From Visibility to Circular Intelligence: Digital Supply Chain Control Towers for Closed-Loop and Regenerative Supply Chains

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ABSTRACT

Linear to circular supply chain transformation necessitates coordination infrastructures capable of managing reverse flows, lifecycle information, and multi-dimensional sustainability objectives. While the utilisation of Supply Chain Control Towers (SCCT) to enhance visibility and responsiveness in traditional linear supply chains is well established, their potential role in supporting circular economy (CE) adoption has not yet been conceptually examined. This study conducts a systematic literature review of 13 peer-reviewed publications from 2000 to 2025 to investigate the intersection of CE principles with Industry 4.0 technologies and SCCT architectures. Adhering to the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines, the review synthesises digital enablers, orchestration capabilities, governance structures, and performance management mechanisms relevant to circular supply chain transformation. The findings indicate that traceability systems, advanced analytics, and cross-tier data integration enable SCCT to function as circular orchestration mechanisms rather than mere monitoring tools. Nonetheless, empirical validation of CE-enabled SCCT designs remains scarce. To address this gap, the study proposes a multi-layer conceptual framework that differentiates digital resource infrastructures from circular orchestration capabilities while integrating governance and performance measurement systems within a unified structure. By combining resource-based, dynamic capability, and socio-technical perspectives, this research advances theoretical understanding of digital circular coordination and provides a structured foundation for future empirical studies and managerial applications.

Keywords: Circular Economy; Supply Chain Control Towers; Industry 4.0; Closed-Loop Supply Chains; Digital Transformation

INTRODUCTION

The industrial and technological developments of the 21st century have transformed traditional production paradigms, giving rise to environmental, economic, and social pressures (Onukwulu et al., 2022; Zils et al., 2023). The linear economic model (make, consume, dispose) (Zils et

al., 2023) has led to depletion of resources, increased waste, and environmental deterioration. The CE framework seeks to reconceptualize resource utilisation by maximising material reuse, minimising waste, and fostering regeneration throughout product life cycles (Hazen et al., 2020; Kazancoglu et al., 2021). Nevertheless, the application of CE principles within operational tools such as SCCT remains underexplored (Howard et al., 2018). The role of SCCT in supply chain management is well recognised, offering real-time visibility, transparency, and centralised governance across complex networks (Khanna et al., 2025). This capacity enables proactive decision-making, risk mitigation, and stakeholder collaboration (Khanna et al., 2025). However, conventional optimisation approaches focused on linear supply chain efficiency have constrained SCCT functionalities in circular contexts, where enhanced transparency, reverse logistics, resource recovery, and life cycle extension aligned with CE principles are essential (MahmoumGonbadi et al., 2021). Both empirical and theoretical studies investigating SCCT adaptation for CE implementation remain limited, restricting organisational ability to leverage these platforms for sustainable supply chain transformation (Govindan & Hasanagic, 2018; Hazen et al., 2020; Kazancoglu et al., 2021). This gap underscores the necessity of operationalising CE principles within SCCT and identifying enablers and barriers to this transition (Lahane et al., 2020). Support for closed-loop supply chains, environmentally responsible transport governance, and product return management via SCCT is critical to advancing sustainable supply chain practice.

The purpose of this study is to review literature at the intersection of CE and SCCT to evaluate how SCCT can facilitate CE implementation. It addresses three research questions: (1) which aspects of CE and SCCT are addressed in current literature; (2) what gaps exist in understanding CE integration within SCCT frameworks; and (3) what directions can advance current knowledge and research on SCCT frameworks. The study aims to contribute to the formulation of a comprehensive taxonomy and conceptual frameworks for CE-enabled SCCT, supporting enhanced supply chain resilience, end-to-end visibility, and data governance in circular systems. Integration of digital innovations and Industry 4.0 technologies within SCCT offers promising pathways to improve sustainability performance. The study's significance lies in guiding organisations towards circular supply chains rather than traditional linear models, aligning with sustainability objectives. Clarifying how SCCT can be reconfigured to incorporate CE principles can optimise resource utilisation, reduce environmental impacts, and foster collaboration across supply chain nodes.

Current research on CE digitalisation predominantly treats technologies as discrete enablers rather than embedded coordination mechanisms. In contrast, SCCT represents a meso-level orchestration infrastructure bridging firm-level capabilities and network-level governance. A critical gap in supply chain scholarship is the lack of theory-driven understanding regarding how SCCT resources can be translated into circular orchestration capabilities.

METHOD

Study Design

This study employs a systematic literature review (SLR) approach to identify, evaluate, and synthesise existing research concerning the integration of CE principles within SCCT. The review is conducted in line with PRISMA 2020 guidelines to ensure methodological transparency, rigor, and reproducibility. The SLR incorporated all pertinent studies addressing CE principles through systematic identification, appraisal, and synthesis. Adopting a systematic

