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| RESEARCH ARTICLE

Toward Circular Economy and Intelligent FSCs: A Critical Review of AI-Driven Sustainability Transformation

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| ABSTRACT

The global fashion industry is at a critical juncture, where increasing environmental challenges and rapid digital innovation are reshaping supply chain systems. This study provides a comprehensive review of the evolution of circular and intelligent FSCs by integrating artificial intelligence (AI) with circular economy (CE) principles. Using a narrative synthesis approach, the research analyzes 58 peer-reviewed studies published between 2020 and 2026, focusing on sustainability, supply chain management, and emerging digital technologies. The findings reveal a significant transition from traditional sustainability discourse toward AI-driven, system-level transformation. Technologies such as machine learning (ML), big data analytics, and the Internet of Things (IoT) enhance predictive capabilities, operational efficiency, and resource optimization. However, the analysis also identifies critical limitations, including a persistent gap between the theoretical potential of AI-enabled sustainability and its empirical validation in real-world applications. Furthermore, the literature demonstrates a strong emphasis on environmental sustainability, with comparatively limited attention to social dimensions such as labor conditions and ethical sourcing. To address these challenges, this study proposes the Technology–Sustainability Integration Model (TSIM), a socio-technical framework that conceptualizes sustainable transformation as the alignment and co-evolution of technological and sustainability maturity. The model highlights the importance of integrating digital capabilities with multidimensional sustainability practices to enable fully circular and intelligent supply chains. By synthesizing existing knowledge, identifying key research gaps, and offering a structured conceptual framework, this study contributes to advancing research and practice in sustainable fashion supply chain transformation.

| KEYWORDS

Artificial Intelligence (AI); Circular Economy (CE); Digital Transformation; Fashion Industry; Intelligent Supply Chains; Industry 4.0/5.0; Sustainability Integration; Supply Chain Resilience; Socio-Technical Systems

| ARTICLE INFORMATION

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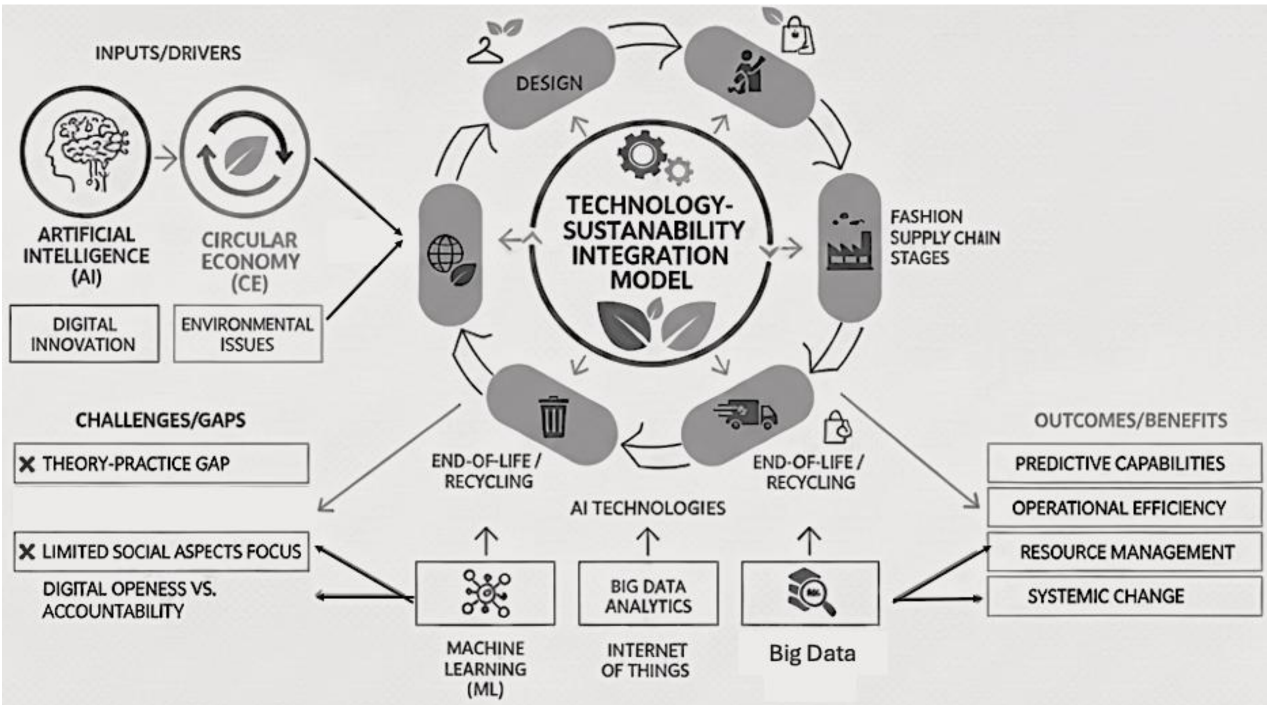

Graphical Abstract

Introduction

The global fashion industry is widely recognized as one of the most environmentally and socially impactful sectors, marked by significant resource use, substantial waste production, and intricate, dispersed supply chain systems. The emergence of fast fashion has exacerbated these issues by hastening production cycles and consumption trends, resulting in considerable environmental harm and societal inefficiencies. Initial studies on FSCs mostly concentrated on evaluating environmental effects using lifecycle methodologies, emphasizing concerns such as carbon emissions, water use, and textile waste. These issues prompted the prioritization of sustainability as a key focus in research and industry, highlighting the need for more responsible production and consumption systems.

The circular economy (CE) is a system in which products, materials, and resources are continuously reused, repaired, remanufactured, and recycled to minimize waste and environmental impact. Circularity advocates for closed-loop systems, resource efficiency, recycling, reuse, and lifespan extension, seeking to replace the conventional linear "take–make–dispose" approach. Despite significant advancements in the conceptualization of circular practices, especially in waste management, recycling technology, and sustainable materials, the execution of CE concepts remains disjointed. Current research often emphasizes discrete phases of the product lifecycle instead of creating cohesive, comprehensive circular supply chain systems.

Simultaneously, the rapid advancement of digital technology has created new opportunities for transforming supply chain processes. The amalgamation of AI, big data analytics, blockchain, and IoT has marked a substantial transition towards data-driven, intelligent supply chains. These technologies provide predictive analytics, demand forecasting, real-time monitoring, and operational optimization, ultimately improving efficiency and responsiveness. Recent research emphasizes that AI is not only a technological tool but a strategic facilitator of sustainable and circular supply chain transformation. This combination of digitization with sustainability signifies a larger paradigm shift from normative sustainability rhetoric to practical and systemic implementation.

