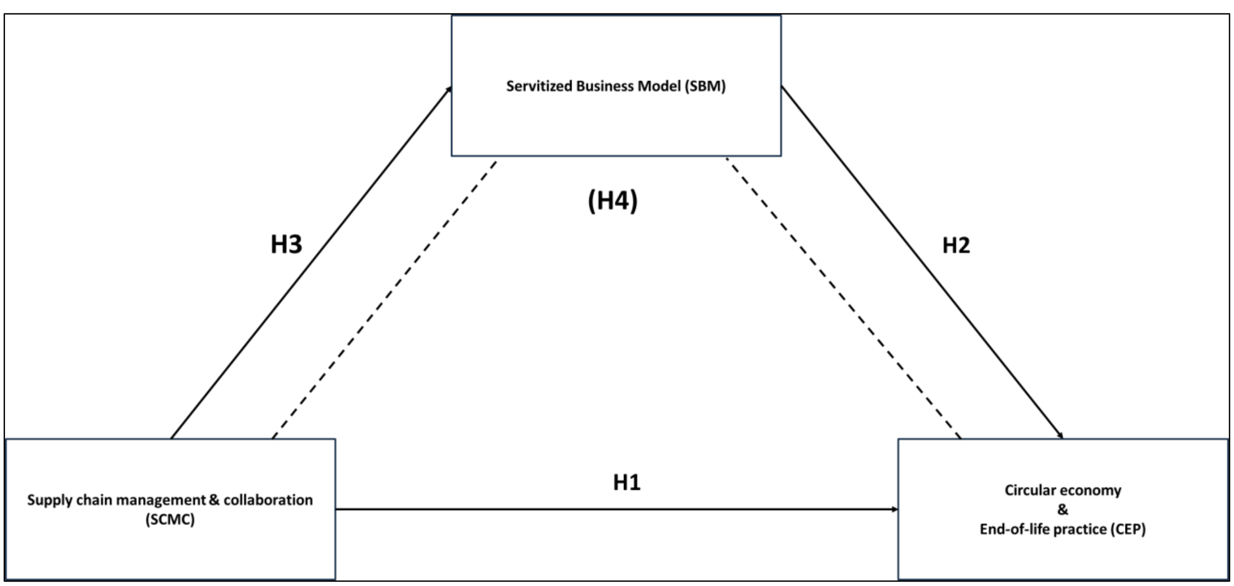


Figure 7. 1 Theoretical Model for testing the hypotheses

Based on these hypotheses, Figure 1 illustrates the theoretical framework, for the adoption of supply chain management collaboration and servitized business model for achieving CE practice.

7.2 Methodology

7.2.1 Sample and Survey design

The hypotheses were examined using a questioner-based survey instrument and structural equation modelling (SEM). This study employed a structured, theory-driven methodology to ensure robustness. The process began with the identification of survey items, which were systematically designed based on an extensive review of peer-reviewed literature. The researchers utilized established methods to develop and refine the survey instrument. A pretest of the questionnaire was conducted with a sample of Italian companies, allowing for improvements based on feedback. The final questionnaire comprised 37 questions, including demographic information. Specifically, it included a substantial number of questions assessing overall understanding of the circular economy, three questions on supplier integration and external collaboration, three questions on SBMs adopted by the companies, and five questions on CE practices implemented within their operations. This ensured alignment with established constructs in supply chain integration, servitized business models, and CE performance. Table 7. 2 discusses the "Instrument development and questionnaire design" and "survey construct" specified the variables selected from the survey. A 5-point Likert-type scale (1 = "strongly disagree", 2 = "disagree", 3 = "neutral", 4 = "agree", 5 = "strongly agree") was employed for measurement, as such scales are widely utilized in research for their reliability and simplicity. Firm size was incorporated as a control variable to account for potential variations attributable to organizational scale.

Table 7. 2 Model latent variables and constructs

Latent variable	ID	Measurement Constructs	References
Supply chain management & collaboration	SC1	To what extent can your company track products, components, and materials along the supply chain (e.g., through sensors, IoT, RFID, blockchain technologies)?	(Calzolari et al., 2024; Hassan et al., 2023)
	SC2	To what extent does your company select suppliers	(Calzolari et al., 2024; Di

		based on green criteria and on their environmental performances?	Maria et al., 2022)
	SC3	To what extent does your company collaborate with value chain partners to co-design product-service systems for the Circular Economy?	(Hassan et al., 2023; Le et al., 2024; Rijal et al., 2024)
Servitized Business Model	SBM1	Does your company offer product-service systems solutions such as product leasing, renting, pay-per-use and, if so, to what extent these offerings are spread?	(Chowdhury et al., 2025)
	SBM2	To what extent is it possible to share your products among different users (product sharing)?	(Bressanelli et al., 2021; Johl et al., 2024)
	SBM3	To what extent does your company use cloud-based trading platforms for scraps and waste?	(Chowdhury et al., 2025)
Circular Economy & End of life Practices	CE1	Are there any products take-back initiatives directly organized by the company and, if so, to what extent are these initiatives diffused?	(Bressanelli et al., 2021; Bressanelli & Saccani, 2025; Calzolari et al., 2024; Le et al., 2024)
	CE2	Is there a reverse logistics for your end-of-life products and, if so, to what extent does your company manage and control its infrastructures?	(Bressanelli et al., 2021; Calzolari et al., 2024)
	CE3	To what extent do initiatives for the reuse of your products exist and are widespread?	(Calzolari et al., 2024; Hassan et al., 2023)
	CE4	To what extent do initiatives for the remanufacturing of your components exist and are widespread?	(Calzolari et al., 2024)(Hassan et al., 2023)
	CE5	To what extent do initiatives for the recycling of your materials exist and are widespread?	(Hassan et al., 2023; Le et al., 2024)

As India accelerates its transition toward sustainable industrial practices, policymakers and manufacturers face a critical juncture: reconciling economic growth with circular principles. The Indian government has been actively encouraging manufacturers to adopt CE principles to achieve resource efficiency. To examine the readiness of Indian manufacturers for this transition, a structured questionnaire was developed which described before. The questionnaire was designed to capture relevant insights from respondents representing Indian manufacturing firms and was administered through an online survey.

A pilot study was conducted with a sample of 10 industries to evaluate the clarity and validity of the survey instrument. Feedback from the pilot study was incorporated to refine the questionnaire, ensuring comprehensibility and relevance. The pilot testing aimed to determine the minimum sample size required for the full-scale study and to assess respondent comprehension. A random sampling approach was adopted, utilizing multiple databases to identify Indian manufacturers. These databases included the Micro, Medium & Small-Scale Industry registry from the Government of India, the Confederation of Indian Industry (CII), the Open Government Data (OGD) Platform India, and the Indian Industry Association. Initial contact with firms was established through cold emails, followed by phone calls to senior management personnel. The research background was explained, and consent for participation was sought. Discussions were primarily held with HR professionals or Top management or managerial personnel, including managers responsible for supply chain and operations.

The objective was to assess whether these firms had integrated servitized business models, implemented supplier collaboration procedures, and established performance guidelines aligned with circular economic principles. If senior personnel responded positively, they were provided with further details on the study, including confidentiality assurances. To maximize response rates, multiple experts from each firm were approached, primarily including owners, directors, factory managers, supply chain managers, and operational managers. Respondents were contacted via email and telephone, with follow-up explanations provided where necessary. Data collection occurred between January and June 2024, utilizing online modes. A total of 950 questionnaires were distributed, of which 462 were returned. Responses with more than 10% missing values were excluded from the analysis. After thorough screening, 380 valid responses were retained for the study. "Don't know" responses inside the survey questionaries, though minimal, were replaced with item-wise means after sensitivity analysis confirmed negligible distortion. Data collection was conducted using an online survey tool, ensuring efficient and standardized data gathering. Table 7. 3 shows the characteristics of the respondents, including job title and Industry type, which were used as control variables in the analysis.

Table 7. 3 Respondent job profile and Industrial sector

Characteristics	**N**	**%**
Job title		
Top management	76	20%

Mid level Management	72	18.9%
Production/Quality	61	16.1%
Technical / production department	48	12.6%
Purchasing/Supply Chain Management / Logistics	41	10.8%
Sales / Commercial / Marketing department	35	9.2%
Administration, Finance and Control	25	6.6%
Other	22	5.8%
Industry		
Textile, clothing and leather	93	24.5%
Electrical and electronic equipment	86	22.6%
Metallurgy	73	19.2%
Oil, chemical and pharmaceutical	73	19.2%
Rubber and plastic products	19	5.0%
Machinery	14	3.7%
Food, beverage and tobacco	11	2.9%
Others	11	2.9%

7.3 Data analysis and Result

7.3.1 Common Method Bias

Survey-based research is often susceptible to common method bias (CMB), which can arise from various sources, such as respondent perspective, social desirability, or consistent response patterns. CMB occurs when the measurement process introduces systematic variance that is unrelated to the constructs being measured, potentially compromising the validity of the findings. To mitigate this risk, this study implemented several procedural and statistical measures during the research design and data analysis phases. First, the study relied on carefully selected key respondents from senior management teams with extensive industry experience, which ensured their ability to provide reliable and informed responses to the survey questions. This methodological approach enhanced the credibility of the data by leveraging the expertise of respondents who were well-versed in the subject matter. Additionally, Harman's single-factor test (Podsakoff et al., 2003) was conducted to assess the presence of CMB. The results indicated that no single factor accounted for the majority of the variance in the data, suggesting that common method bias is not a significant concern in this study. This finding aligns with established methodological practices (Flynn et al., 2018) and reinforces the robustness of the research design. Based on the methodological discussion employed that common bias is unlikely to have influenced the results, supporting the validity and reliability of the findings.

7.3.2 Nonresponse bias

To assess whether there is any non-response bias, the wave method (Armstrong & Overton, 1977) was used with a single follow-up email to non-responders. The data collected from the early wave (initial respondents) and the later wave (respondents who replied after the follow-up) were compared using an independent samples t-test. The results revealed no statistically significant differences between the two groups ($p > 0.05$), indicating that the responses from early and late participants were consistent. This finding suggests that non-response bias is unlikely to be a concern in this study.

7.3.3 Data Analysis

The researchers conducted hypothesis testing to examine the proposed relationships among the constructs. A variance-based Structural Equation Model (SEM) was developed to analyse the data. Structural Equation Modelling, a well-suited analytical technique, was used to simultaneously evaluate multiple relationships within an integrated framework. This statistical technique is widely recognized for its capacity to model specified independent variables and account for all potential forms of measurement error, making it suitable for testing comprehensive theoretical frameworks. This approach constructs measurement models and path analysis to estimate model parameters. We used statistical Jamovi 2.6.23 and AMOS 23.0 covariance-based structural equation modelling (CB-SEM) to evaluate our measurement model and research hypotheses. This makes it particularly suitable for testing comprehensive theoretical frameworks, as it allows for the simultaneous examination of multiple relationships within a single model. The data analysis is structured into two key components to ensure comprehensive and robust examination of the research objectives. Firstly, Confirmatory Factor Analysis (CFA) was conducted to validate the factor structure and further path model assess the model's fit, ensuring alignment with theoretical expectations.