review methodology enables an impartial assessment of relevant literature under stringent criteria, thereby supporting evidence-based conclusions. The review was executed according to established PRISMA protocols to ensure methodological robustness. The review protocol was not preregistered on PROSPERO or the Open Science Framework (OSF). All methodological steps were predetermined and implemented following PRISMA 2020 standards.
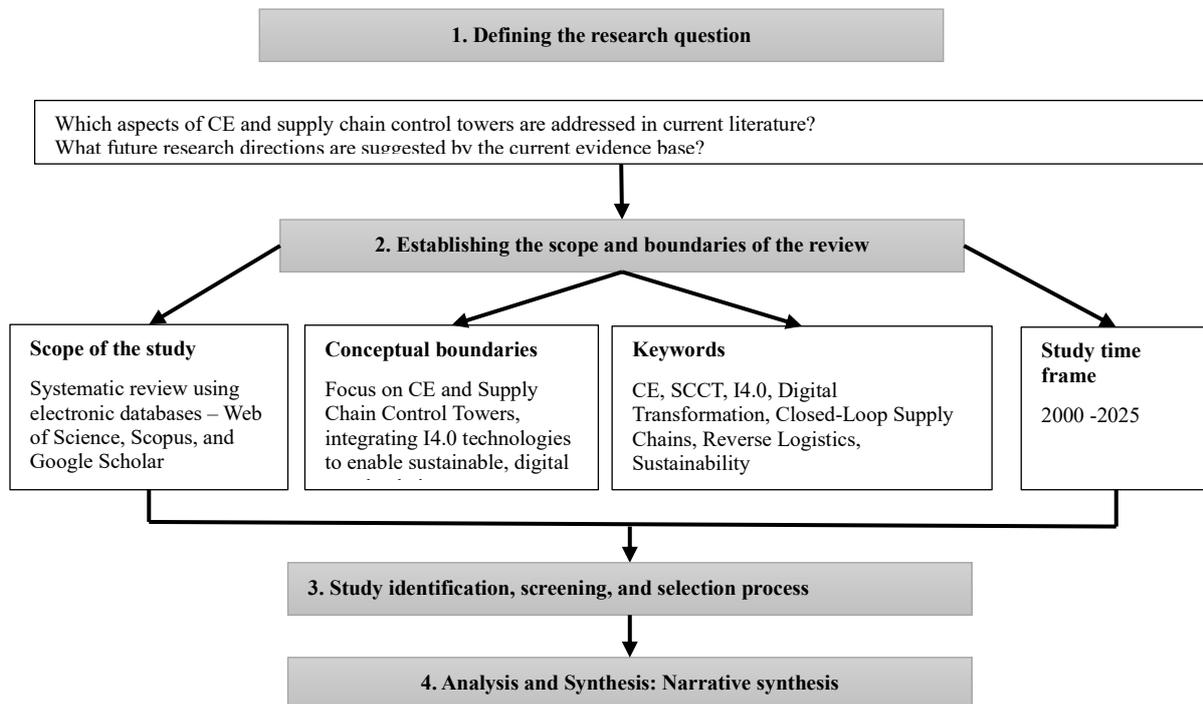

Figure 1: Research Design

Information Sources and Search Strategy

The SLR examined three principal electronic databases: Web of Science, Scopus, and Google Scholar. The search period encompassed publications from 2000 to 2025, capturing studies relevant to CE and SCCT within this timeframe. The final database search was completed on 15 July 2025.

Database-Specific Search Strings

Search queries were systematically developed to capture research at the convergence of CE, SCCT, and Industry 4.0 (I4.0) technologies. The search strings included synonyms, related terminology, and wildcard operators to ensure comprehensiveness, as detailed in Appendix A. An illustrative search string employed in Scopus was: ("Supply Chain Control Tower" OR "Digital Control Tower") AND ("CE" OR "Closed-loop supply chain") AND ("Industry 4.0" OR "IoT" OR "Blockchain" OR "Digital Twin").

Inclusion and Exclusion Criteria

Studies were incorporated if they met the following conditions:

- Published in peer-reviewed journals between 2000 and 2025.
- Written in English.

• Explicitly addressed the intersection of CE, SCCT, and I4.0 technologies, encompassing either operationalisation or conceptualisation of CE principles through SCCT enabled by I4.0 tools.
• Employed empirical, conceptual, SLR, or modelling research methodologies.

Studies were excluded if they:

• Took the form of conference papers, editorials, opinion pieces, or book chapters.
• Did not sufficiently address CE integration within SCCT or lacked relevance to digital I4.0 enablers.
• Were published in languages other than English.

Screening and Study Selection Process

All retrieved records were imported into reference management software, and duplicates were eliminated. An initial title and abstract screening was conducted independently by two reviewers to assess adherence to the inclusion criteria. Any disagreements were resolved through discussion, with a third reviewer adjudicating unresolved cases. Subsequently, full-text screening of shortlisted articles was performed by the same reviewers, evaluating each study for eligibility. The study selection procedure followed PRISMA guidelines and is illustrated in the PRISMA flow diagram (see Figure 2).

Data Extraction and Quality Assessment

Records obtained from the databases were imported into reference management software with duplicates removed. Two reviewers independently conducted title and abstract screening to ensure alignment with inclusion criteria. Discrepancies were resolved through discussion, with a third reviewer providing final decisions when consensus was not achieved. Full-text assessment of shortlisted articles was then undertaken, ensuring careful evaluation of all eligible studies. The study selection adhered to PRISMA standards, as depicted in the PRISMA flow diagram (see Figure 2). A standardised data extraction template was utilised to systematically capture key information, including author(s), publication year, industry context, research objectives, methodology, principal findings, and implications related to CE and SCCT integration. Quality appraisal was performed independently by the reviewers, assessing the robustness of study designs, methodological transparency, and relevance to the review questions. Risk of bias was evaluated across domains such as clarity of search strategy, data synthesis, and transparency of reporting.

Data Synthesis and Thematic Analysis

A narrative synthesis method was applied to integrate findings from studies with heterogeneous designs. Thematic analysis was conducted following the subsequent procedural steps:

1. **Coding Procedure:** Study finding coding was carried out by two independent coders following a systematic coding procedure using an initial study question-driven codebook.
2. **Software:** Coding was performed by using qualitative analysis software NVivo in order to facilitate the organization and retrieval of themes.
3. **Intercoder Reliability:** To confirm coding consistency, intercoder reliability was calculated using the Cohen's Kappa coefficient, which resulted in the value of 0.85, which is a good agreement.