Despite these developments, the integration of AI-driven technology with sustainability and CE concepts remains underdeveloped and inconsistent. An exhaustive examination of the literature uncovers several enduring constraints. There exists a substantial disparity between the theoretical potential of AI-driven sustainability and its practical verification inside actual FSCs. Although many studies emphasize AI's capacity to minimize waste, optimize resources, and improve decision-making, substantial industry-specific data and extensive implementation studies are still limited. The research landscape is mostly focused on environmental sustainability, with very little emphasis paid to social aspects such as labour conditions, ethical sourcing, and supply chain equality. This disparity leads to a limited understanding of sustainability that fails to encompass its multifaceted nature. The literature demonstrates a lack of systemic integration between technological innovation and sustainable practices. Digital transformation and sustainability are sometimes seen as parallel or loosely related activities instead of as interconnected elements of a cohesive system. This disconnection is further shown by numerous significant deficiencies, including the tenuous relationship between supply chain resilience and circularity, the division between material innovation and digital supply chain systems, and the inadequate incorporation of consumer behavior into circular models. Moreover, whereas digital technologies improve openness and traceability, they do not automatically guarantee accountability, underscoring the need for governance systems that convert data visibility into sustainable results.

These limitations indicate a broader structural problem in the literature: the lack of a unified framework that systematically links technology capabilities to sustainability goals. Consequently, contemporary research is fragmented across several fields, with technical progress, CE initiatives, and sustainability objectives advancing in isolation rather than through cohesive integration.

Research Gap:

This study finds three main research gaps based on the preceding analysis: ***Empirical Gap:*** Insufficient real-world validation of AI-driven sustainability applications in FSCs, characterized by a predominance of conceptual and review-oriented research. ***Theoretical Gap:*** Absence of a cohesive socio-technical paradigm that harmonizes digital transformation with multidimensional sustainability (environmental, social, and economic). ***System Integration Gap:*** Inadequate end-to-end integration across supply chain phases, characterized by feeble linkages among AI systems, circular processes, customer behavior, and governance frameworks.

Research Aim and Contribution

This research critically evaluates and synthesizes the growing evidence of literature on AI-driven sustainability transformation in FSCs to address the identified gaps. Specifically, it aims to examine the evolution of sustainability and CE principles within FSCs; analyze the role of AI and digital technologies as key enablers of sustainable transformation; identify major tensions, limitations, and research gaps in the existing literature; and develop an integrated conceptual framework to guide future research and practice.

This study makes several key contributions to the emerging field of AI-driven sustainable supply chain transformation in the fashion industry. The paper provides a comprehensive and up-to-date synthesis of interdisciplinary literature at the intersection of AI, CE, and FSCs. By integrating insights from 58 reviewed studies (2020–2026), the research consolidates fragmented knowledge across sustainability science, supply chain management, and digital transformation, offering a structured understanding of how these domains are evolving together. The primary contribution of this study is the development of the Technology–Sustainability Integration Model**,** which conceptualises sustainable transformation as the outcome of the co-evolution and alignment between technological maturity and sustainability maturity. Unlike existing approaches that treat digital transformation and sustainability as parallel or inherently synergistic processes, this model emphasizes that meaningful sustainability outcomes emerge only when both dimensions co-evolve in an integrated manner. This perspective extends existing theories in circular economy and digital transformation by explicitly addressing the problem of misalignment. By adopting a socio-technical perspective, this research advances existing theories in CE, digital transformation, and supply chain management, offering a more holistic understanding of intelligent circular supply chains. Furthermore, the study provides a structured synthesis of current knowledge, identifies critical research frontiers, and delivers strategic insights for academics and practitioners seeking to operationalize sustainability through digital innovation.

Literature Review

Conceptual Foundations of Sustainability and CE in FSCs

The conceptual foundations of sustainability and CE in FSCs have evolved through the contributions of several pioneering scholars rather than a single originator. Early research emerged from growing concerns about environmental degradation, overproduction, and the systemic inefficiencies of fast fashion, with influential contributions from scholars such as Niinimäki et al. (2020) and Kozlowski et al. (2020), who highlighted the environmental footprint of textile systems and advanced lifecycle-based sustainability frameworks. These foundational works positioned sustainability as a critical transformation agenda, emphasizing resource efficiency, lifecycle thinking, and stakeholder responsibility. Building on this, circular economy principles were further developed by key contributors such as Camacho-Otero et al. (2018), who integrated circular consumption perspectives, and Memon et al. (2021), who formalized closed-loop systems, recycling, reuse, and waste minimization within textile supply chains. Subsequent studies reinforced circularity as a dominant sustainability paradigm, focusing on lifecycle extension and resource optimization strategies (De Felice et al., 2023; Parnell et al., 2025; Sharma et al., 2025). However, despite these significant conceptual advancements, the literature remains fragmented, often addressing isolated lifecycle stages rather than achieving full end-to-end supply chain integration (de Koning et al., 2024; Ramírez-Escamilla et al., 2024), highlighting an important gap in the development of cohesive circular fashion systems.

Evolution Toward Digital and AI-Driven Supply Chain Transformation

A significant shift in the literature has occurred since 2022, where sustainability discourse increasingly converges with digital transformation. Earlier conceptual sustainability frameworks have evolved into technologically enabled models integrating Industry 4.0/5.0 technologies (Chiappetta Jabbour et al., 2020; Samuels, 2024). AI, big data analytics, and digital platforms are now positioned as critical enablers of supply chain optimization and sustainability performance (Ahmed et al., 2023; Zamani et al., 2022; Zhang et al., 2023). These technologies facilitate predictive analytics, demand forecasting, and operational efficiency, contributing to more responsive and adaptive supply chain systems (Tsolakis et al., 2022; Gao, 2023). This transition reflects a broader paradigm shift from normative sustainability discourse to operational and system-level transformation, where digital intelligence plays a central role in enabling sustainable practices (Hong & Xiao, 2024; Lopes de Sousa Jabbour et al., 2025).

AI as a Strategic Enabler of Sustainable Supply Chains

The reviewed literature consistently identifies AI as a strategic enabler rather than merely a technical tool. AI-driven systems enhance decision-making capabilities across supply chains, supporting risk mitigation, inventory management, and sustainability optimization (Ahmed et al., 2023; Zhang et al., 2025). AI applications are particularly relevant for predictive demand management, resource optimization, carbon reduction strategies and intelligent manufacturing systems (Zamani et al., 2022; Liu et al., 2024). However, a critical gap persists between theoretical potential and empirical validation. While many studies highlight AI's capacity to reduce waste and improve efficiency, real-world implementation remains limited due to constraints such as data availability, infrastructure readiness, and organizational capabilities (Liu et al., 2024; Lopes de Sousa Jabbour et al., 2025). Thus, AI-enabled sustainability remains largely aspirational, requiring further empirical substantiation through industry-based studies.

Dominance of Environmental Sustainability and Circular Practices

Environmental sustainability dominates the research landscape, with a strong emphasis on lifecycle assessment (LCA), carbon footprint reduction, and resource efficiency (Ahmed et al., 2025; Niinimäki et al., 2020). LCA frameworks provide robust tools for evaluating environmental impacts across production and consumption stages. Circular practices, such as recycling, upcycling, and waste management, are widely explored as mechanisms for reducing environmental burden (Rahaman & Khan, 2024; Shamsuzzaman et al., 2025). These approaches reinforce the importance of transitioning from linear to circular production systems. However, this environmental focus has resulted in a systematic imbalance, where social sustainability dimensions, such as labor rights, ethical sourcing, and equity, are comparatively underrepresented (Sarker et al., 2021). This limitation highlights the need for a more multidimensional sustainability framework that integrates environmental, social, and economic aspects.