7.3.4 Validity and Reliability measurement of the model:

Prior to testing the hypotheses using the structural model, the validity and reliability of the measures were confirmed, and the model's data fit was assessed. To assess the validity of our theoretical model, we conducted Confirmatory Factor Analysis (CFA) (Result can found in APPENDIX B1-2). This statistical technique evaluates the extent to which the hypothesized factor structure aligns with the observed data (Byrne, 2013). This approach enables us to confirm the dimensionality of our constructs and assess the convergent and discriminant validity of our measurement scales. This then allows for further hypothesis testing to be conducted. These assessments ensure that the constructs in the model are both theoretically sound and empirically robust. Convergent validity refers to the degree to which multiple indicators of the same construct converge, indicating that they measure the same underlying concept consistently. This is typically assessed using several statistical measures: factor loadings, Cronbach's alpha (α), composite reliability (CR), and average variance extracted (AVE) (as shown in Table 7. 4). Prior studies have outlined six key indicators for assessing model fit (Hooper et al., 2008). The chi-square/degree of freedom (CMIN/DF) should be below 5, ideally under 3; both Goodness-of-Fit Index (GFI) and Relative fit indices (RFI) should be at least 0.8, preferably above 0.9; Normed Fit Index (NFI) and Tucker–Lewis Index (TLI) are expected to be no less than 0.8, with an optimal level above 0.9; Comparative fit index (CFI) should be at least 0.9; and Root Mean Square Error of Approximation (RMSEA) should remain below 0.08, ideally under 0.05 (Browne and Cudek, 1993; Hu and Bentler, 1999; Hair et al., 2010; Yang et al., 2011). Our results indicate an adequate model fit, with CMIN/DF = 3.184, GFI = 0.947, RFI = 0.940, NFI = 0.959, TLI = 0.958, CFI = 0.971, and RMSEA = 0.076. Discriminant validity assesses the extent to which constructs are distinct from one another, ensuring that indicators intended to measure different constructs do not overlap. It is assessed through cross-loadings and the Heterotrait-Monotrait (HTMT) ratio, which remains below 0.85 to confirm that the constructs are adequately differentiated (Bag et al., 2020b; Ghadge et al., 2022).

Table 7. 4 Loadings, Cronbach"s alphas (Alpha), construct reliability (CR) and average variance extracted of the constructs

Latent variable	ID	Factor Loading	Cronbach alpha	Composite Reliability	Average Variance Extracted	Significance level
Supply chain management & collaboration			0.824	0.826	0.615	
	SC1	0.789				P < 0.001
	SC2	0.674				P < 0.001
	SC3	0.876				P < 0.001
Servitized Business Model			0.834	0.837	0.631	
	SBM1	0.824				P < 0.001
	SBM2	0.735				P < 0.001
	SBM3	0.821				P < 0.001
Circular Economy Practices			0.873	0.890	0.691	
	CE1	0.731				P < 0.001
	CE2	0.758				P < 0.001
	CE3	0.849				P < 0.001
	CE4	0.859				P < 0.001
	CE5	0.727				P < 0.001

7.3.5 Structural model and Hypothesis test:

We used AMOS to test the hypothesized relationships shown in Figure 7.2. Covariance-Based Structural Equation Modelling (CB-SEM) was selected as it allows simultaneous testing of direct and indirect effect of SBM, SCMC and CE practice. The estimates of the hypothesis testing are Discrepancy divided by degree of freedom (CMIN/Df) is 2.374, and the value is <5 (threshold value) (Hu & Bentler, 1999). The value for Goodness of Fit Index (GFI) (0.960), which is >0.8; Root Mean Square Error of Approximation (RMSEA) (0.060), which is <0.08 (Kline, 2016); Comparative Fit Index (CFI) (0.9), which is >0.8 (Mueller & Hancock, 2018); Incremental fit index (IFI) (0.9), which is >0.8; TLI (0.97), which is >0.8 (Kline, 2016); Parsimony Comparative Fix Index (PCFI) (0.679), which is >0.5 (Hair et al., 2010) and Parsimony Normed Fixed Index (PNFI) (0.671), which is also

>0.5 (Byrne, 2001). Therefore, it can be concluded that the absolute fit index and incremental fit index indicate the model fit.

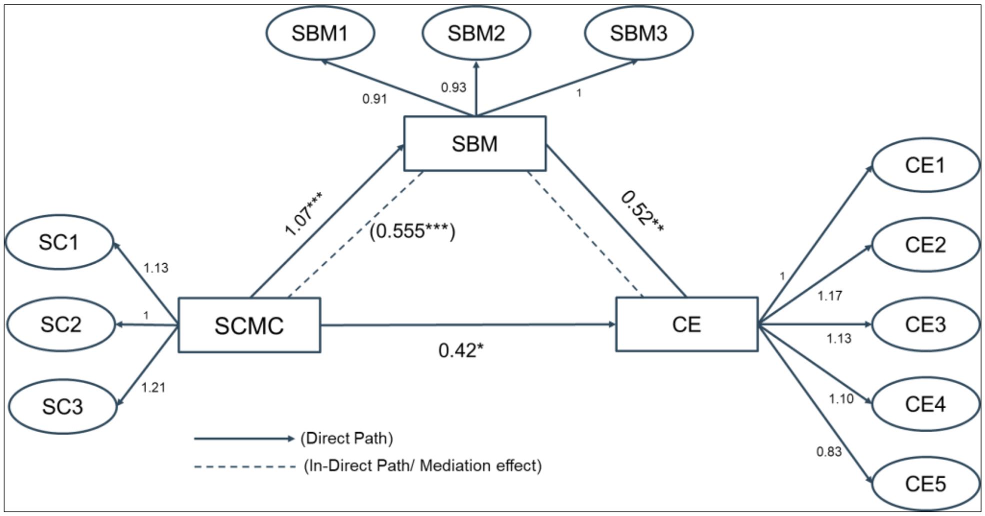


Figure 7. 2 Covariance based structural equation model (Path analysis) of the hypothesised relationship

The model includes three direct hypotheses and one indirect mediation relationship, as shown in Figure 7. 2. Table 7. 5 represents the result with their value β and *p* value of the relationship. The results highlighted that all the hypotheses are confirmed. The results show that there is a positive relationship between SBM and CE hence the H1 is confirmed. Further the second and third hypotheses will be supported by value of 0.521 and 1.065. Further, H4 confirmed a significant indirect effect mediated by SBM (β = 0.555). The significance of the mediating effect was tested using the Sobel test and confirmed and reported in table 5 (Sobel, 1982).

Table 7. 5 Results of hypothesis testing

Hypotheses	Relationship	Std. β	Std. Error	P values	Notes	Linking to existing research
H1	SCMC → CE	0.423	0.195	p <0.05	Accepted	
H2	SBM → CE	0.521	0.216	p <0.007	Accepted	
H3	SCMC → SBM	1.065	0.079	p < 0.001	Accepted	New findings, No similar study
Indirect Relationship						
H4	SCMC →SBM→CE	0.555		p < 0.008	Partial Mediation	New findings, No similar study
Sobel Test	2.620 (test statistic)		0.211	p < 0.008		

Aroian Test	2.613 (test statistic)	0.212	$p < 0.008$
Goodman test	2.627 (test statistic)	0.211	$p < 0.008$

7.4 Discussion

The paper presents an original perspective on the relationship between SCMC and the CE & End of life practice (Hassan et al., 2023; Rijal et al., 2024; Zhu et al., 2011), with a specific focus on the mediating role of SBMs. By analyzing the Indian manufacturing sector, the study explores the direct and indirect effects of the relationships outlined in the conceptual model. The findings advance theoretical discussion on the CE by highlighting SCMC and SBM as critical levers. The model reveals that while SCMC exhibits a strong relationship with the CE, it alone is insufficient to fully explain the underlying mechanisms. However, when paired with a complementary variable like SBM, its explanatory capability increases. Importantly, this impact is not entirely direct but partially mediated by SBM (the direct path exhibits a lower beta value than the mediating path), underscoring the nuanced interplay between these variables.

The regression analysis confirms Hypothesis 1 (H1), which supported that SCMC positively influences CE practices. These results align with prior studies by Zhu et al. (2011), Le et al. (2024), and Di Maria et al. (2022), as well as recent work by Calzolari et al. (2024), Chowdhury et al. (2025), Hassan et al. (2023), and Rijal et al. (2024), all of which emphasize SCMC's critical role in enabling CE adoption. The findings are grounded in Resource-Based View (RBV) and Dynamic Capabilities Theory. In manufacturing industries, SCMC improves relational capabilities by fostering cooperation with suppliers and consumers. To advance the transition to the CE, collaborative, cross-industry, multi-level efforts centered on joint planning and coordination of forward and reverse material flows are critical (Nag et al., 2021). Supporting prior studies, our findings highlight that collaboration with suppliers, customers, and internal departments enhances integration capabilities for resource efficiency and waste minimization across manufacturing. By collaborating closely with suppliers and customers, firms can source sustainable materials and incorporate waste from other sectors into their processes. The authors contend that SCMC is a key component of industrial symbiosis and supports CE (Herczeg et al., 2018). Critically, CE-driven supply chain operations must be understood as parts of an interrelated system involving manufacturing, suppliers, consumers, and waste management organizations, where long-term collaboration and trust are essential. According to Li et al. (2020), such integration improves CE performance in material and resource flows. They emphasize that effective integration requires extensive collaboration in channel facilities, resource sharing, and logistics operations within dynamic, multi-stakeholder CE scenarios. Furthermore, strong SCMC enhances the adaptive capability of manufacturing companies by prioritizing green product design. To create competitive differentiation, green suppliers are increasingly viewed as strategic resources. By prioritizing green suppliers, manufacturers enhance their ability to respond to market changes and implement CE strategies more effectively. Alignment of supply chain strategies driven by SCMC improves decision-making regarding environmental investments and practices (Calzolari et al., 2024; Zhu et al., 2011). Green suppliers selected for their expertise in recycled materials or eco-certifications represent opportunities for CE advancement. Green supplier selection frameworks (e.g., Kusi-Sarpong et al., 2023) enable rigorous evaluation, while Industry 4.0 technologies support collaboration through shared technologies, machinery, and R&D. The literature widely acknowledges that tracking systems (e.g., IoT, blockchain) are valuable, rare, and inimitable resources for SCMC (Hassan et al., 2023; Schöggl et al., 2024). These systems provide transparency to stakeholders, track market demands and user behaviour and foster dynamic capabilities for closed-loop systems. CE requires close collaboration and information exchange across supply chain tiers (Bressanelli et al., 2019). Collaborative networks (e.g., cross-industry symbiosis platforms) act as non-substitutable resources, supported by digital tools that optimize negotiations and asset tracking. For example, Hassan et al., (2023)found that real-time information exchange enables supply chain integration, while digitalized waste management procedures enhance visibility, trust, and transparency in closed-loop systems. Long-term collaboration within such networks is necessary for high supply chain performance (Li et al., 2020). Finally, digital product passports (DPPs) are imperative for CE, as they enable collaboration between partners (Chauhan et al., 2021).