4. **Theme Development:** Codes were grouped into broader themes iteratively, reflecting digital enablers, CE operational frameworks, network collaboration, CE implementation best practices, and CE foundational principles. Thematic analysis guided the integration of existing knowledge and the identification of research gaps concerning the incorporation of CE principles within SCCT. For instance, references to "blockchain-enabled traceability" were initially coded as "traceability mechanism" and subsequently consolidated into the higher-level construct "Digital Transparency Enabler."
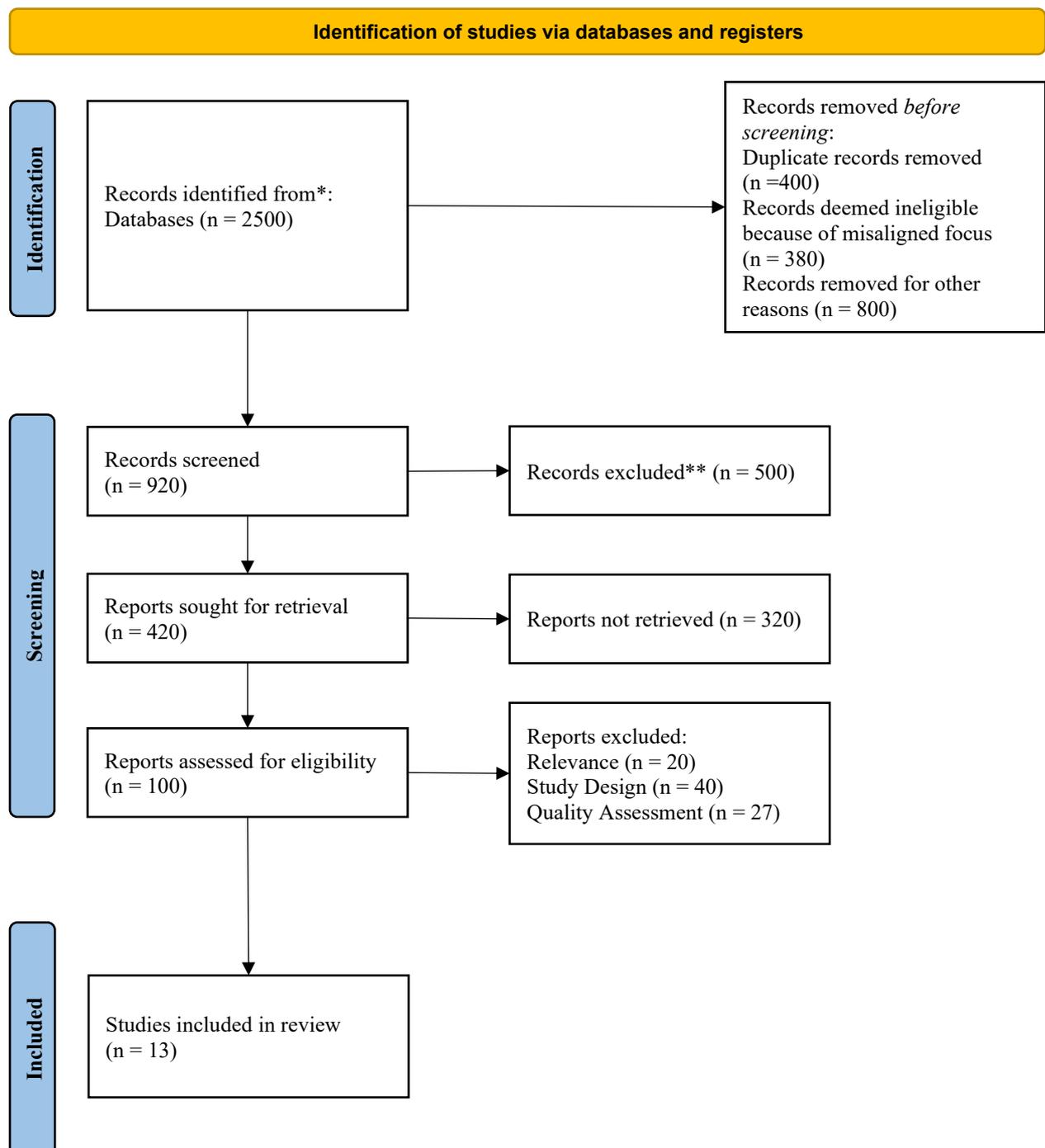

Figure 1: PRISMA Flow Diagram

Despite rigorous screening, limiting the review to English-language peer-reviewed publications may exclude practitioner experiences and non-indexed case studies, particularly in the context of rapidly evolving SCCT applications.