Digital Technologies, Transparency, and the Accountability Gap

Blockchain, IoT, and data analytics technologies are increasingly proposed as solutions to improve supply chain transparency and traceability (Gardner et al., 2019; Zrelli & Rejeb, 2024). These technologies enable real-time monitoring and data-driven decision-making across complex supply networks. Despite these advancements, the literature identifies a critical transparency–accountability gap. While digital systems enhance visibility, they do not inherently ensure ethical or sustainable practices (Lopes de Sousa Jabbour et al., 2025). Transparency alone does not translate into accountability without governance mechanisms, regulatory enforcement, and stakeholder pressure. Therefore, digital transparency is recognized as a necessary but insufficient condition for achieving sustainable supply chains.

Interlinkages Between Supply Chain Resilience and Circularity

Recent studies increasingly link sustainability with supply chain resilience, particularly in the post-COVID-19 context (Bui et al., 2021; Kazancoglu et al., 2023). AI-driven systems contribute to resilience by enabling adaptive planning, disruption management, and risk forecasting (Zamani et al., 2022). However, the relationship between resilience and circularity remains underexplored. While circular systems may reduce dependence on virgin resources, they also introduce complexity through reverse logistics and multi-stakeholder coordination (Sarker et al., 2021). The literature suggests that the alignment between resilience and circularity is theoretically assumed but empirically untested, representing a key research gap.

Methodological Trends and Empirical Limitations in Current Research

The methodological composition of the literature is dominated by: systematic reviews, narrative reviews and conceptual frameworks (Al-Okaily et al., 2024; Rejeb et al., 2023; Montag, 2023). While these approaches contribute to theoretical consolidation, they reveal a lack of empirical depth. There is limited availability of longitudinal studies, large-scale implementation evidence and cross-industry comparisons. This indicates that the field is still in a knowledge development and conceptualization phase, where theoretical advancement outpaces practical validation.

System-Level Perspective and the Role of Consumer Integration

Recent literature emphasizes that sustainable transformation must be understood as a system-level transition rather than a production-centric process (Sahakian et al., 2024; Jewitt et al., 2025). Consumer behavior, usage patterns, and post-consumption systems are increasingly recognized as critical components of circular supply chains. Despite this recognition, the integration between AI-driven supply chain systems and consumer-facing circular practices remains limited. This disconnect suggests that achieving circularity requires alignment across production systems, consumption behaviors and digital infrastructures

Material Innovation and the Digital Integration Gap

Material innovation represents another important research stream, focusing on sustainable fibers, biomaterials, and textile waste transformation (Rahman & Forhad, 2021; Zhang et al., 2025). These innovations are essential for enabling circular production systems. However, the literature reveals a significant gap between material science and digital supply chain research. Few studies integrate AI with material lifecycle management, such as automated sorting or predictive degradation analysis (Tu et al., 2024). Bridging this gap is critical for advancing fully integrated circular supply chains.

Synthesis of Key Gaps and Research Directions

The synthesis of the reviewed literature identifies three fundamental tensions:

- *Technological optimism vs. empirical validation*
- *Environmental dominance vs. social sustainability neglect*
- *Conceptual richness vs. system integration gaps*

These tensions indicate that while the vision of AI-enabled circular FSCs is well established, its practical realization remains limited.

Toward an Integrated Socio-Technical Framework: Technology–Sustainability Integration Model

The literature increasingly converges on the need to integrate technological and sustainability dimensions within a unified framework. Existing studies often treat digital transformation and sustainability as parallel processes, leading to misalignment

(Chiappetta Jabbour et al., 2020; Tsolakis et al., 2022). The proposed Technology–Sustainability Integration Model addresses this gap by conceptualizing sustainable transformation as a function of the co-evolution of technological maturity (AI, IoT, digital systems) and sustainability maturity (environmental, social, circular practices). This perspective aligns with socio-technical systems theory and extends CE and digital transformation theories by emphasizing alignment rather than technological accumulation. The literature review demonstrates that most studies are concentrated in either technology-driven but sustainability-shallow systems, or sustainability-led but technologically limited approaches, with limited research achieving full integration. This imbalance highlights a critical research frontier in developing intelligent circular supply chains.

Methodology:

1) *Research Design and Rationale*

This study adopts a structured narrative review with thematic synthesis to examine the intersection of AI, CE, and sustainability in FSCs. Unlike purely descriptive narrative reviews, this approach combines systematic search and structured data extraction with interpretive, theory-driven analysis**,** enabling both comprehensive coverage and critical insight. The choice of a narrative synthesis is appropriate given the emergent and interdisciplinary nature of the research field, where conceptual development, technological innovation, and sustainability discourse are evolving simultaneously. Rather than aiming for statistical aggregation, the study focuses on identifying recurring patterns, theoretical tensions, and integration gaps across the literature.

2) *Search Strategy and Corpus Selection*

The literature corpus was developed through a targeted search of major academic databases, including Scopus, Web of Science, and Google Scholar, covering the period from 2018 to early 2026**.** This timeframe captures the transition from early Industry 4.0 discussions toward more recent Industry 5.0 and AI-driven sustainability paradigms.

The search process was guided by combinations of keywords across three core domains:

- ***Digital technologies****: "artificial intelligence", "machine learning", "data analytics", "blockchain", "IoT"*
- ***Sustainability frameworks****: "circular economy", "circularity", "closed-loop systems", "sustainable supply chain"*
- ***Industry context****: "fashion supply chain", "textile industry", "apparel industry"*

To ensure relevance and analytical focus, studies were selected based on the following inclusion criteria:

- *Peer-reviewed journal articles and high-quality conference papers*
- *Explicit engagement with AI or digital technologies in supply chain contexts*
- *Direct linkage to sustainability and/or circular economy concepts*
- *Relevance to the fashion, textile, or apparel industry*

Studies that lacked clear relevance to these domains or focused solely on unrelated sectors without transferable insights were excluded. Following an iterative screening process, a final corpus of 58 studies was selected. This sample size was considered sufficient to achieve thematic saturation, ensuring adequate representation of key research streams while maintaining analytical depth. Figure 1 depicts the study selection process used in this study.

3) *Data Extraction and Analytical Framework*

To ensure methodological rigor and consistency, a structured data extraction matrix was developed using Excel. Each of the 58 studies was systematically coded across multiple dimensions, including:

- *Research objectives and thematic focus*
- *Methodological approach (conceptual, empirical, modeling, review)*
- *Type of digital technology applied (e.g., AI, IoT, blockchain)*
- *Sustainability dimension addressed (environmental, social, economic)*
- *Supply chain stage and level of integration*
- *Key findings, contributions, and identified limitations*

This structured matrix enabled cross-study comparison and facilitated the identification of recurring patterns and divergences within the literature.