Our finding confirmed the hypothesis 2 that SBM are a way to foster the transition to a CE. This result aligns with empirical support from Johl et al. (2024) and Kühl et al. (2022), who emphasize SBMs' role in enabling resource efficiency and closed-loop systems. However, while Chowdhury et al. (2025) found that CE practices positively influence SBMs, our study reveals a reciprocal dynamic: SBMs themselves drive CE. This bidirectional relationship advances theoretical understanding by highlighting the mutual reinforcement between SBMs and CE, suggesting that their interplay is not unidirectional but synergistic. This outcome can explain using RBV. For example, natural resource-based view (NRBV), an extension of traditional RBV, demonstrates that green servitization directly promotes CE implementation and sustainable performance (Kühl et al., 2022). For long-term competitiveness, SBMs enhance economic and environmental performance by closing resource loops, slowing resource depletion, and narrowing material use. By prioritizing service delivery over selling tangible products (Aarikka-Stenroos et al., 2022), firms optimize resource efficiency and minimize waste. Bressanelli et al. (2019) emphasize that servitization models (e.g., leasing, sharing, and pay-per-use) enhance resource efficiency and product lifetime extension by fostering organizational capabilities aligned with the circular economy, while also enabling firms to retain product ownership throughout the lifecycle, thereby extending utility through maintenance, repair, and reuse services, which directly support circularity by slowing resource loops. SBMs enable manufacturers to shift from product ownership to service provision, incentivizing designs for durability, repairability, and recyclability, which encourages the production of longer-lasting goods (Pieroni et al., 2021). This transition reduces reliance on new production, conserves resources, and minimizes waste generation (Stahel, 2016). SBM supports reverse supply chain processes, allowing for product repair, refurbishment, and recycling to facilitate a closed-loop material system. The synergy between SBMs and CE practices enhances operational performance by leveraging unique, scarce resources. From a Resource-Based View (RBV), these capabilities are invaluable competencies that provide competitive advantages to manufacturing organization. SBMs require information exchange between manufacturers and customers regarding the timing, location, quantity, and quality of product returns, enabling closed-loop practices. Digital technologies integrated with SBM enhances circular capabilities through tracking, predictive maintenance, and systems that maintain material utility (Chowdhury et al., 2025). By analysing usage data, companies optimize service schedules, reduce downtime, and enhance product longevity, contributing to sustainable resource use. This facilitates information sharing and integration between stakeholders, manufacturers can use this information and knowledge to create economic and environmental benefits, by maximising value recovery at end-of-life, for example through recycling. SBMs act as strategic foundations for CE integration. Manufacturers implement incremental innovations (e.g., designing for maintenance) and retain ownership in use-oriented PSSs, ensuring product return responsibility (Tukker, 2004) further Efficient material use and extended product lifecycles reduce costs associated with new material purchases (Manninen et al., 2018) and waste management (Kühl et al., 2022)

The hypotheses H3 is support by the result and SCMC was found positive and strong associated with SBM (the beta value is highest in the model showing a strongest association in the model). SCMC serves as a critical lever for successful SBM initiatives by providing manufacturers with access to complementary resources, knowledge, and capabilities necessary for service-oriented business transformations. The synergy between supply chain colloboration and SBM supports long-term relationships built on trust and collaboration among stakeholders and companies (Abideen et al., 2021). The relationship between Supply Chain Collaboration (SCC) and servitization is particularly significant, as manufacturers often lack the resources and capabilities to independently develop and deliver comprehensive service offerings. Pieroni et al., (2021) identified the critical role of supply network infrastructure and capabilities in enabling SBM operations. By involving suppliers in service delivery, companies can ensure sustainability practices throughout the supply chain through shared accountability. This collaborative approach fosters synergies among partners, facilitates joint planning, and enables real-time information exchange to anticipate, respond to, and recover from supply chain disruptions while supporting service innovation. Furthermore, it enhances risk management in service delivery frameworks reliant on sustained customer engagement and contractual obligations (Calzolari et al., 2023; Kühl et al., 2020). Strategic supplier partnerships drive innovation, enabling novel value-creation models such as subscription-based or "as-a-service" offerings, which generate continuous revenue streams and reinforce competitive positioning. Second, collaborative efforts including decision synchronization, resource-sharing, and incentive alignment allow manufacturers to mobilize complementary capabilities across organizational boundaries. Supply chain collaboration addresses resource limitations by integrating external assets into a network of non-replicable capabilities. Empirical evidence suggests that firms implementing servitization strategies through collaboration achieve improved performance outcomes, particularly when structured through formal mechanisms like performance-based contracts and shared service design processes (Johnstone, 2024; Pieroni et al., 2021; M. Yang et al., 2018). Further these capabilities enable firms to sense shifts in service demand and allowing manufacturers to overcome individual resource limitations and develop unique service capabilities that create sustainable competitive advantage.

SBMs enhance the relationship between SCMC and the CE. The hypothesis indicates a strong mediating effect of SBMs. This finding aligns with case studies by Geissdoerfer et al. (2018), which argue that SBMs advance CE and circular supply chain practices. SCMC provides the infrastructure (e.g., supplier networks, logistics), while SBMs provide the operational mechanisms (e.g., product-service systems, performance contracts) to implement CE practices. One of the key aspect of SBMs for the CE is proactive stakeholder management, requiring collaborative innovation, information-sharing, and communication across supply chains to enhance visibility, flexibility, and customer responsiveness, while digital technologies improve transparency, tracking, and decision-making coordination through seamless information sharing (Aarikka-Stenroos et al., 2022). SBMs drive innovation among supply chain partners and foster collaboration to co-develop material recovery services, maximizing value recovery (e.g., recycling) and generating economic-environmental benefits (Tukker, 2015; M. Yang & Evans, 2019). Huynh, (2022) discussed how blockchain-integrated SBMs increase reuse, repair, and recycling capabilities in CE by improving traceability and automated sorting in fashion value chains. Furthermore, SBMs foster proactive stakeholder management through long-term partnerships and strategies to close, slow, and narrow resource loops. Pieroni et al. (2021) developed a process model for servitization business models (e.g., leasing, sharing, pay-per-use), which emphasizes the establishment of supply chain collaboration in both forward and reverse logistics to simplify end-of-life product recovery and waste reduction. The mediating effect arises because SBMs fundamentally restructure value creation and capture. By emphasizing resource recovery and material valorization, SBMs increase collaboration with stakeholders to source secondary materials and integrate them into production (Kühl et al., 2023; Nag et al., 2021). Additionally, SBMs extend producer responsibility, requiring enhanced reverse logistics to manage product returns, refurbishment, and recycling. For example, collaborative R&D and business innovation under SBMs—such as Philips' "Light-as-a-Service"—accelerate CE innovation (Rusch et al., 2023).

7.4.1 Theoretical Implications

The study makes a significant theoretical contribution, as the majority of existing research is predominantly exploratory. To the best of our knowledge, no prior study has empirically examined the role of SCMC and SBMs in implementing CE practices, particularly within manufacturing firms. The findings offer actionable insights for researchers and professionals advancing CE adoption in manufacturing organizations. This study addresses a research gap highlighted by Bressanelli et al. (2021), who underscored the need to investigate CE levers such as SCMC and SBMs holistically, as they are seldom investigated together. Nag et al. (2021) also emphasized the pressing requirement for expanding the existing literature regarding the adoption of CE research in developing countries, which is mainly conceptual in nature, through evidence from empirical studies. This study supports the previous finding by demonstrating that collaborative supply chain networks, rather than isolated firm-level resources, are important in achieving CE goals. This challenges firm-centric focus and positions SCMC as a structural lever that transforms relational capabilities (e.g., supplier-customer integration) into strategic CE outcomes like industrial symbiosis and resource efficiency. Further, the Natural Resource-Based View (NRBV) extension highlights how SBMs operationalize CE principles by codifying green servitization (e.g., recycling expertise, closed-loop systems) into strategic, inimitable assets. This bridges a critical gap in literature, which has put importance of collaborative resource orchestration in sustainability transitions. The findings extend dynamic capabilities theory by explaining how SBMs act as high-level capabilities that improve cross-organizational flexibility in implementing the circular economy Whereas prior research has predominantly examined dynamic capabilities within organizational boundaries (Teece, 2000), our results demonstrate that collaborative decision making, formalized risk-sharing mechanisms, and incentive alignment across supply chains serve as the three distinct processes enabling SBMs to strengthen inter-organizational dynamic capabilities. For example, real-time data sharing (via IoT) and stakeholder integration enable firms to reconfigure in their operation and sustain CE practices in dynamic markets. This research advances theory by examining the operational aspects of CE transitions, an area that has received less attention. By showing how SBMs enable the development of adaptive capabilities, our findings provide a stronger theoretical basis for understanding how organizations can build operational flexibility into CE strategies while managing complex multi-stakeholder supply chain environments. By challenging unidirectional models (e.g., CE → SBMs) discussed in Chowdhury et al., (2025), this study introduces a mutually complementary SBMs-CE relationship that advances sustainability theory. SBMs not only operationalize CE practices but are also enhanced by CE principles such as extended producer responsibility and material valorization. CE transitions are iterative processes where Supply chain collaborative networks and business model innovation develop together. The findings thus call for integrated theoretical models that account for the interplay between structural levers (SCMC), operational mechanisms (SBMs), and CE outcomes.

7.4.2 Practical and Managerial implications

Examining relationships from a managerial perspective offers five major implications. First, this research highlights that integrating SCMC and SBMs could enhance performance in establishing a CE. Furthermore, while established theories have been applied to CE adoption across fields, this study provides a theoretically grounded investigation of CE implementation to improve sustainability performance. To fully realize CE adoption, companies must simultaneously strengthen organizational components such as cross-functional collaboration and stakeholder alignment. Improved integration of supply chain stakeholders particularly with suppliers and customers, can support implementation of CE where decision-making is not straightforward. Second, practitioners must prioritize SBMs as foundational mechanisms for advancing CE practices. Overcoming challenges in CE implementation requires greater adoption of SBMs to enable feasible adoption, as isolated firm-level efforts often prove insufficient. Third, firms must prioritize long-term, formal partnerships with suppliers, waste management entities, and cross-industry stakeholders to co-develop circular solutions. Collaborative frameworks, such as Kusi-Sarpong et al. (2023) supplier evaluation criteria, ensure shared accountability for sustainability metrics, fostering trust and lifecycle-wide innovation. Fourth, invest in Industry 4.0 technologies and its application (e.g., IoT, blockchain, Digital Product Passports) to optimize supply chain visibility and decision-making. Blockchain, support in dynamic configuration by integrating the supply chain members to integrate their activities (Hassan et al., 2023), enhances material traceability, while IoT-enabled tracking systems improve reverse logistics transparency (Manavalan & Jayakrishna, 2019). These tools support SBMs through predictive maintenance, real-time data sharing, and closed-loop coordination, critical for adapting to disruptions and demand fluctuations. Design revenue-sharing models and performance-based contracts targeted at high-risk CE initiatives like material recovery to motivate cross-supply chain collaboration. Simultaneously, strong policies (e.g., tax breaks, cross-industry symbiosis platforms) should reduce barriers to the implementation of SCMC and SBMs and incentivize circular innovation. Further, manufacturers should prioritize long-term partnerships to co-develop SBMs (e.g., leasing platforms, recycling networks) with their supply network. Proactive stakeholder management, as seen in Philips' "Lighting-as-a-Service" model, ensures alignment across forward logistics (FL) and reverse logistics (RL) operations.