RESULTS

The systematic review identified 13 pivotal studies published between 2000 and 2025, reflecting a notable increase in interest regarding CE and SCCT. Publication frequency, particularly after 2020, underscores the rising scholarly and industry focus on integrating digital technologies with sustainability in supply chains. These studies address central themes including I4.0 technology enablers, multidimensional CE management, and cross-network collaboration, all of which are critical for the effective adoption of SCCT. Figure 3 illustrates the yearly distribution of relevant publications and their categorisation, providing a comprehensive overview of research progression within this emerging field.
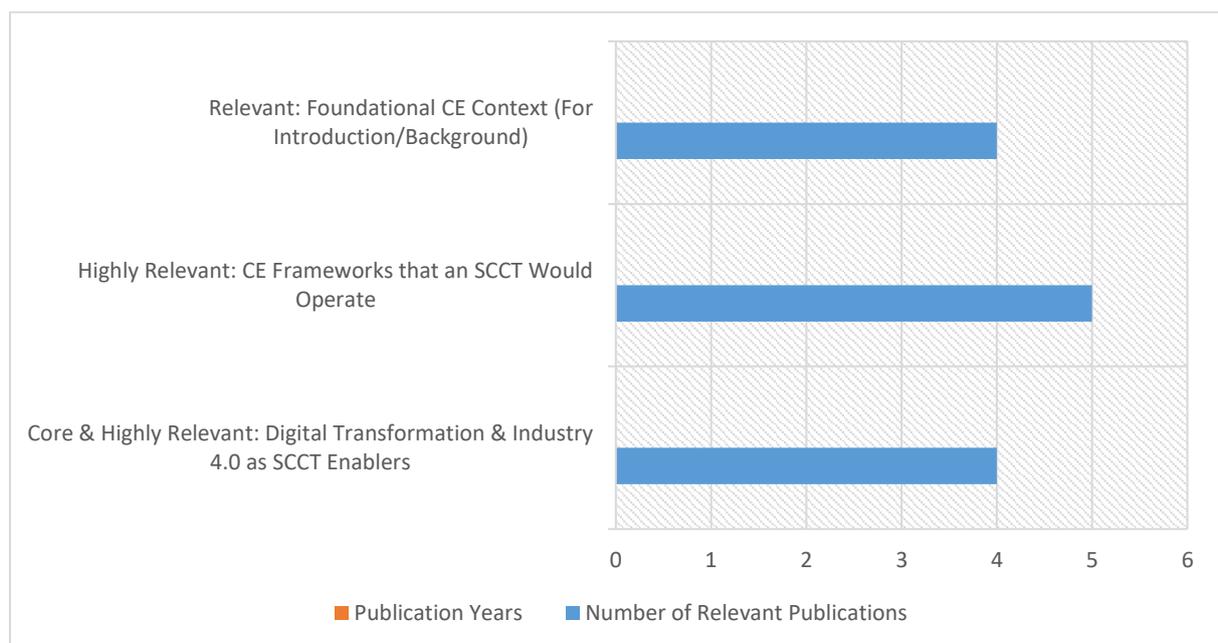

Figure 3: Number of Relevant Publications and their Publication Years for the Categories

Methodological Quality Assessment

The methodological quality of the studies included in this synthesis was assessed using the AMSTAR 2 instrument. In accordance with the instrument's guidance, evaluation focused on overall confidence in the results (high, moderate, low, critically low) rather than domain-specific risk-of-bias ratings or traffic-light visualisations. The appraisal considered both critical and non-critical methodological limitations, including clarity of the protocol, comprehensiveness of the literature search, study selection procedures, data extraction processes, and execution of quality appraisal methods. These deficiencies were identified across all studies and compiled to generate overall confidence ratings. Systematic reviews demonstrating rigorous methodology—such as clearly described search strategies, explicit inclusion criteria, and robust analytical procedures—were assigned higher confidence levels. In contrast, studies with poorly described methods or limited transparency received lower confidence ratings. Table 1 presents the AMSTAR 2 results, providing a structured overview for evaluating the strength and reliability of the evidence synthesised in this study.

Table 1: Characteristics and Methodological Quality of Included Systematic Literature Reviews

Study (Author, Year)	Population / Setting (Industry Focus)	Intervention / Exposure / Core Finding	Comparisons / Key Outcomes Discussed	Methodology & Study Characteristics	Implication for SCCT Integration (Our Synthesis)	AMSTAR 2 Overall Confidence
Core & Highly Relevant: Digital Transformation & I4.0 as SCCT Enablers						
Agrawal et al. (2021)	General Manufacturing & Logistics	Integrating I4.0 and AI tools within CE practices; proposes a framework to guide CE decision-making	Improved logistics efficiency, resource utilization, safety, product quality, and reduced environmental impact	Comprehensive systematic literature review (165 articles); bibliometric and network analysis	Directly relevant. SCCT represent an applied I4.0 platform; this study provides the technological foundation (IoT, AI, analytics) enabling CE outcomes via SCCT	**High**
de Mattos Nascimento et al. (2024)	Sustainable Supply Chains	Examines interrelationships between I4.0 technologies and CE principles; proposes a validated classification and research agenda	Cyber-physical systems and smart manufacturing most influential for CE goals (lifespan extension, smarter product use)	Systematic literature review combined with focus group interviews and Fuzzy Delphi analysis	Directly relevant. Identifies which I4.0 technologies—core SCCT building blocks—are most critical for achieving specific CE objectives	**High**
Nguyen et al. (2023)	General Supply Chains	Introduces Supply Chain Quality Management 4.0 (SCQM 4.0) to support CE transition; proposes a four-stage CE practice route	Infrastructure practices linked to sustainable performance (input management, waste handling, preservation)	PRISMA-based systematic literature review (126 studies); thematic analysis	Highly relevant. SCQM 4.0 closely aligns with SCCT logic; proposed practices and metrics are directly transferable to SCCT functionality	**High**
Khanna et al. (2025)	General Supply Chains	Identifies best practices for integrating CE through digital technologies such as IoT and blockchain	Highlights integration barriers and enabling practices; proposes future CE directions	Narrative literature review	Highly relevant. Explicitly identifies core SCCT technologies (IoT, blockchain) as enablers of CE implementation	**Moderate**

Table 1(continued): Characteristics and Methodological Quality of Included Systematic Literature Reviews