4) Thematic Synthesis and Coding Process

The analysis followed an iterative, inductive thematic synthesis approach. Initial coding focused on identifying recurring concepts, relationships, and inconsistencies across the extracted data. Through repeated comparison and refinement, these codes were grouped into higher-order thematic clusters. Particular attention was given to identifying areas of **"**theoretical friction**"**, where technological capabilities (e.g., AI-driven optimization) did not align with sustainability outcomes (e.g., circularity, social equity). This process led to the emergence of core thematic disjunctions, which serve as the basis for the study's critical analysis. The use of a structured extraction matrix ensured that thematic development was grounded in the reviewed studies, enhancing the transparency and traceability of the analytical process.

5) *Critical Interpretation and Scope*

The objective of this study is to provide a critical and integrative interpretation of the literature rather than a statistically exhaustive or meta-analytic evaluation. The narrative synthesis enables exploration of conceptual relationships, structural gaps, and emerging research trajectories across disciplines. While the approach involves interpretive judgment, efforts were made to ensure balanced representation and analytical consistency through systematic data extraction, iterative coding, and cross-comparison of studies. This methodology is particularly suited to capturing the complex, socio-technical nature of AI-driven sustainability transformation, where technological innovation, organizational processes, and sustainability objectives interact in dynamic and often non-linear ways.

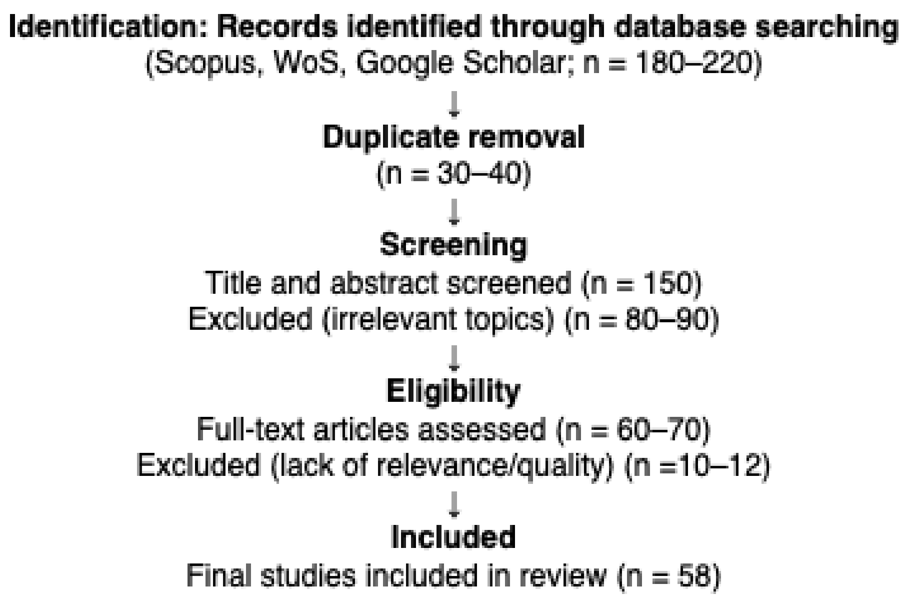

Figure 1: Flow Chart of the Study Selection Process

Results

Statistical Distribution of the Reviewed Studies:

The methodological composition of the reviewed literature provides important insights into the maturity of the research field. Table 1 presents the distribution of the 58 selected studies across different methodological approaches. The chronological distribution of the reviewed studies reveals a significant increase in publications post-2022, indicating growing scholarly interest in AI-enhanced sustainable supply chains (Figure 2). As shown in Table 1, the methodological composition of the reviewed literature is heavily skewed toward conceptual and review-based studies. Conceptual and applied research accounts for the largest share (37.9%), followed by systematic reviews (20.7%) and narrative or critical reviews (15.5%). In contrast, empirical studies are notably scarce, representing only 1.7% of the sample. This imbalance indicates that the field remains largely in a conceptual and theory-building phase, with limited real-world validation of AI-driven sustainability applications in FSCs.

Table 1: Methodological Distribution of Reviewed Studies (n = 58)

Methodological Category	Number of Studies	Percentage (%)
Conceptual / Applied Research	22	37.9%
Systematic Review	12	20.7%
Narrative / Critical Review	9	15.5%
Framework / Decision Support	4	6.9%
Modeling / Decision Analysis	3	5.2%
Review with Framework / Research Agenda	3	5.2%
Bibliometric Analysis	1	1.7%
Empirical Study	1	1.7%
Benchmarking Study	1	1.7%
Edited Book / Handbook	1	1.7%
Total	**58**	**100%**