7.5 Conclusion

This study advances the theoretical and empirical understanding of CE implementation by examining the synergistic interplay between SCMC and SBMs. A structured questionnaire was designed for survey-based research in Indian MSMEs, and using CB-SEM, the hypotheses of the theoretical framework were tested. The analysis confirmed that all four hypotheses (three direct and one indirect) were supported. SBMs act as both direct drivers and mediators, operationalizing CE & End of life practices. The findings reveal that while SCMC effectively supports CE by enhancing relational capabilities, resource efficiency, and industrial symbiosis through supplier-customer integration and digital tools like IoT and blockchain; its full potential is unlocked only when paired with SBMs. This bidirectional relationship challenges unidirectional frameworks and underscores the necessity of collaborative networks to restructure value creation. The strongest association observed between SCMC and SBMs (highest beta value) highlights how collaborative networks bridge resource gaps, enabling risk-sharing, innovation (e.g., "as-a-service" models), and resilience in dynamic markets. Theoretically, this research extends the Resource-Based View (RBV) by redefining "resource advantage" to prioritize cross-supply chain collaboration over firm-level assets, while dynamic capabilities theory is enriched through the lens of cross-organizational agility.

7.5.1 Limitation

There are certain limitations to this investigation. First, our empirical framework is based on data exclusively collected from a developing economy such as India, potentially limiting the generalizability of findings to other economic environments. Future research should consider cross-country comparative analyses to examine how these relationships are evident across different institutional, cultural, and economic settings. Second, our sample contained a relatively small proportion of large manufacturing firm. Future studies should use a more balanced representative sampling to adequately represent different company sizes. Third, we did not incorporate company size as a potential moderating variable in our theoretical model, which constrains our understanding of how organizational size might influence the strength or direction of the hypothesized relationships between supply chain management and collaboration, servitized business models, and CE performance. This represents a significant opportunity for future research to examine whether the mediating role of servitization varies systematically with firm size. Finally, our conceptual framework focused on SBM and SCMC levers of CE adoption, but several other potential levers remain unexplored. Future investigations could incorporate additional enablers and levers such as digital technologies, users' active role, organizational culture, sustainable production process, and circular product design to develop more comprehensive conceptual frameworks of CE implementation. Such research could also examine potential interaction effects between multiple enablers to better understand their combined influence on CE outcomes in various industrial contexts.

Chapter 8. Conclusion

This thesis provides a comprehensive discussion on the synergistic relationship between Industry 4.0 (I4.0) technologies or Digital technologies (DTs), CE practices, and environmental sustainability, with a particular focus on the manufacturing sector. By addressing three interconnected research questions, the study advances theoretical, methodological, and practical understanding in this interdisciplinary domain. Through its interdisciplinary approach combining bibliometric analysis, theoretical modelling (content-based and contingency-based analysis), survey-based assessments, and empirical validation using Structural Equation Modelling (SEM) techniques, this research bridges conceptual gaps and provides actionable implications for CE implementation. By emphasizing the critical roles of supply chain collaboration and Servitized Business Models (SBMs) as enablers of circularity, this research provides actionable insights for policymakers and industry leaders aiming to align economic growth with environmental sustainability goals.

Through a bibliometric analysis (Chapter 4) of the evolving academic landscape, the research identified a fragmented yet growing body of literature at the intersection of CE, sustainability, and I4.0. Eight major research clusters were identified, ranging from high-level conceptual approaches to technology-specific studies focusing on Big Data analytics, additive manufacturing, and blockchain. The findings reveal a dichotomy between broad explorations of sustainability in I4.0 contexts and more focused investigations into specific technologies. This chapter also lays a structured research agenda with ten promising directions, including advancements in data integration, material innovation through additive manufacturing, policy alignment, and managerial frameworks. These insights provide a strong foundation for future interdisciplinary research by identifying underexplored areas critical to advancing CE implementation.

Building on these insights, the development of a theoretical framework elucidated how Digital technologies (DTs) interact with Operations Management (OM) processes to activate environmental drivers (chapter 5). The framework's methodological innovation, employing contingency analysis, provided a structured understanding of causal relationships between DTs, OM processes, and sustainability outcomes, offering a replicable model for future research. The findings reveal that the environmental benefits of digital technologies are contingent on their application within specific OM processes and the activation of five environmental drivers, such as resource efficiency and dematerialization. For instance, IoT-enabled tracking systems enhance supply chain visibility, material tracking, and material sorting, while additive manufacturing reduces material waste in production processes. The study also identifies antecedent-process-outcome patterns that explain how digital technologies trigger environmental benefits through OM processes.

The empirical assessment of Indian manufacturing firms using the C-Readiness tool further contextualized these findings by evaluating the circularity readiness of Indian manufacturing companies across six dimensions: product structure, production processes, business models, supply chain integration, regeneration practices, and green culture. With an average C-Score of 47 (out of 100), the sector's transition to CE remains nascent, constrained by limited adoption of end-of-life management practices. Larger firms and regulated industries, such as automotive and chemicals, demonstrated higher readiness, underscoring the role of resource availability and regulatory pressure. In contrast, SMEs and less-regulated sectors lagged, highlighting systemic barriers such as limited access to technology and financial constraints. The findings also reveal that while companies demonstrate moderate readiness in supply chain integration (average score: 52/100) and green culture (57/100), significant gaps exist in business models (38/100) and end-of-life management (40/100). These findings emphasize the need for targeted interventions at both the firm and sectoral levels. The thesis also examines the synergistic relationship between supply chain management & Collaboration (SCMC) and Servitized Business Models (SBMs), finding that SCMC enhances resource efficiency and relational capabilities but realizes its full potential when integrated with SBMs. The mediating role of SBMs is explored in Chapter 7 through structural equation modelling (SEM). The analysis confirms that SBMs act as both direct drivers and mediators in operationalizing CE practices. While SCMC enhances relational capabilities, resource efficiency, and industrial symbiosis through supplier-customer integration and digital tools like IoT and blockchain, their full potential is unlocked only when paired with SBMs. This research highlights the importance of collaborative networks in implementing CE practices and underscores the necessity for manufacturing firms to emphasize cross-supply chain collaboration for effective value creation in dynamic markets. Overall, the thesis provides crucial insights into CE adoption in India, contributing a theoretical framework that connects digital technologies, operations management, and sustainability practices, thus setting the groundwork for future research and practical applications in the manufacturing sector.

From a theoretical perspective, this thesis makes several contributions. Firstly, the bibliometric literature review identifies interdisciplinary convergence by offering a systematic understanding of three dimensions: Industry 4.0, sustainability, and circular economy. By synthesizing the current state of research and proposing future research directions, this study provides a structured framework to guide further academic and practical developments. Secondly, the thesis offered a comprehensive view of DTs' contributions to sustainability and circularity using a systemic approach. Further, it discussed the mechanism through which DTs enhance environmental sustainability when integrated into specific OM processes, enhancing academic understanding. Lastly, it extends the Resource-Based View (RBV) by redefining "resource advantage" to prioritize cross-supply chain collaboration over firm-specific assets: it enriches dynamic capabilities theory by characterized by synchronized decision-making processes, risk-sharing mechanisms, and aligned incentives across stakeholders - to explain how firms adapt to complex sustainability challenges. It also integrates these frameworks with CE principles to provide a holistic understanding of how digital technologies enable sustainable transitions in industrial systems.

The practical implications of this research are equally significant. Firstly, managers and practitioners can benefit from understanding how different technologies can be applied, and their impacts across various domains. This helps in making strategic decisions, finding opportunities to use I4.0 solutions in their operations management, and preparing for challenges related to the adoption of circularity and sustainability. Secondly, the empirical findings highlight the promising potential for Indian manufacturing companies to transition to fully circular models. However, this transition is complex and requires long-term efforts across multiple dimensions of the industries. This research underscores the disparity in readiness between larger firms and SMEs, indicating that strategic changes need to be tailored to bridge this gap. Companies can prioritize actions based on readiness assessments by using a structured approach to evaluate their current status and identify strategic focus areas. Additionally, the study highlights the interconnectedness of CE levers, particularly the relationship between supply chain readiness and business model innovation. Understanding these connections can provide valuable insights into how improvements in one area can facilitate progress in another, thereby accelerating overall CE implementation. Manufacturing firms are encouraged to prioritize investments in digital technologies such as IoT for real-time tracking or blockchain for secure data sharing to enhance transparency across supply chains. Policymakers should incentivize SBMs through tax benefits or subsidies for leasing-based services to accelerate CE adoption. Additionally, sector-specific interventions are needed to address gaps in circular readiness among industries lagging behind in CE implementation. SMEs require targeted support programs focusing on resource efficiency training or access to green financing to overcome barriers related to limited resources and regulatory pressures.

Methodologically, this thesis employs innovative approaches that advance research practices in this domain. The bibliometric analysis provides a replicable framework for mapping interdisciplinary knowledge streams at the intersection of I4.0 technologies and CE. The C-Readiness tool offers a novel assessment framework for evaluating circularity readiness globally, while contingency analysis enriches operations management research by uncovering nuanced relationships between digital technologies, OM processes, and environmental outcomes.