Study (Author, Year)	Population / Setting (Industry Focus)	Intervention / Exposure / Core Finding	Comparisons / Key Outcomes Discussed	Methodology & Study Characteristics	Implication for SCCT Integration (Our Synthesis)	AMSTAR 2 Overall Confidence
Highly Relevant: CE Frameworks Operated via SCCT						
Zhang et al. (2021)	Multi-Industry	Proposes a multi-dimensional circular supply chain management (CSCM) framework covering closed-loop, reverse, and remanufacturing SCM	Synthesizes interrelationships and categorizes CSCM practices across dimensions	Comparative systematic review (68 cases; 124 publications)	Highly relevant. An SCCT would serve as the operational backbone to manage and coordinate complex multi-dimensional CSCM frameworks	**High**
MahmoumGonbadi et al. (2021)	General Manufacturing	Reviews closed-loop supply chain design for CE transition; identifies disconnect from full CE principles	CLSC studies often ignore social dimension; performance metrics largely monetary	Systematic literature review (254 articles)	Highly relevant. Identifies the precise gap SCCT can fill by providing holistic, real-time economic, environmental, and social performance visibility	**High**
Berardi and Peregrino de Brito (2021)	General Supply Chains	Analyses supply chain collaboration as a prerequisite for CE transition	Collaboration critical but constrained; trust and partner selection are major barriers	Systematic literature review	Highly relevant. SCCT directly address transparency, trust, and collaboration constraints identified in CE supply networks	**High**
Sudusinghe and Seuring (2022)	Circular Supply Chains	Examines relationship between supply chain collaboration and sustainability performance in CE	Collaboration improves environmental and economic performance; social dimension underexplored	Systematic literature review; content analysis (82 studies)	Highly relevant. Supports SCCT value proposition as a collaboration-enabling platform for CE performance improvement	**High**
Howard et al. (2018)	Multinational Corporations	Develops CE performance indicators for monitoring and reporting	Identifies internal and external CE indicators; highlights need for metrics beyond closed-loop flows	Multiple case study (9 MNCs); abductive analysis	Highly relevant. Provides foundational KPI structures required for CE dashboards within SCCT	**Moderate**

Table 1(continued): Characteristics and Methodological Quality of Included Systematic Literature Reviews

Study (Author, Year)	Population / Setting (Industry Focus)	Intervention / Exposure / Core Finding	Comparisons / Key Outcomes Discussed	Methodology & Study Characteristics	Implication for SCCT Integration (Our Synthesis)	AMSTAR 2 Overall Confidence
Relevant: Foundational CE Context						
Govindan and Hasanagic (2018)	Supply Chain Perspective	Reviews drivers, barriers, and practices for CE adoption	Government policy strongest driver; key barrier is technological capability	Systematic literature review (60 studies)	Relevant. Positions SCCT as technological solutions to overcome CE implementation barriers	**High**
Bressanelli et al. (2018)	Household Appliance Industry	Identifies challenges in supply chain redesign for CE and managerial levers to address them	Coordination and information flow critical; vertical integration not mandatory	Systematic review with multiple case studies	Relevant. Operational challenges identified align with problems SCCT are designed to solve	**Moderate**
Masi et al. (2017)	General Supply Chains	Proposes CE supply chain configurations based on goals rather than implementations	Identifies eco-industrial parks, green SCM, and closed-loop SCM	Systematic literature review (five-step approach)	Relevant. Suggests SCCT must be adaptable to multiple CE supply chain configurations	**Moderate**
Lahane et al. (2020)	General Supply Chains	Reviews CSCM literature and identifies modelling and optimization opportunities	Calls for advanced quantitative modelling and new business models	Content analysis (125 studies over 10 years)	Relevant. Highlights need for advanced analytics—core capabilities of sophisticated SCCT systems	**High**

Overview and Interpretation of Included Studies

The 13 studies incorporated in the review are summarised in Table 1, detailing sectoral focus, principal findings, research design, and implications for applying CE principles within SCCT. The literature spans diverse contexts, encompassing traditional manufacturing and logistics as well as multi-industry supply chains, consistently highlighting the importance of digital transformation and I4.0 technologies as central elements of circular supply chain practices. Table 1 also reflects methodological diversity among the reviewed studies, including SLRs, case-based analyses, and thematic or content analyses. These approaches were applied to examine CE, collaborative systems, and performance measurement mechanisms relevant to SCCT implementation. The synthesised evidence offers insights into both technological and managerial dimensions of circular supply chain transformation and demonstrates how SCCT can function as a coordinating, transparent, and data-driven system in pursuit of CE objectives.

Summary of Included Systematic Literature Reviews

Table 2 presents the 13 SLRs forming the basis of this synthesis, detailing author(s), publication year, article title, and source journal. These reviews encompass a broad spectrum of topics at the convergence of I4.0 technologies, CE principles, and supply chain management. Predominantly published in high-impact journals such as Sustainability, Journal of Cleaner Production, and International Journal of Production Research, they provide critical insights into contemporary practices, challenges, and prospects for integrating digital transformation with sustainable supply chains. This collection serves as the foundation for thematic analysis and conceptual development in the present study.

Table 2: Included Systematic Literature Reviews for Thematic Analysis

No.	Author(s) (Year)	Article Title	Journal
1	Agrawal et al. (2021)	Progress and trends in integrating Industry 4.0 within the CE: A comprehensive literature review and future research propositions	*Business Strategy and the Environment*
2	de Mattos Nascimento et al. (2024)	Unlocking the potential of Industry 4.0 for sustainable supply chains: Challenges and benefits	*Sustainability*
3	Nguyen et al. (2023)	Navigating environmental challenges through Supply Chain Quality Management 4.0 in the CE: A comprehensive review	*Sustainability*
4	Khanna et al. (2025)	Circular supply chain management: Bridging business innovation and sustainability through best practices	*Journal of CE*
5	Zhang et al. (2021)	Multi-dimensional circular supply chain management: A comparative review of state-of-the-art practices and research	*Transportation Research Part E: Logistics and Transportation Review*
6	MahmoumGonbadi et al. (2021)	Closed-loop supply chain design for the transition towards a CE: A systematic literature review of methods, applications, and current gaps	*Journal of Cleaner Production*