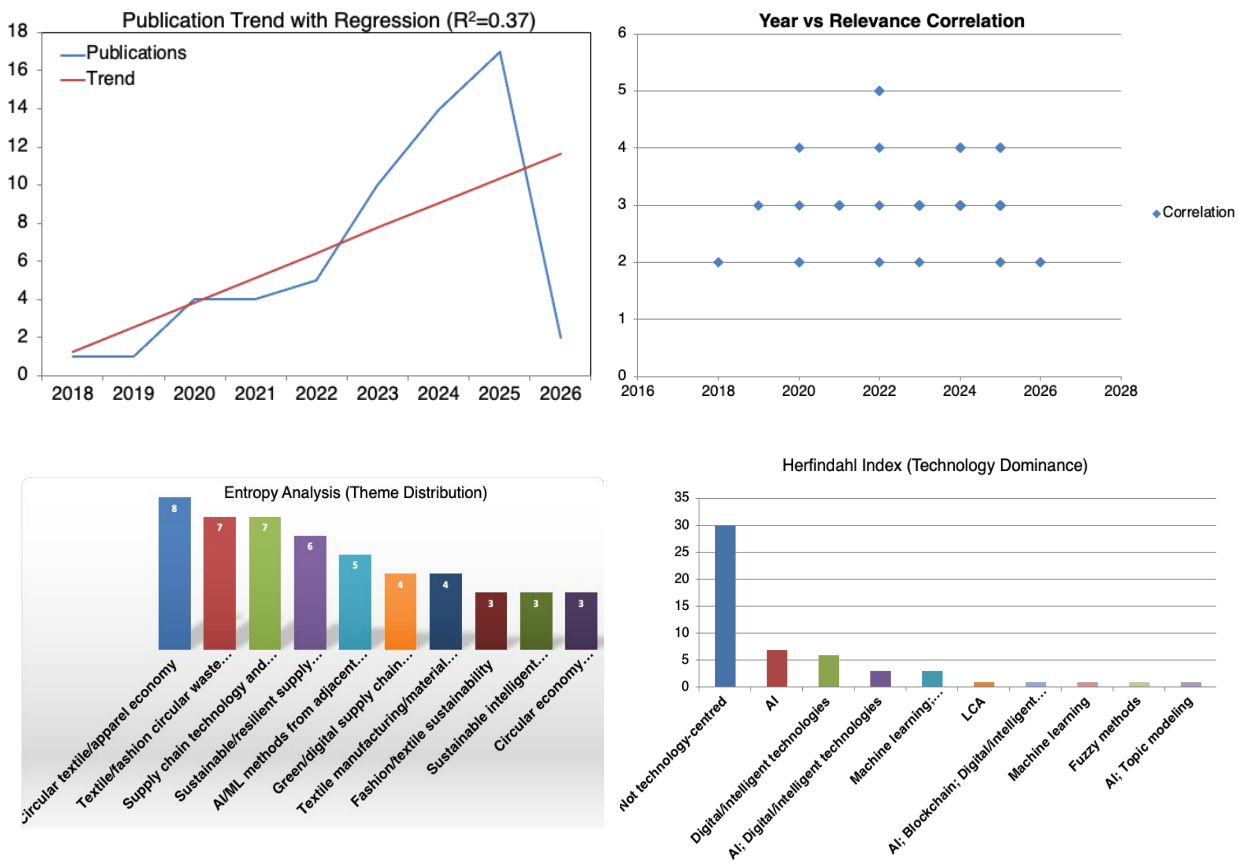

Figure 2. Multi-dimensional thematic and chronological analysis of the analyzed literature. The top-left panel depicts the chronological progression of publications, indicating a significant rise in research effort in recent years, accompanied by a comparison trend line. The upper-right panel illustrates the distribution of studies across thematic categories, emphasizing the relative concentration of research in principal fields. The bottom-left panel presents an entropy-based study of theme distribution, highlighting the predominance of key research domains such as circular economy, sustainability, and AI integration, while demonstrating less variety in emerging or specialized subjects. The bottom-right panel illustrates the proportional weight of each subject, highlighting a strong emphasis on environmental sustainability and circular processes, while social sustainability is represented to a lesser extent.

6) Thematic Analysis of Reviewed Studies

The thematic synthesis of the 58 reviewed studies reveals that, despite significant conceptual advancement in AI-enabled circular supply chains, the transition toward “intelligent circularity” remains constrained by four recurring structural disjunctions. These themes emerged from iterative coding of the literature corpus, in which patterns of convergence and divergence were identified across technological, sustainability, and system-integration dimensions.

- ***The Empirical Implementation Gap: Technological Optimism vs. Industrial Reality***

A dominant pattern across the reviewed literature is the imbalance between conceptual advancement and empirical validation**.** A substantial proportion of studies, particularly those published after 2022, emphasize the theoretical potential of AI-driven sustainability solutions, including predictive analytics for demand forecasting, carbon optimization models, and intelligent production systems (e.g., Liu et al., 2024; Zhang et al., 2025). However, only a limited subset of the reviewed studies provides robust empirical or longitudinal evidence demonstrating large-scale implementation within real-world FSCs. Most contributions remain confined to simulation models, conceptual frameworks, or pilot-level applications. This imbalance creates an implementation gap, where technological feasibility is well articulated, but practical scalability remains largely untested. As a result, the literature offers a sophisticated conceptual “blueprint” for intelligent circular systems but provides insufficient evidence of their operational viability in the highly volatile, demand-sensitive context of global FSCs.

- ***The Dimensional Imbalance: Environmental Dominance and Social Marginalization***

The analysis further reveals a systematic imbalance in sustainability dimensions**.** The majority of the reviewed studies focus predominantly on environmental performance indicators, such as carbon emissions, resource efficiency, lifecycle assessment, and waste reduction (e.g., Niinimäki et al., 2020; Ahmed et al., 2025). In contrast, social sustainability dimensions—including labor conditions, ethical sourcing, worker welfare, and supply chain equity—are addressed in only a limited number of studies (e.g., Sarker et al., 2021). This indicates that sustainability is frequently operationalized as a technical optimization problem, rather than as a multidimensional socio-technical construct.

This imbalance raises a critical concern: advancing AI-enabled circular systems risks reinforcing environmentally efficient yet socially inequitable production models. Without integrating social indicators into digital and circular frameworks, the transition toward sustainability may remain partial and structurally incomplete**.**

- ***The Accountability Gap: Transparency Without Governance***

A third recurring theme concerns the distinction between technological transparency and ethical accountability. Many studies highlight the role of blockchain, IoT, and data analytics in enhancing supply chain visibility and traceability (e.g., Tsolakis et al., 2022; Lopes de Sousa Jabbour et al., 2025). While these technologies significantly improve data availability and monitoring capabilities, the synthesis indicates that transparency does not inherently translate into accountability. Only a small proportion of the reviewed literature explicitly addresses the governance mechanisms required to convert visibility into enforceable ethical practices.

This results in an accountability gap, where digital systems function primarily as passive recording infrastructures rather than active mechanisms for ensuring compliance, responsibility, or systemic change. Consequently, transparency initiatives risk becoming symbolic or performative unless embedded within broader institutional, regulatory, and stakeholder-driven governance frameworks.

- ***The Integration Gap: Disconnection Between Material Innovation and Digital Intelligence***

The final major disjunction identified in the literature is the lack of integration between material innovation and digital supply chain systems**.** A significant body of research focuses on developing sustainable materials, circular fibers, and textile recycling technologies (e.g., Rahman & Forhad, 2021; Zhang et al., 2025). In parallel, another stream emphasizes AI-driven optimization, forecasting, and supply chain intelligence (e.g., Zamani et al., 2022). However, only a limited number of studies explicitly link these domains.

This separation creates a **"**silo effect**"**, where advancements in material science are not effectively integrated into digital decision-making systems. As a result, circular economy initiatives remain fragmented, preventing the realization of fully closed-loop systems in which material properties, lifecycle data, and AI-driven processes co-evolve. Bridging this gap is critical, as the effectiveness of intelligent circular systems depends on the synchronization of physical material flows and digital information systems. To further explicate the cross-domain inconsistencies and research gaps, a comparative thematic synthesis is presented in Table 2. Figure 3 shows a cross-dimensional mapping of technologies and sustainability objectives, revealing a strong concentration of research linking AI and digital technologies to environmental performance, while comparatively limited attention is given to social sustainability dimensions.

Table 2: Comparative Analysis of the Reviewed Studies

Thematic Domain	Dominant Focus in Literature	Key Contributions	Critical Limitations	Contradictions / Tensions	Research Gap
AI & Digital Intelligence	Predictive analytics, optimization, automation (Ahmed et al., 2023; Zamani et al., 2022; Zhang et al., 2023)	Enhances forecasting, efficiency, and decision-making	Limited real-world implementation evidence	Strong claims of sustainability impact vs weak empirical validation	Need for longitudinal and industry-based studies
CE in Fashion	Recycling, upcycling, lifecycle extension (Parnell et al., 2025; Sharma et al., 2025; Rahaman & Khan, 2024)	Establishes circularity as core sustainability strategy	Fragmented across lifecycle stages (materials, waste, logistics)	Circularity assumed beneficial without systemic validation	Integrated circular supply chain models lacking
Environmental Sustainability	Carbon reduction, resource efficiency, LCA (Ahmed et al., 2025; Niinimäki et al., 2020)	Strong measurement frameworks and environmental metrics	Overemphasis on environmental indicators	Environmental gains may not align with social outcomes	Need for multi-dimensional sustainability models
Social Sustainability	Limited focus; labor, ethics (Sarker et al., 2021)	Highlights worker vulnerability and supply chain inequities	Marginalized in majority of studies	Sustainability framed as environmental rather than socio-technical	Integration of social indicators into AI/circular models
Digital Transparency & Traceability	Blockchain, IoT, data systems (Hong & Xiao, 2024; Tsolakis et al., 2022)	Improves visibility and traceability	Data ≠ accountability	Transparency does not guarantee ethical compliance	Governance frameworks needed to link data to action
Supply Chain Resilience	Risk mitigation, adaptability (Bui et al., 2021; Kazancoglu et al., 2023)	Positions AI as resilience enabler	Limited exploration of circularity-resilience relationship	Circular systems may increase complexity	Empirical testing of circular-resilient systems
Material Innovation	Sustainable fibers, biomaterials (Rahman & Forhad, 2021; Zhang et al., 2025)	Enables physical basis for circularity	Disconnected from digital systems	Material innovation vs supply chain digitalization gap	Integration of AI with material lifecycle management
System-Level Transition	Holistic sustainability systems (Jewitt et al.,	Expands scope beyond	Weak integration with AI-	Consumer-side circularity under-linked	Need for end-to-end