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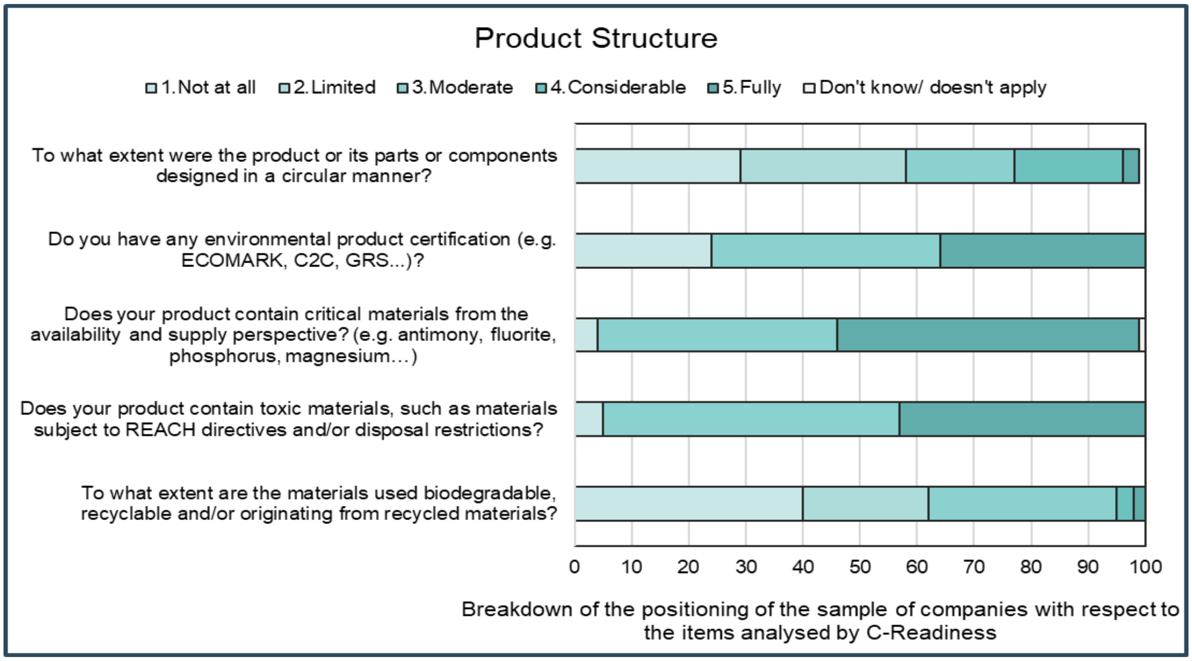
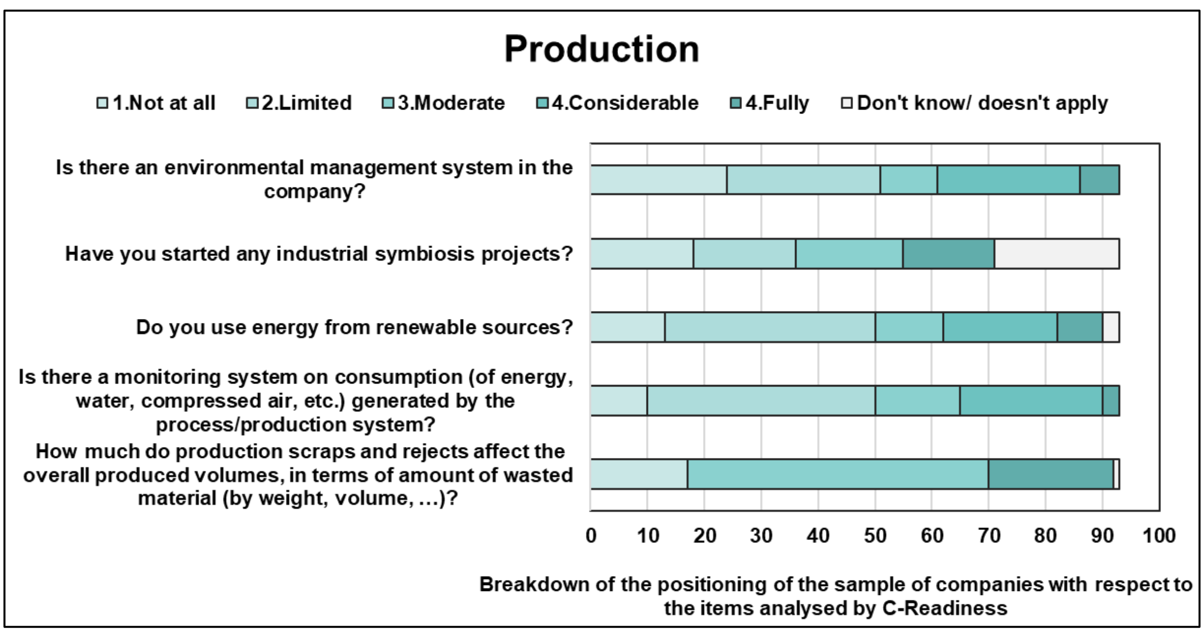
APPENDIX A - Summary of C-Readiness Tool application

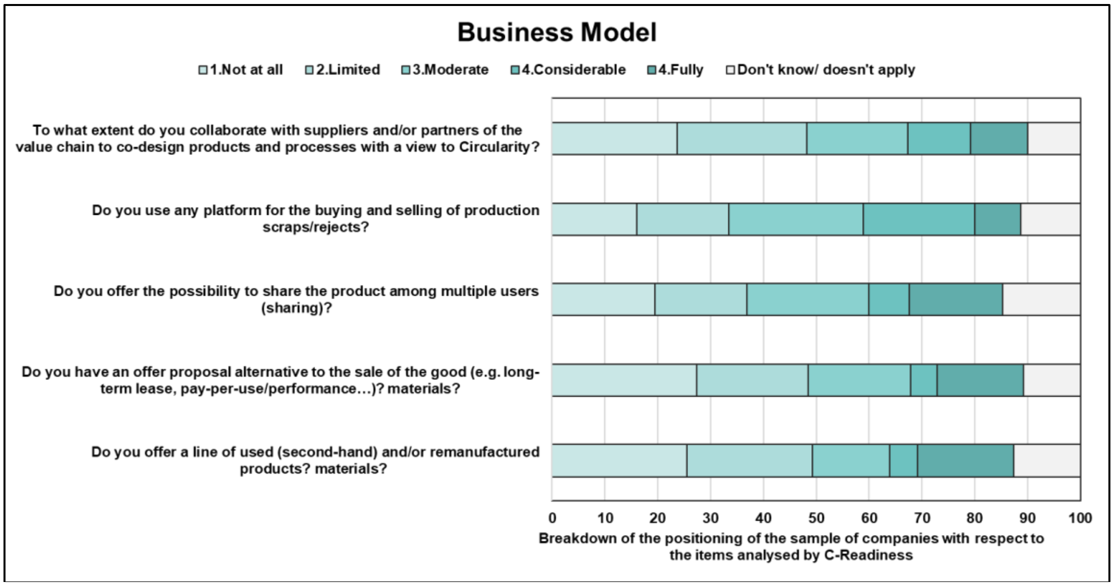
A.1 Product structure items analysed by C-Readiness tool for Textile sector



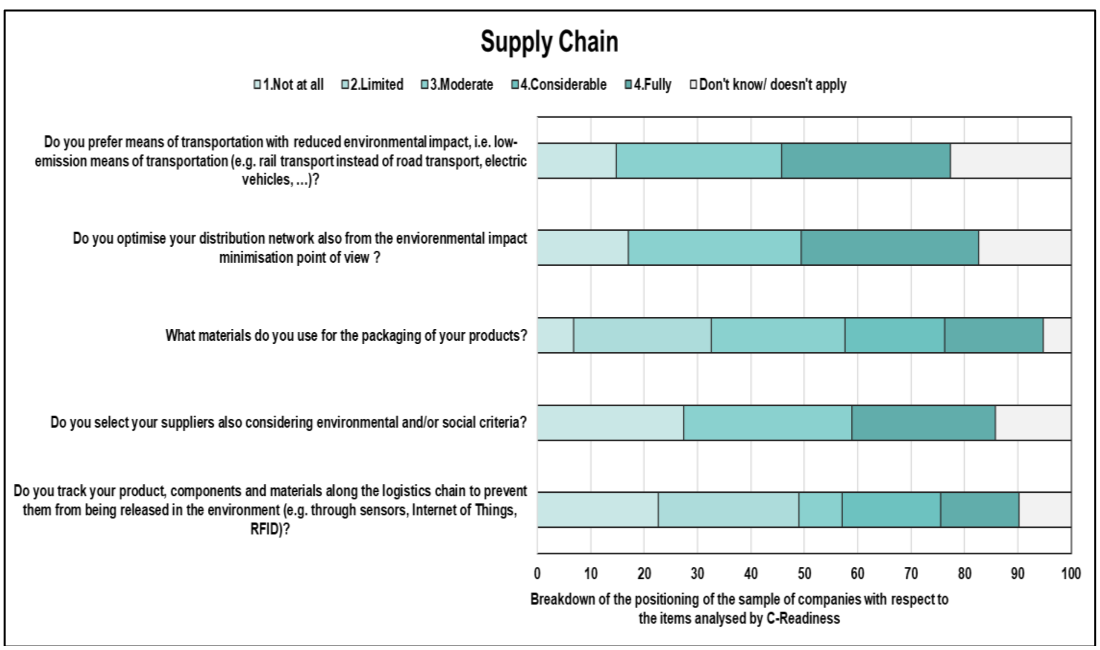
A.2 Production process items analysed by C-Readiness tool for Textile sector



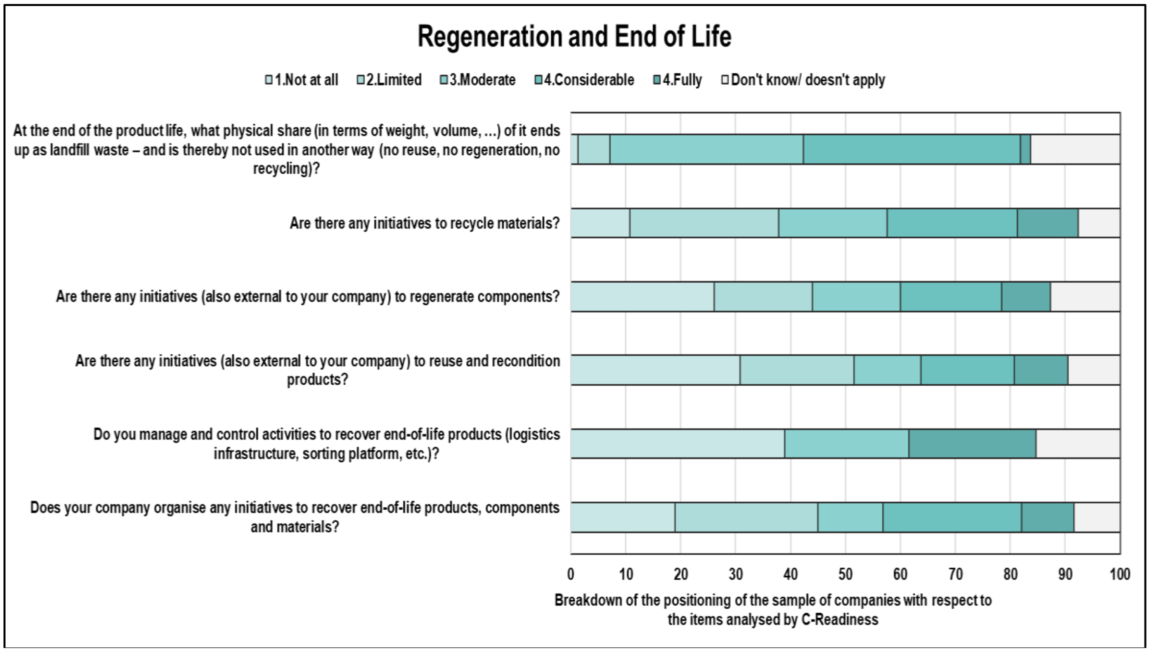
A.3 Business Model items analysed by C-Readiness tool for Textile sector