Table 2(continued): Included Systematic Literature Reviews for Thematic Analysis

No.	Author(s) (Year)	Article Title	Journal
7	Berardi and Peregrino de Brito (2021)	Supply chain collaboration for a CE: From transition to continuous improvement	*Journal of Cleaner Production*
8	Sudusinghe and Seuring (2022)	Supply chain collaboration and sustainability performance in the CE: A systematic literature review	*International Journal of Production Economics*
9	Howard et al. (2018)	The regenerative supply chain: A framework for developing CE indicators	*International Journal of Production Research*
10	Govindan and Hasanagic (2018)	A systematic review on drivers, barriers, and practices towards the CE: A supply chain perspective	*International Journal of Production Research*
11	Bressanelli et al. (2018)	Challenges in supply chain redesign for the CE: A literature review and a multiple case study	*International Journal of Production Research*
12	Masi et al. (2017)	Supply chain configurations in the CE: A systematic literature review	*Sustainability*
13	Lahane et al. (2020)	Circular supply chain management: A state-of-the-art review and future opportunities	*Journal of Cleaner Production*

Thematic Analysis

Table 3 presents the codes derived from the 13 SLRs and the overarching themes they collectively generate. These themes represent the key architectural and functional requirements necessary for an effective SCCT platform.

Table 3: Thematic Analysis of Literature: Codes and Emergent Themes

Overarching Theme	Sub-Theme	Extracted Codes and Contributing Articles*
Theme 1: Digital Technological Enablers	I4.0 Core Technologies	Integration of Industry 4.0 and AI tools to support CE (1); I4.0 technologies as foundational building blocks (2); IoT and blockchain as key digital enablers (4); digital transformation of supply chains (3).
	Data-Driven Decision-Making	Frameworks guiding CE decision-making through digital tools (1); data analytics enabling CE outcomes (1); advanced quantitative modelling and analytics (13).
	Smart Infrastructure	Smart manufacturing and cyber-physical systems (CPS) enable CE practices (2); digital infrastructure practices supporting sustainability (3).

Table 3: Thematic Analysis of Literature: Codes and Emergent Themes

Overarching Theme	Sub-Theme	Extracted Codes and Contributing Articles*
Theme 2: CE Operational Frameworks	Multi-Dimensional Management	Multi-dimensional CSCM frameworks (5); management of complex circular supply chain configurations (5); closed-loop, reverse, and remanufacturing SCM configurations (5, 12).
	Performance Measurement	Sustainable performance metrics aligned with CE (3); holistic performance measurement across economic, environmental, and social dimensions (6); standardized CE KPIs and indicators (9); development of metrics beyond traditional closed-loop approaches (9).
	Waste Elimination	Zero-waste objectives within CSCM (5); improved resource efficiency (1); reduction of environmental impacts and emissions (1).
Theme 3: Collaboration and Transparency	Network Integration	Collaboration and transparency as enablers of CE (7); supply chain collaboration as a foundational requirement (7, 8); collaboration-driven improvement in CE performance (8).
	Trust and Partner Selection	Critical importance of trust among supply chain partners (7); challenges in selecting trustworthy partners for CE initiatives (7).
	Information Flow	Addressing coordination problems and improving information flow across supply chain networks (11).
Theme 4: Strategic Implementation and Value Creation	Best Practices and Implementation Routes	Best practices for CE integration in supply chains (4); four-stage CE-based implementation routes (3); managerial levers for CE transition (11).
	Value Proposition	Improved logistics efficiency, safety, and product quality (1); CE drivers such as job creation and climate change mitigation (10).
	Overcoming Barriers	Digital and technological solutions to overcome CE implementation barriers (10); addressing technological challenges related to product durability and lifecycle management (10).
Theme 5: Foundational CE Principles	CE Principal Integration	Interrelationships between Industry 4.0 technologies and CE principles (2); integration of CE principles into supply chain strategies (4); transition from linear models to continuous improvement in CE (7).
	Design and Product Lifespan	Product lifespan extension through digital and CE practices (2); smarter product use enabled by digital technologies (2); design for durability and longevity (10).
	Business Model Innovation	Business innovation supporting CE transitions (4); exploration of new circular business models (13).

Distinguishing SCCT from General Digital Platforms

While prior literature generally suggested that CE implementation occurs within broad digital platforms, SCCT differ along three structural dimensions:

1. Real-time orchestration and control across multiple nodes,
2. Integrated performance governance dashboards,
3. Cross-tier exception management capabilities.

These structural characteristics enable SCCT to function as circular coordination systems rather than mere data aggregation tools.

DISCUSSION

This study provides insights to assist decision-makers in integrating CE principles within SCCT. The growing demand for CE practices in SCCT is acknowledged, and this research clarifies the nature of existing studies, highlighting anticipated benefits and best practices valuable to both practitioners and industrial stakeholders. Several factors have limited the direct applicability of CE principles in SCCT, including a lack of industrial and practical orientation, as well as insufficient systematic analyses and proposed methodologies. Thematic analysis of the reviewed literature identifies five primary themes critical for embedding CE concepts into SCCT.

First, I4.0 core technologies such as IoT, AI, and blockchain emerge as essential digital enablers, forming the technological foundation for real-time monitoring and data-driven decision-making (Masi et al., 2017; Nguyen et al., 2023). Second, multi-dimensional management models highlight the need to measure circular supply chain performance across economic, environmental, and social dimensions, alongside strategies aimed at achieving "zero waste" objectives (Onukwulu et al., 2022; Sudusinghe & Seuring, 2022). Third, network integration underscores the importance of collaboration and transparency, where trust and efficient information exchange among supply chain partners significantly enhance circular supply chain performance (Govindan & Hasanagic, 2018). Fourth, strategic implementation focuses on best practices and value creation pathways, addressing challenges such as partner selection and adoption of new technologies through managerial levers and business innovation (Hazen et al., 2020; Zhang et al., 2021).