	2025; Sahakian et al., 2024)	production to consumption	driven supply chains	to digital systems	system integration

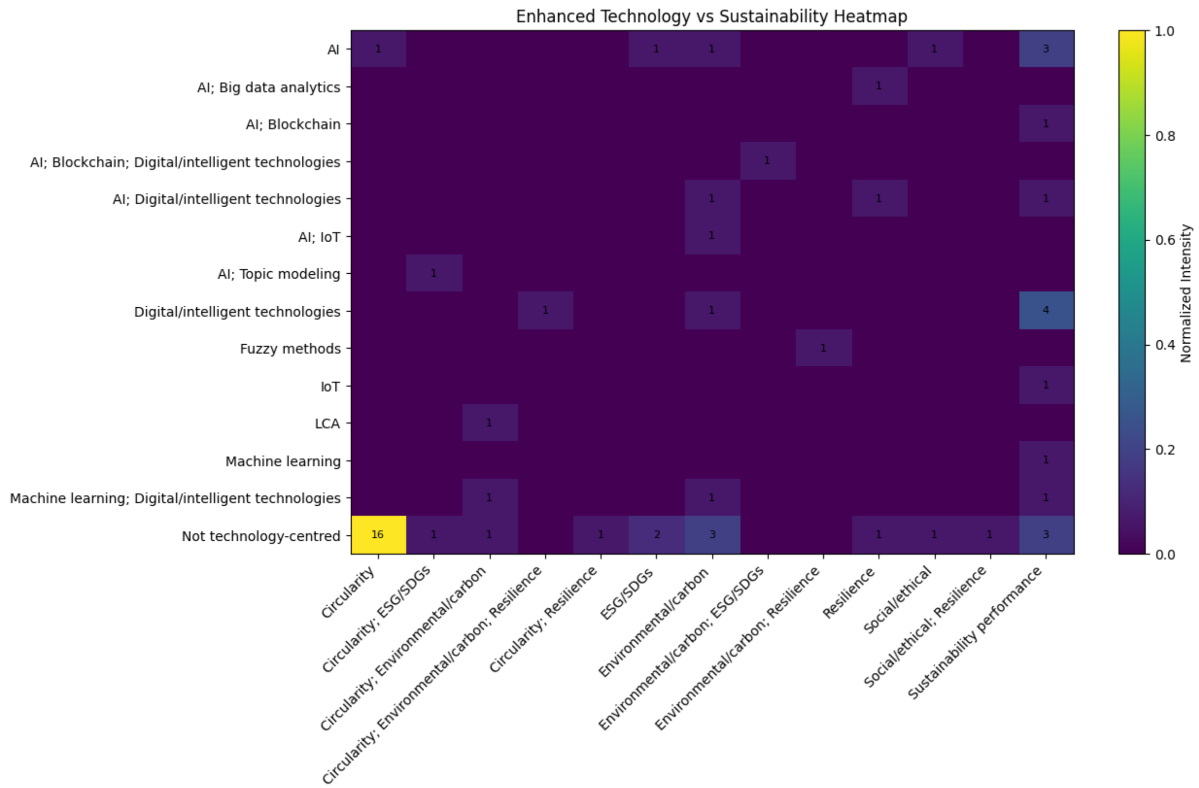

Figure 3. Enhanced technology–sustainability integration heatmap of reviewed studies. The heatmap shows the cross-dimensional distribution of technical applications and sustainability goals in the reviewed literature. AI, ML, blockchain, IoT, and digital/intelligent systems are on the vertical axis, while CE practices, resource efficiency, environmental sustainability, social sustainability, and supply chain resilience are on the horizontal axis. Color intensity shows how often and strongly various technologies are linked to sustainability topics in reviewed studies. The picture shows that AI and digital technologies are well connected with environmental sustainability and CE goals, while social sustainability is less integrated. This trend highlights the literature's imbalance and the need for more holistic, multidimensional integration of technology and sustainability in fashion supply chain studies.

These findings suggest that while the vision of AI-enabled circular FSCs is conceptually well established, its practical realization remains constrained by insufficient empirical grounding, fragmented system integration, and a narrow interpretation of sustainability. These structural limitations underscore the need for a unified socio-technical framework that systematically aligns technological capabilities with multidimensional sustainability objectives. In response, the following section develops the TSIM, which conceptualizes sustainable transformation as a process of co-evolution between technological maturity and sustainability maturity across FSCs.

TSIM: a dual-maturity analytical framework in Fashion Supply Chain

Definition: The TSIM is a dual-maturity analytical framework that conceptualizes sustainable transformation in FSCs as the outcome of the co-evolution and alignment between technological maturity and sustainability maturity. Rather than assuming a linear or automatically synergistic relationship between digitalization and sustainability, the model argues that meaningful sustainability outcomes emerge only when advanced technological systems are systematically integrated with multidimensional sustainability practices. The model is built upon two core dimensions:

(i) ***Technological Maturity:*** The extent to which advanced digital technologies such as AI, IoT, blockchain, ML, and data analytics are integrated into supply chain operations and decision-making systems

(ii) ***Sustainability Maturity:*** The degree to which environmental, social, economic, and circular economy principles are embedded across supply chain processes and governance structures.

The central proposition of TSIM is that sustainable transformation is not achieved through technological advancement alone, nor through isolated sustainability initiatives. Instead, sustainability performance depends on the degree of alignment between technological capabilities and sustainability integration across supply chain systems. Consequently, organizations with high technological maturity but weak sustainability integration may achieve operational efficiency without meaningful sustainability outcomes, while sustainability-oriented systems lacking digital capabilities may struggle with scalability, coordination, and real-time optimization. Fully intelligent circular supply chains emerge only when both dimensions co-evolve simultaneously within an integrated socio-technical architecture.