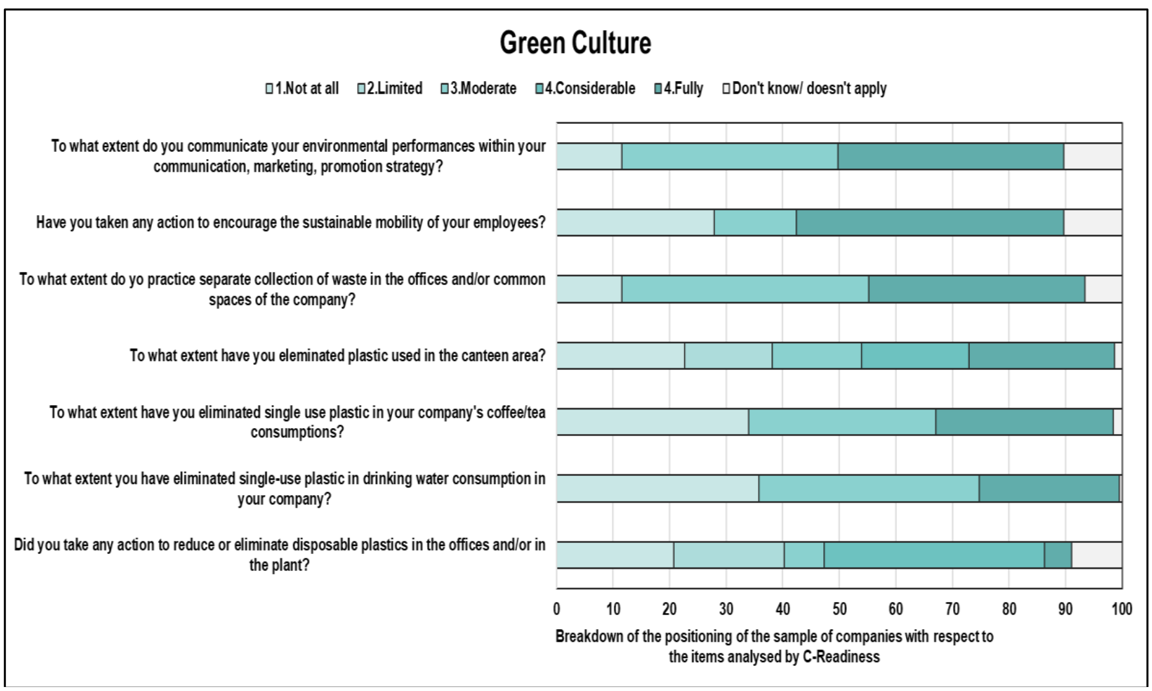
A.4 Supply chain items analysed by C-Readiness tool for Textile sector



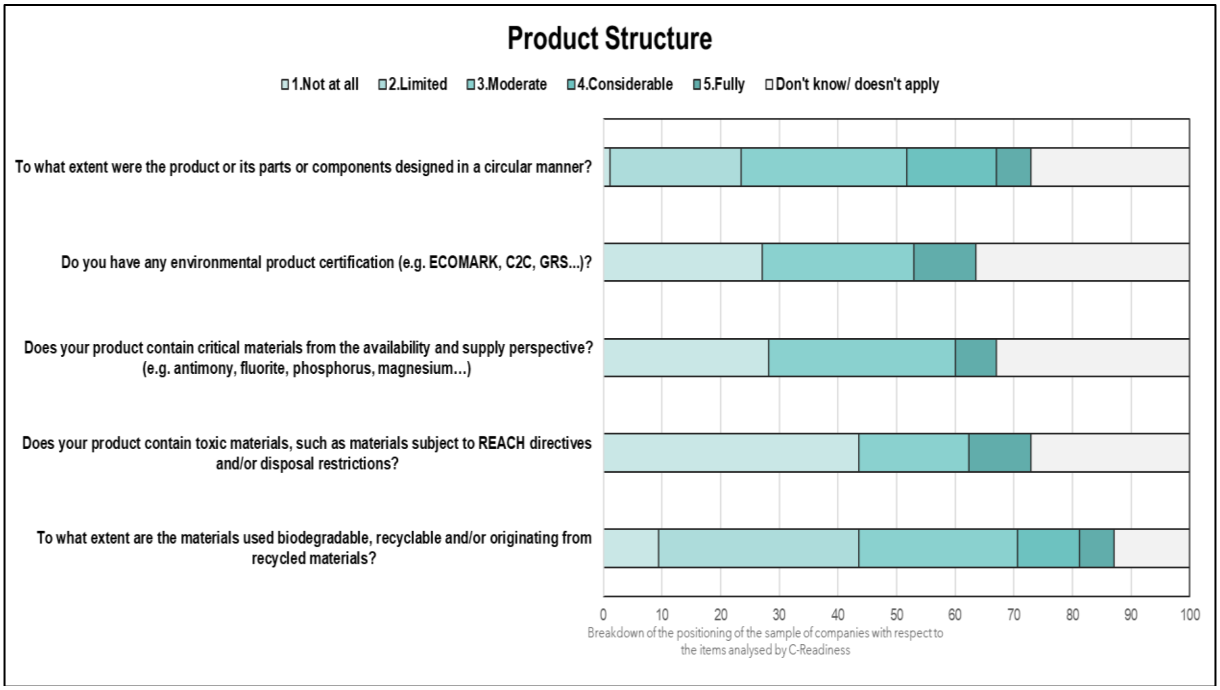
A.5 Regeneration and End of life items analysed by C-Readiness tool for Textile sector



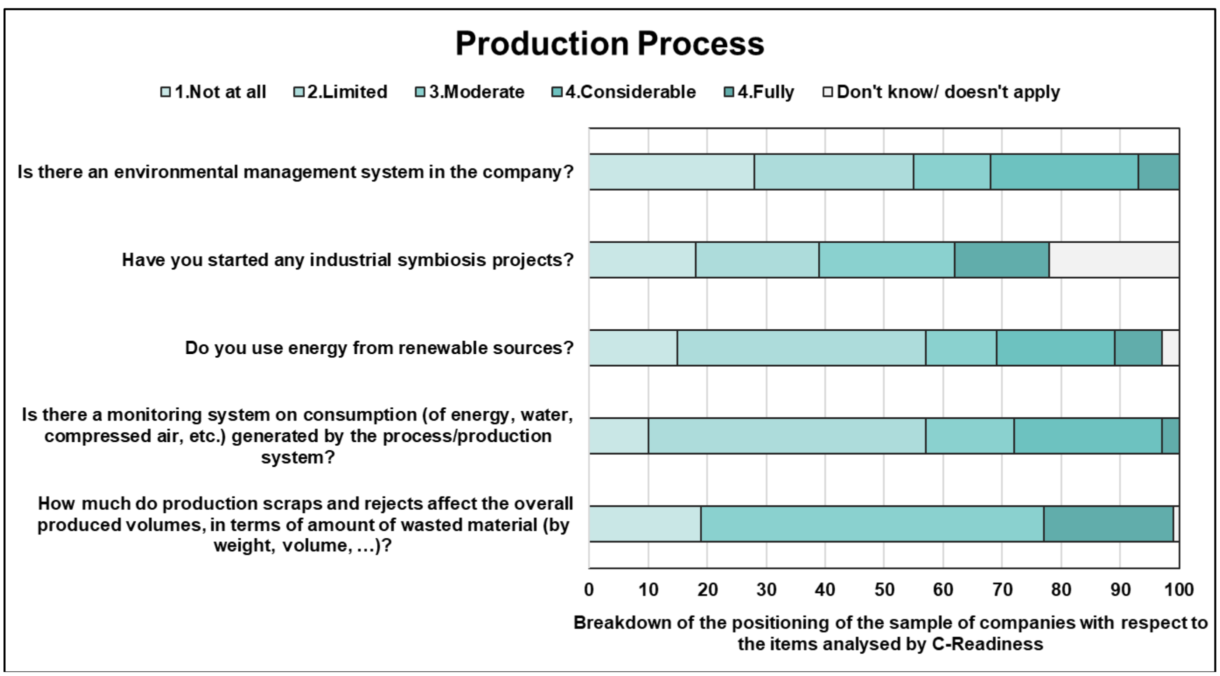
A.6 Green Culture items analysed by C-Readiness tool for Textile sector



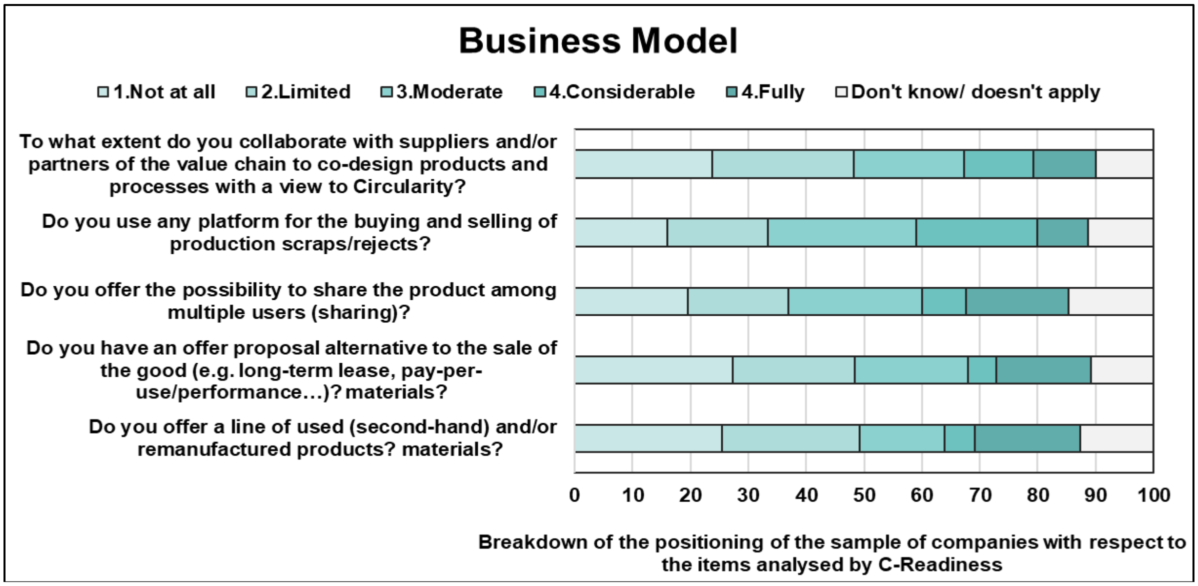
A.7 Product structure items analysed by C-Readiness tool for EEE sector