Fifth, fundamental CE principles—such as product design for durability, extending product lifespan, and novel business models—guide the transition from traditional supply chains to regenerative systems (Kazancoglu et al., 2021). Collectively, these themes reflect a multidisciplinary approach required to design intelligent CE technology platforms within SCCT, providing both theoretical insight and practical guidance. Nevertheless, empirical studies remain limited, emphasising the urgent need for research that translates these concepts into real-world applications. To consolidate the findings, a multi-layered CE-based SCCT framework is proposed, integrating technological enablers, operational capabilities, governance mechanisms, and performance measurement systems (see Figure 3). This framework offers a roadmap for translating CE principles into structural SCCT design elements and measurable outcomes.

The multi-layered architecture presented in Figure 4 offers an integrative framework for operationalising CE principles within SCCT. It translates the thematic insights of this review

into a practical blueprint for both researchers and practitioners, demonstrating the interactions between technologies, processes, and strategic outcomes.

LAYER 1
Digital Resource Infrastructure
Foundational resource base enabling circular information flows (RBV)

— Traceability Systems
— Analytics Engines
— Data Integration Platforms
— Cyber-Physical Connectivity

Enables ↓

LAYER 2
Circular Orchestration Capabilities
Dynamic capabilities for sensing, seizing, and reconfiguring circular opportunities (DCT)

— Reverse Flow Coordination
— Closed-Loop Resource Planning
— Lifecycle Visibility & Exception Management
— Predictive Circular Optimization

↓ Requires

LAYER 3
Inter-Organizational Governance Mechanisms
Structural arrangements enabling cross-boundary circular coordination (STS, TCE)

— Data Governance & Sharing Protocols
— Trust & Transparency Mechanisms
— Cross-Tier Coordination Structures
— Circular Incentive Alignment

Measured by ↓

LAYER 4
Circular Performance Governance System
Feedback mechanisms enabling continuous circular transformation (IPT)

— Economic Circular Metrics
— Environmental Impact Indicators
— Social & Compliance Measures
— Circular Maturity Assessment

↓ Produces

LAYER 5
System-Level Circular Outcomes
Strategic value creation from integrated circular SCCT architecture

— Supply Chain Resilience
— Environmental Regeneration
— Circular Value Creation
— Sustained Competitive Advantage

Figure 4: CE-Enabled SCCT Architecture

Layer 1 (Digital Enablers) forms the technological foundation of CE-enabled SCCT. This layer aligns with the first theme identified in the review, highlighting that technologies such as IoT sensors, blockchain, and AI not only support circular flows but also enable the real-time transparency and traceability necessary for circular operations (Agrawal et al., 2021; Khanna et al., 2025). For instance, IoT provides live updates on product location and condition, blockchain maintains immutable records of material provenance and transactions (digital product passports), and AI algorithms process these data to deliver predictive analytics, optimised remanufacturing, dismantling, and recycling pathways. This layer directly addresses technological gaps in product durability and tracking, providing the requisite data infrastructure (Govindan & Hasanagic, 2018).

Layer 2 (SCCT Capabilities) represents the primary functional adaptation of traditional control towers. Moving beyond linear efficiency optimisation, it assumes an active role in circularity management. Capabilities such as Reverse Logistics Orchestration and Closed-Loop Material Planning fulfil the operational requirements of CE frameworks identified in Theme 2 (MahmoumGonbadi et al., 2021; Zhang et al., 2021). Data from Layer 1 is converted into actionable intelligence, enabling predictive risk management to estimate return volumes and end-to-end visibility to determine optimal end-of-life pathways for products, whether resale, refurbishment, or raw material recovery. The dynamic control of reverse flows is what differentiates CE-enabled SCCT from conventional systems.

Layer 3 (Governance & Collaboration) ensures the effective functioning of technological and operational layers. This layer corresponds to the third theme from the review, which emphasises that technological capabilities are insufficient without appropriate organisational structures and partnerships (Berardi & Peregrino de Brito, 2021; Sudusinghe & Seuring, 2022). Components such as Data Sharing Agreements and Partner Trust Scoring mitigate information silos and mistrust across multi-tier networks. This layer coordinates incentives across the network, fostering collaboration necessary for a functioning circular ecosystem and bridging the digital system with the human and organisational dimensions of the supply chain.

Layer 4 (Performance Measurement System) completes the architecture by providing metrics to evaluate and improve organisational performance, as highlighted throughout the literature (Howard et al., 2018; MahmoumGonbadi et al., 2021). This layer enables firms to shift from traditional, economically-focused KPIs towards a triple bottom line. Circularity is quantitatively assessed using metrics such as Resource Recapture Rate and percentage of Secondary Materials in Production, while environmental impact is measured through Lifecycle GHG Emissions. These measures are critical for evaluating the return on CE investments and supporting informed decision-making regarding genuine sustainability outcomes.

The architecture's value lies in the integration across layers. Layer 1 (Digital Enablers) provides the resource base (Resource-Based View) for developing Layer 2 SCCT Capabilities. These capabilities allow firms to sense and respond to disruptions and opportunities in reverse flows through orchestration and planning (Dynamic Capabilities). Finally, Layers 3 (Governance & Collaboration) and 4 (Performance Measurement) constitute the socio-technical system, reducing uncertainty, aligning information processing with capabilities, and guiding the network towards CE outcomes (Socio-Technical Systems & Information Processing Theory).

Implications for Theory

This study has identified, synthesised, and critically evaluated the potential for embedding CE principles within SCCT. By situating the proposed framework within three established management theories, the research contributes to the literature on supply chain management, CE, and sustainability. Although SCCT research predominantly emphasises operations management, empirical studies examining the integration of CE within SCCT remain limited (Burke et al., 2021). This study extends SCCT scholarship by incorporating insights from related CE literature. SCCT is often conceptualised as a comparative mechanism to achieve comprehensive visibility and effective management across complex global supply chains. Notably, circularity is closely linked to supply chain complexity: as supply chains become more intricate, logistics and waste recovery processes also grow in complexity. Given that

control towers are primarily deployed in advanced economies while take-back logistics and (re)manufacturing centres are located in developing regions, the proposed framework provides guidance for implementing SCCT enablers in both contexts (Awan et al., 2022).