Theoretical Basis of the TSIM:

Socio-Technical Systems (STS)Theory: The primary theoretical foundation of TSIM is STS theory, which conceptualizes organizational transformation as the interaction between technological infrastructures, organizational processes, governance systems, and human actors. From this perspective, sustainable supply chains cannot be achieved solely through technological adoption or environmental policy reforms in isolation. Instead, sustainability emerges through the joint optimization and alignment of technical and social subsystems. This theoretical lens supports the model's central argument that intelligent circular systems require coordinated integration between digital technologies, sustainability practices, and governance mechanisms. Recent literature also emphasizes that sustainable supply chain transformation depends on the coordinated integration of digital technologies, organizational adaptation, and sustainability practices rather than isolated technological adoption (Chiappetta Jabbour et al., 2020; Tsolakis et al., 2022; Ahmed et al., 2023; Kazancoglu et al., 2023). From this perspective, TSIM conceptualizes sustainability as a socio-technical alignment process in which technological and sustainability capabilities must co-evolve simultaneously.

Resource-Based View (RBV) and Dynamic Capabilities: This theory positions technological resources and digital competencies as strategic capabilities that enable firms to achieve competitive advantage. Within this framework, advanced digital technologies such as AI, ML, predictive analytics, and IoT systems are viewed as dynamic organizational capabilities that enhance supply chain responsiveness, adaptability, and operational efficiency (Zamani et al., 2022; Zhang et al., 2023). However, TSIM extends the RBV perspective by arguing that technological capabilities alone are insufficient to generate sustainable outcomes unless strategically aligned with environmental and social sustainability objectives. This argument is supported by studies showing that many digitally advanced supply chains remain weakly integrated with circular economy practices and sustainability governance mechanisms (Samuels, 2024; Lopes de Sousa Jabbour et al., 2025). Consequently, TSIM challenges efficiency-oriented interpretations of digital transformation by emphasizing capability alignment rather than technological accumulation.

CE Theory: TSIM also builds upon CE theory, which advocates the transition from linear "take–make–dispose" production systems toward regenerative and closed-loop systems emphasizing recycling, reuse, resource efficiency, and lifecycle extension (Niinimäki et al., 2020; Memon et al., 2021; Parnell et al., 2025). Recent studies further demonstrate that CE practices such as recycling, upcycling, waste reduction, and circular material flows are increasingly positioned as core sustainability strategies within FSCs (Rahaman & Khan, 2024; Sharma et al., 2025). TSIM further extends this CE theory by integrating digital capability considerations into lifecycle-based sustainability systems, arguing that fully circular supply chains require synchronization between material flows and intelligent information systems. However, the literature also identifies substantial fragmentation across lifecycle stages and limited integration between material circularity and intelligent digital infrastructures (de Koning et al., 2024; Ramírez-Escamilla et al., 2024).

Digital Transformation (DT) Theory: Finally, the framework contributes to DT theory by critically challenging techno-deterministic assumptions that technological advancement inherently produces sustainability improvements. Existing DT research frequently positions AI, Industry 4.0/5.0 technologies, and intelligent automation as drivers of operational optimization and competitive advantage (Samuels, 2024; Gao, 2023). While these technologies enhance efficiency and predictive capabilities, empirical evidence suggests that DT does not automatically translate into sustainable outcomes. Several studies indicate that technologically advanced supply chains often prioritize efficiency, automation, and performance optimization without adequately embedding environmental, social, or circular economy objectives (Zamani et al., 2022; Zhang et al., 2023). Moreover, research on digital transparency systems demonstrates that technologies such as blockchain and IoT improve visibility and traceability but do not inherently ensure accountability or ethical compliance (Hong & Xiao, 2024; Lopes de Sousa Jabbour et al., 2025). TSIM therefore reframes DT as a conditional, alignment-dependent process, in which sustainability outcomes depend on the extent to which digital capabilities are systematically integrated with sustainability governance and CE practices.

Quadrant-level interpretation of the TSIM Theories

Why Quadrant-level: TSIM quadrant-level interpretation (Figure 4) organizes the reviewed literature into four analytical quadrants based on the interaction between technological maturity and sustainability maturity. This provides a structured lens for interpreting the uneven evolution of research at the intersection of DT and sustainability in FSCs, revealing a pronounced structural imbalance in the literature.

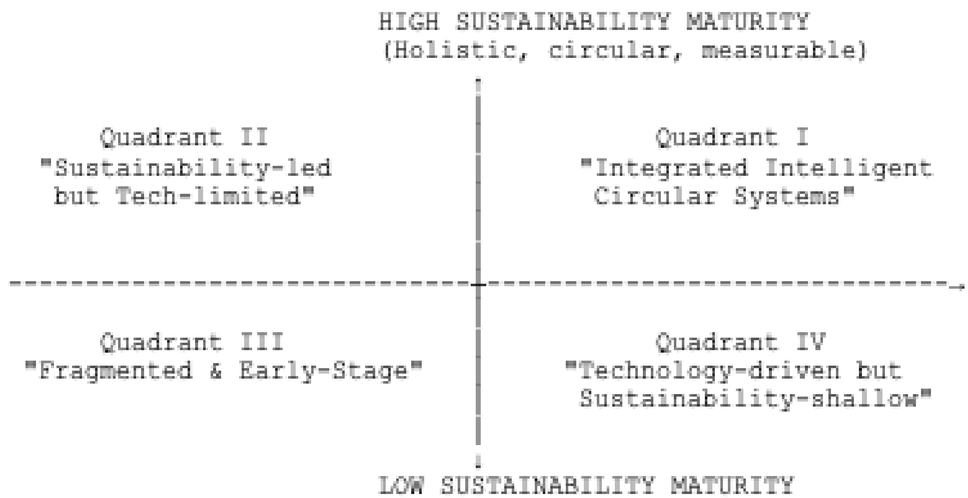

Figure 4: Analytical framework of TSIM in fashion supply chain research.

Quadrant I: *Integrated Intelligent Circular Systems (High Technology – High Sustainability)*

Quadrant I represents the ideal and most advanced configuration, in which digital technologies and sustainability practices are fully integrated into intelligent circular supply chains. Systems in this quadrant combine AI-driven optimization, real-time data infrastructures, circular economy strategies, governance mechanisms, and multidimensional sustainability objectives. This quadrant aligns closely with STS theory because sustainable transformation emerges through the coordinated alignment of technological, organizational, and governance systems. Studies positioned in this quadrant (e.g., Ahmed et al., 2023; Hong & Xiao, 2024; Lopes de Sousa Jabbour et al., 2025) highlight the potential of integrating AI-driven decision systems with CE strategies and governance mechanisms, although empirical validation remains limited.

B. ***Quadrant II:*** *Sustainability-Led but Technology-Limited Systems (Low Technology – High Sustainability)*

Quadrant II represents sustainability-oriented systems that prioritize CE principles, lifecycle assessment, recycling, and environmental responsibility but demonstrate limited digital integration. These systems typically rely on institutional reforms, policy interventions, and resource-efficiency practices rather than advanced AI-driven infrastructures. This quadrant reflects ecological modernization theory, which assumes that environmental improvements can be achieved through process redesign and sustainability-oriented governance even without sophisticated digital systems (Niinimäki et al., 2020; Rahaman & Khan, 2024; Ramírez-Escamilla et al., 2024). However, limited technological integration constrains scalability, coordination, and operational responsiveness.