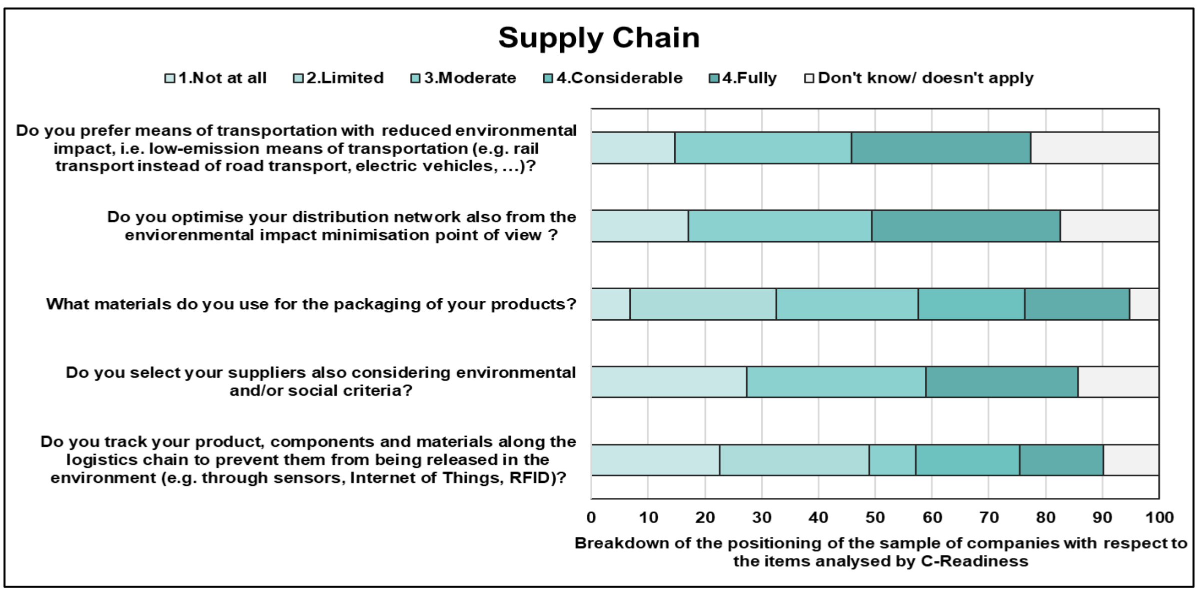
A.8 Production Process items analysed by C-Readiness tool for EEE sector



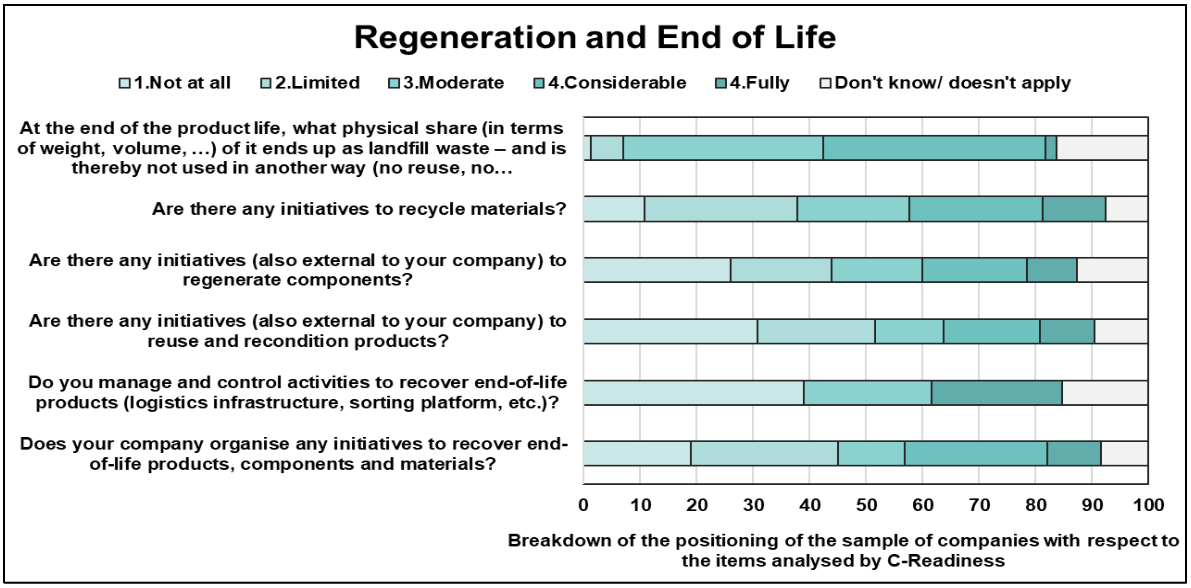
A.9 Business Model items analysed by C-Readiness tool for EEE sector



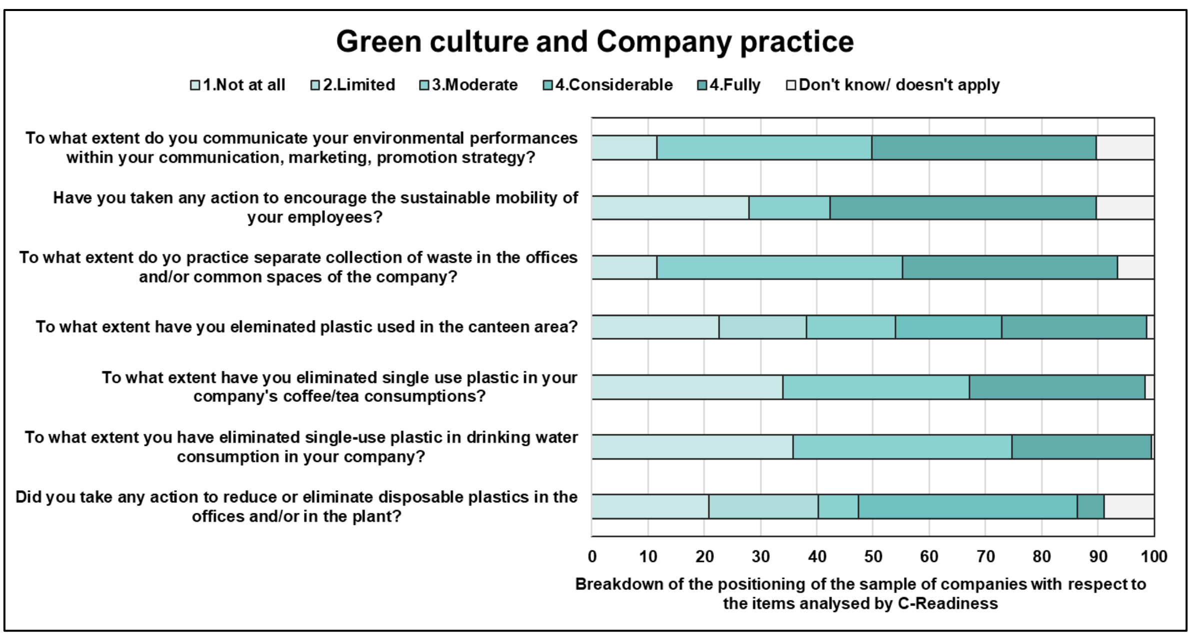
A.10 Supply chain items analysed by C-Readiness tool for EEE sector



A.11 Regeneration and End of life items analysed by C-Readiness tool for EEE sector



A.12 Green culture and company practice items analysed by C-Readiness tool for EEE sector



APPENDIX B – Structural Equation Modelling

B.1 Estimate factor for Measurement Model

Correlation Matrix

Correlation Matrix

		SBM1	SBM2	SBM3	SC3	SC1	SC2	CE1	CE2	CE3	CE4	CE5
SBM1	Pearson"s r	—										
	Spearman"s rho	—										
	Kendall"s Tau B	—										
SBM2	Pearson"s r	0.638 ***	—									
	Spearman"s rho	0.627 ***	—									
	Kendall"s Tau B	0.552 ***	—									
SBM3	Pearson"s r	0.668 ***	0.585 ***	—								
	Spearman"s rho	0.644 ***	0.577 ***	—								
	Kendall"s Tau B	0.565 ***	0.491 ***	—								
SC3	Pearson"s r	0.678 ***	0.607 ***	0.689 ***	—							
	Spearman"s rho	0.663 ***	0.605 ***	0.675 ***	—							
	Kendall"s Tau B	0.581 ***	0.525 ***	0.599 ***	—							
SC1	Pearson"s r	0.661 ***	0.592 ***	0.640 ***	0.685 ***	—						
	Spearman"s rho	0.649 ***	0.600 ***	0.612 ***	0.656 ***	—						
	Kendall"s Tau B	0.552 ***	0.517 ***	0.531 ***	0.582 ***	—						
SC2	Pearson"s r	0.534 ***	0.461 ***	0.526 ***	0.600 ***	0.534 ***	—					
	Spearman"s rho	0.528 ***	0.480 ***	0.513 ***	0.579 ***	0.527 ***	—					
	Kendall"s Tau B	0.455 ***	0.411 ***	0.444 ***	0.497 ***	0.453 ***	—					

Correlation Matrix

		SBM1	SBM2	SBM3	SC3	SC1	SC2	CE1	CE2	CE3	CE4	CE5
CE1	Pearson''s r	0.553 ***	0.633 ***	0.613 ***	0.639 ***	0.512 ***	0.420 ***	—				
	Spearman''s rho	0.540 ***	0.637 ***	0.605 ***	0.647 ***	0.504 ***	0.413 ***	—				
	Kendall''s Tau B	0.465 ***	0.548 ***	0.520 ***	0.556 ***	0.432 ***	0.362 ***	—				
CE2	Pearson''s r	0.591 ***	0.478 ***	0.625 ***	0.603 ***	0.544 ***	0.513 ***	0.535 ***	—			
	Spearman''s rho	0.581 ***	0.483 ***	0.639 ***	0.607 ***	0.539 ***	0.513 ***	0.532 ***	—			
	Kendall''s Tau B	0.507 ***	0.421 ***	0.564 ***	0.532 ***	0.476 ***	0.464 ***	0.470 ***	—			
CE3	Pearson''s r	0.654 ***	0.570 ***	0.685 ***	0.685 ***	0.602 ***	0.543 ***	0.579 ***	0.654 ***	—		
	Spearman''s rho	0.617 ***	0.543 ***	0.659 ***	0.651 ***	0.565 ***	0.525 ***	0.534 ***	0.670 ***	—		
	Kendall''s Tau B	0.528 ***	0.451 ***	0.573 ***	0.562 ***	0.480 ***	0.455 ***	0.468 ***	0.599 ***	—		
CE4	Pearson''s r	0.679 ***	0.560 ***	0.620 ***	0.755 ***	0.628 ***	0.528 ***	0.525 ***	0.583 ***	0.740 ***	—	
	Spearman''s rho	0.649 ***	0.545 ***	0.583 ***	0.724 ***	0.597 ***	0.509 ***	0.497 ***	0.572 ***	0.726 ***	—	
	Kendall''s Tau B	0.561 ***	0.466 ***	0.493 ***	0.628 ***	0.516 ***	0.438 ***	0.436 ***	0.510 ***	0.645 ***	—	
CE5	Pearson''s r	0.554 ***	0.451 ***	0.603 ***	0.538 ***	0.537 ***	0.496 ***	0.405 ***	0.566 ***	0.660 ***	0.605 ***	—
	Spearman''s rho	0.515 ***	0.453 ***	0.574 ***	0.485 ***	0.508 ***	0.497 ***	0.372 ***	0.559 ***	0.628 ***	0.564 ***	—
	Kendall''s Tau B	0.427 ***	0.368 ***	0.476 ***	0.387 ***	0.418 ***	0.431 ***	0.304 ***	0.494 ***	0.540 ***	0.473 ***	—