The study further advances the Resource-Based View (RBV) by distinguishing digital assets (such as data, IoT infrastructure, and analytics engines) from circular orchestration capabilities embedded in SCCT structures. Whereas RBV traditionally focuses on firm-level resource heterogeneity, the findings indicate that SCCT-enabled circularity depends on inter-organisational alignment of capabilities, shifting the competitive advantage perspective from a firm-centric to a network-centric orchestration approach. This reconceptualisation contributes to emerging discussions on relational and ecosystem-based competitive advantage within circular supply chains.

Implications for Practice

The proposed framework offers practical guidance for practitioners aiming to embed CE principles within SCCT. Its benefits for non-integrated control tower–circularity approaches are evident: the SCCT enablers framework provides a roadmap for circularity, emphasising customers, products, and processes, contingent upon consideration of associated enablers and circular supply chain management directions when redesigning service offerings (Bressanelli et al., 2021). Recent calls for the adoption of circular supply chains highlight the need to integrate key enablers to maximise return on investment, with SCCT serving as a facilitating mechanism.

The framework generates tangible advantages, particularly for managers, including supply chain and logistics managers responsible for coordinating product movements between consolidation and transshipment points (Amir et al., 2022). This research addresses calls for further inquiry into the relationship between SCCT and CE objectives, specifically focusing on embedding CE principles within SCCT (Berardi & Peregrino de Brito, 2021; de Mattos Nascimento et al., 2024). Future research could expand on this work by exploring synergies within the circularity–SCCT framework and applying circular principles in the context of big data analytics-enabled SCCT. By offering a stepwise process and guiding framework for technology selection in SCCT, this study contributes to resolving an issue that has been extensively debated in the literature.

Research Gaps and Future Directions

Regarding theoretical gaps, there is a scarcity of studies specifically focusing on the integration of CE principles with SCCT, particularly in terms of empirical research and case-based analyses. Furthermore, as the SCCT concept is still emerging, current discussions are predominantly centred on retail and distribution networks. Future research should expand these investigations to encompass entire supply chains. Additional areas for inquiry include more complex multi-tier networks, evaluating alternative platforms, calculating ROI, enhancing management practices, monitoring technological advancements, and applying innovative supply chain tools and methodologies.

Methodological gaps suggest the need for employing more diverse research approaches, such as case studies, action research, and mixed methods, while leveraging existing knowledge with appropriate methodological rigor. Concerning industry gaps, the integration of sustainability

considerations within SCCT remains largely absent from the literature, potentially limiting the realisation of the full benefits of control tower concepts in supply chain management. Consequently, industrial practitioners, organisational logistics teams, and policymakers have the opportunity to fully exploit the advantages of embedding CE principles within SCCT. In terms of practical gaps, CE remains an evolving concept, and businesses increasingly require guidance on SCCT implementation to navigate emerging opportunities and challenges in dynamic marketplaces.

CONCLUSION AND RECOMMENDATIONS

This study reconceptualises SCCT from platforms that primarily enhance visibility to circular orchestration systems capable of coordinating regenerative supply networks. By embedding CE principles within SCCT capabilities, the research advances theory in both supply chain digitalisation and CE, offering a structured pathway for transforming linear efficiency-oriented platforms into regenerative coordination architectures. The study further provides an updated overview for enterprise practitioners, assisting them in orienting supply chains towards more sustainable circular practices. It also serves as a foundation for both early-career and experienced researchers to address broader global challenges associated with limiting resource use to levels that the planet can sustainably support. Although existing literature explores macroeconomic, firm-level, and supply chain implications of aligning CE principles with SCCT capabilities, and identifies numerous promising directions in sustainability-oriented research, practical guidance on implementation remains scarce. Consequently, it is currently difficult to position companies on maturity models or to directly relate documented supply chain practices in exemplar cases to theoretical constructs for empirical testing. Based on the preliminary review of integration possibilities and state-of-the-art methods, it is evident that literature detailing practical implementation of these opportunities is lacking. We contend that integrating CE principles with SCCT represents both a significant challenge and a unique opportunity at the enterprise level.

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Appendix A

Supply Chain Control Towers (SCCT), and I4.0 technologies. The strings were adapted to the specific syntax and field tags of each database.

Database	Field Tags & Syntax	Search String
Web of Science	TS = Topic (Title, Abstract, Keywords)	TS=(("circular econom*" OR "closed-loop" OR "reverse logistic*" OR remanufactur* OR refurbish*) AND ("supply chain control tower*" OR "digital control tower*" OR "control tower*" OR "supply chain command center" OR "visibility platform") AND ("i4.0" OR i4.0 OR "digital twin*" OR "cyber-physical system*" OR IoT OR blockchain OR "artificial intelligence" OR "real-time analytics"))
Scopus	TITLE-ABS-KEY = Title, Abstract, Keywords	TITLE-ABS-KEY (("circular econom*" OR "closed-loop" OR "reverse logistic*" OR remanufactur* OR refurbish*) AND ("supply chain control tower*" OR "digital control tower*" OR "control tower*" OR "supply chain command center" OR "visibility platform") AND ("i4.0" OR i4.0 OR "digital twin*" OR "cyber-physical system*" OR IoT OR blockchain OR "artificial intelligence" OR "real-time analytics"))
Google Scholar	[Natural language; terms automatically stemmed]	"CE" "supply chain control tower" "i4.0" visibility blockchain IoT Note: Due to the simplistic and proprietary algorithm of Google Scholar, a complex Boolean string is not effective. The search was performed using a combination of the most critical phrases.