Note. * p < .05, ** p < .01, *** p < .001

Regression Weights: (Group number 1 - Default model)

			Estimate	S.E.	C.R.	P	Label
SBM3	<---	SBM	1.000				
SBM2	<---	SBM	.909	.047	19.365	***	par_1
SBM1	<---	SBM	.923	.046	20.015	***	par_2
SC2	<---	SCMC	1.000				
SC1	<---	SCMC	1.132	.083	13.644	***	par_3
SC3	<---	SCMC	1.206	.082	14.728	***	par_4
CE1	<---	CE	1.000				
CE2	<---	CE	1.203	.083	14.570	***	par_5
CE3	<---	CE	1.181	.071	16.596	***	par_6
CE4	<---	CE	1.108	.069	16.082	***	par_7
CE5	<---	CE	.844	.063	13.413	***	par_8

Standardized Regression Weights: (Group number 1 - Default model)

			Estimate
SBM3	<---	SBM	.833
SBM2	<---	SBM	.823
SBM1	<---	SBM	.841
SC2	<---	SCMC	.663
SC1	<---	SCMC	.796
SC3	<---	SCMC	.876
CE1	<---	CE	.722
CE2	<---	CE	.759
CE3	<---	CE	.861
CE4	<---	CE	.835
CE5	<---	CE	.701

Standardized Regression Weights: (Group number 1 - Default model)

			Estimate
SBM3	<---	SBM	.833
SBM2	<---	SBM	.823
SBM1	<---	SBM	.841
SC2	<---	SCMC	.663
SC1	<---	SCMC	.796
SC3	<---	SCMC	.876
CE1	<---	CE	.722
CE2	<---	CE	.759
CE3	<---	CE	.861

	Estimate
CE4 <--- CE	.835
CE5 <--- CE	.701

Model Fit Summary

CMIN

Model	NPAR	CMIN	DF	P	CMIN/DF
Default model	25	135.692	41	.000	3.310
Saturated model	66	.000	0		
Independence model	11	3088.675	55	.000	56.158

RMR, GFI

Model	RMR	GFI	AGFI	PGFI
Default model	.050	.940	.903	.584
Saturated model	.000	1.000		
Independence model	.981	.211	.053	.176

Baseline Comparisons

Model	NFI Delta1	RFI rho1	IFI Delta2	TLI rho2	CFI
Default model	.956	.941	.969	.958	.969
Saturated model	1.000		1.000		1.000
Independence model	.000	.000	.000	.000	.000

Parsimony-Adjusted Measures

Model	PRATIO	PNFI	PCFI
Default model	.745	.713	.722
Saturated model	.000	.000	.000
Independence model	1.000	.000	.000

NCP

Model	NCP	LO 90	HI 90
Default model	94.692	63.118	133.872
Saturated model	.000	.000	.000

Model	NCP	LO 90	HI 90
Independence model	3033.675	2855.254	3219.406

FMIN

Model	FMIN	F0	LO 90	HI 90
Default model	.358	.250	.167	.353
Saturated model	.000	.000	.000	.000
Independence model	8.150	8.004	7.534	8.494

RMSEA

Model	RMSEA	LO 90	HI 90	PCLOSE
Default model	.078	.064	.093	.001
Independence model	.381	.370	.393	.000

B.2 Estimate factor for the Path model and Regression Weight

Computation of degrees of freedom (Default model)

Number of distinct sample moments:	66
Number of distinct parameters to be estimated:	28
Degrees of freedom (66 - 28):	38

Result (Default model)

Minimum was achieved

Chi-square = 90.213

Degrees of freedom = 38

Probability level = .000

Regression Weights: (Group number 5 - Default model)

			Estimate	S.E.	C.R.	P	Label
SBM	<---	SCMC	1.065	.079	13.463	***	par_13
CE	<---	SBM	.521	.195	2.679	.007	par_11
CE	<---	SCMC	.423	.216	1.958	.050	par_12

			Estimate	S.E.	C.R.	P	Label
SBM3	<---	SBM	1.000				
SBM2	<---	SBM	.912	.047	19.335	***	par_1
SBM1	<---	SBM	.928	.046	20.032	***	par_2
SC2	<---	SCMC	1.000				
SC1	<---	SCMC	1.133	.083	13.594	***	par_3
SC3	<---	SCMC	1.213	.082	14.725	***	par_4
CE1	<---	CE	1.000				
CE2	<---	CE	1.169	.076	15.326	***	par_5
CE3	<---	CE	1.125	.065	17.324	***	par_6
CE4	<---	CE	1.096	.070	15.566	***	par_7
CE5	<---	CE	.825	.065	12.602	***	par_14

Standardized Regression Weights: (Group number 5 - Default model)

			Estimate
SBM	<---	SCMC	.958
CE	<---	SBM	.554
CE	<---	SCMC	.405
SBM3	<---	SBM	.831
SBM2	<---	SBM	.824
SBM1	<---	SBM	.843
SC2	<---	SCMC	.661
SC1	<---	SCMC	.794
SC3	<---	SCMC	.878
CE1	<---	CE	.754
CE2	<---	CE	.770
CE3	<---	CE	.856
CE4	<---	CE	.861
CE5	<---	CE	.714

ML discrepancy (implied vs sample) (Default model)

		|--------------------
	72.643	|*
	81.930	|
	91.218	|***
	100.505	|***
	109.793	|*********
	119.080	|**************
	128.368	|*************
N = 200	137.655	|**************
Mean = 139.350	146.943	|******************
S. e. = 1.757	156.230	|**********
	165.518	|*****
	174.805	|***
	184.093	|*****
	193.380	|***
	202.668	|**
		|--------------------

Model Fit Summary

CMIN

Model	NPAR	CMIN	DF	P	CMIN/DF
Default model	28	90.213	38	.000	2.374
Saturated model	66	.000	0		
Independence model	11	3088.675	55	.000	56.158

RMR, GFI

Model	RMR	GFI	AGFI	PGFI
Default model	.040	.960	.931	.553
Saturated model	.000	1.000		
Independence model	.981	.211	.053	.176

Baseline Comparisons

Model	NFI Delta1	RFI rho1	IFI Delta2	TLI rho2	CFI
Default model	.971	.958	.983	.975	.983
Saturated model	1.000		1.000		1.000
Independence model	.000	.000	.000	.000	.000

Parsimony-Adjusted Measures

Model	PRATIO	PNFI	PCFI
Default model	.691	.671	.679
Saturated model	.000	.000	.000
Independence model	1.000	.000	.000

NCP

Model	NCP	LO 90	HI 90
Default model	52.213	28.222	83.910
Saturated model	.000	.000	.000
Independence model	3033.675	2855.254	3219.406

FMIN

Model	FMIN	F0	LO 90	HI 90
Default model	.238	.138	.074	.221
Saturated model	.000	.000	.000	.000
Independence model	8.150	8.004	7.534	8.494

RMSEA

Model	RMSEA	LO 90	HI 90	PCLOSE
Default model	.060	.044	.076	.139
Independence model	.381	.370	.393	.000

AIC

Model	AIC	BCC	BIC	CAIC
Default model	146.213	148.044	256.538	284.538
Saturated model	132.000	136.316	392.051	458.051
Independence model	3110.675	3111.395	3154.017	3165.017

ECVI

Model	ECVI	LO 90	HI 90	MECVI
Default model	.386	.322	.469	.391
Saturated model	.348	.348	.348	.360
Independence model	8.208	7.737	8.698	8.209

HOELTER

Model	HOELTER .05	HOELTER .01
Default model	225	257
Independence model	9	11

APPENDIX C- List of papers published on international journal, or discussed at conferences, based on this research

Journal Publications:

1. Das, S. K., Bressanelli, G., & Saccani, N. (2024). Clustering the Research at the Intersection of Industry 4.0 Technologies, Environmental Sustainability and Circular Economy: Evidence from Literature and Future Research Directions. Circular Economy and Sustainability, 4(4), 2473–2504. https://doi.org/10.1007/s43615-024-00393-3.

2. Das, S. K., Perona, M. (2025) Supply Chain Risk Management Automation: a literature review, Electronic Markets -The International Journal on Networked Business, submitted

3. Das, S. K., Bressanelli, G., & Saccani, N. The adoption of Digital Technologies in Operations Management processes for environmental sustainability and circularity: a review, submitted

4. Das, S. K., Bressanelli, G., & Saccani, N. Examining the interplay of Supply Chain Tracking, Management & Collaboration and Servitized Business Models for Circular Economy and End-of-Life Practices: an empirical study, to be submitted

List of papers discussed at Conferences:

1. Das, S. K. & Saccani, N. (2025). Supporting the Circular Economy Using Digital Technologies in Operations Management Processes, *Artificial Intelligence and the Circular Economy, Edward Elgar Publishing, BAM-ORSI, IIT Mumbai 2024*

2. Das, S. K., Saccani, N. (2025). Analyzing the Role of IoT and Big Data in Circular Supply Chains Using a Comparative Study on Text Mining/Topic Modeling and an Industrial Case Study. *In: Kumar Udgata, S., Sethi, S., Ghinea, G., Kuanar, S.K. (eds) Intelligent Systems. ICMIB 2024. Lecture Notes in Networks and Systems, vol 1149. Springer, Singapore* https://doi.org/10.1007/978-981-97-8160-7_34

3. Das S. K. Bressanelli G. Saccani N. Perona M. (2023). Digital Technologies for the Sustainability of Circular Manufacturing Processes: A Review, *XXVIII Summer School "Francesco Turco"*.

4. Das S. K., Bressanelli G., Saccani N. (2023), Bibliometric Analysis of the Impact of Industry 4.0 Technologies on the Circular Economy, *2nd International Symposium on Industrial Engineering and Automation.*

5. Das S. K., Bressanelli G., Saccani N. (2023). Mapping of Industry 4.0 Technologies on Circular Economy through Bibliometrix, *EurOMA Sustainability Forum*.

6. Das S. K., Bressanelli G., Saccani N. (2022) Bibliometric analysis on Industry 4.0 technologies and circular economy, *XXVII Summer School.*