C. ***Quadrant III:*** *Fragmented and Early-Stage Systems (Low Technology – Low Sustainability)*

Quadrant III represents fragmented or exploratory research characterized by weak technological integration and limited sustainability relevance. Studies in this category often involve isolated experimentation, conceptual exploration, or applications transferred from unrelated industries without being systematically integrated into FSCs (e.g., Afsana, 2022; Imtiaz et al., 2025;

Munni & Mashaka, 2026). This quadrant aligns with innovation diffusion theory in its early adoption phase, where technologies and sustainability concepts remain immature, disconnected, or underdeveloped.

D. ***Quadrant IV:*** *Technology-Driven but Sustainability-Shallow Systems (High Technology – Low Sustainability)*

Quadrant IV represents technologically advanced systems that prioritize operational efficiency, forecasting, automation, and competitive advantage without meaningful integration of sustainability objectives. Many recent AI-driven supply chain studies fall into this category, where technological sophistication is high but environmental and social sustainability considerations are only weakly embedded (Zamani et al., 2022; Samuels, 2024; Zhang, Yang, & Yang, 2023). This quadrant is best explained by the RBV and efficiency-oriented digital transformation logic, in which firms deploy digital technologies primarily as strategic resources for efficiency and market advantage rather than for systemic sustainability transformation. The dominance of this quadrant in the literature highlights a critical limitation of techno-centric digital transformation approaches.

Collectively, these four quadrants demonstrate that sustainable transformation depends not on the independent advancement of technology or sustainability, but on their systematic alignment within a unified socio-technical framework. **Table 3** presents a detailed comparative characterisation of the four quadrants, highlighting their conceptual positioning, underlying theoretical assumptions, and associated research gaps.

Table 3: Comparative Analysis of the Four Quadrants of the TSIM

Dimension	**Quadrant I: Integrated Intelligent Circular Systems (High Tech – High Sustainability)**	**Quadrant II: Sustainability-led but Technology-limited Systems (Low Tech – High Sustainability)**	**Quadrant III: Fragmented and Early-Stage Systems (Low Tech – Low Sustainability)**	**Quadrant IV: Technology-driven but Sustainability-shallow Systems (High Tech – Low Sustainability)**
Core Focus	Alignment of AI, circular economy, and sustainability outcomes	Environmental sustainability and circular practices	Isolated technological or methodological exploration	Technological advancement and operational efficiency
Conceptual Position	Emerging, ideal state of fully integrated systems	Traditional sustainability paradigm	Peripheral or underdeveloped research areas	Dominant contemporary paradigm
Technology Maturity	High (integrated, scalable, system-wide deployment)	Low (minimal or no digital integration)	Low (experimental or unrelated applications)	High (advanced AI, IoT, automation systems)
Sustainability Maturity	High (holistic: environmental + social + economic)	High (primarily environmental)	Low (limited sustainability relevance)	Low (efficiency-focused, weak sustainability linkage)
Supply Chain Integration	End-to-end integration (design → production → consumption → reverse logistics)	Partial integration (focused on production or waste stages)	Fragmented, disconnected systems	Strong operational integration but weak circular linkage
CE Integration	Fully embedded (closed-loop, lifecycle-based systems)	Strong but limited to specific stages (e.g., recycling, materials)	Weak or absent	Limited or superficial
Key Strengths	Holistic, scalable, future-ready systems	Strong sustainability foundations and environmental rigor	Methodological diversity and innovation potential	High efficiency, automation and technological advancement
Role of AI / Digital Technologies	Strategic enabler of circular decision-making and lifecycle optimization	Minimal role or absent	Experimental or transferred from other sectors	Operational optimization (forecasting, automation, efficiency)

Sustainability Scope	Multi-dimensional (environmental, social, economic)	Environmentally focused	Narrow or undefined	Primarily efficiency-driven with indirect environmental effects
Transparency & Governance	High (traceability + accountability + regulatory alignment)	Moderate (conceptual transparency)	Low (not addressed)	High data visibility but weak accountability mechanisms
Critical Limitations	Limited empirical validation; mostly conceptual	Lack of scalability and digital integration	Low relevance to core research domain	Weak linkage between technology and sustainability outcomes
Underlying Assumptions	Technology and sustainability can be fully aligned	Sustainability can be achieved without advanced digital systems	Early-stage experimentation will evolve into maturity	Technological advancement leads to sustainability improvements
Major Tensions	Conceptual integration vs real-world feasibility	Strong theory vs weak implementation	Low impact vs exploratory innovation	Efficiency gains vs sustainability outcomes
Research Gap	Need for empirical validation and real-world implementation	Need for digital integration into sustainability systems	Need for domain-specific relevance and integration	Need to embed sustainability metrics into technological systems
Future Direction	Development of intelligent, circular, and resilient supply chain ecosystems	Digitization of sustainability frameworks	Integration into broader sustainability–technology discourse	Transition toward sustainability-aligned digital systems
Typical Literature Examples	Ahmed et al. (2023); Lopes de Sousa Jabbour et al. (2025); Hong & Xiao (2024)	Niinimäki et al. (2020); Kozlowski et al. (2020); Parnell et al. (2025)	Afsana (2022); Imtiaz et al. (2025); Munni & Mashaka (2026)	Zamani et al. (2022); Samuels (2024); Zhang et al. (2023)

II. Theoretical Implications of the TSIM in FSCs

A. *TSIM as a Structural Interpretation of Sustainability*

TSIM shifts the theoretical understanding of sustainability in FSCs from an operational perspective toward a structural perspective. Rather than evaluating sustainability through isolated practices such as recycling, efficiency improvement, or waste reduction, the model conceptualizes sustainability as a system-level organizational condition emerging from the interaction between technological capability, governance structures, and lifecycle coordination. This perspective enables sustainability to be interpreted not as a collection of environmental initiatives, but as an integrated structural property of supply chain systems (Niinimäki et al., 2020; Chiappetta Jabbour et al., 2020; Tsolakis et al., 2022)..

B. *Introducing Imbalance as an Analytical Condition*

A major theoretical implication of TSIM is the introduction of imbalance as a core analytical condition within sustainable supply chain transformation. The model demonstrates that technological advancement and sustainability development do not necessarily progress simultaneously, creating structurally uneven systems. This perspective provides a new explanation for why digitally advanced organizations may still demonstrate weak sustainability performance, while sustainability-oriented systems may struggle with scalability and operational coordination. Consequently, TSIM reframes sustainability failure not simply as managerial inefficiency, but as a condition of structural asymmetry between different organizational maturity dimensions (Zamani et al., 2022; Samuels, 2024; Lopes de Sousa Jabbour et al., 2025).

C. *Reconceptualizing Circularity as a Dynamic System*

TSIM also extends the theoretical understanding of circularity by framing it as a dynamic, adaptive system rather than a static resource recovery process. Within the model, circularity depends on continuous coordination between information flows, decision systems, governance processes, and material lifecycles. This perspective moves circular economy theory beyond linear lifecycle management approaches and contributes to the emerging concept of intelligent circular systems within FSC research (Memon et al., 2021; Parnell et al., 2025; Hong & Xiao, 2024; Tsolakis et al., 2022).

D. *Advancing a Multi-Dimensional Evaluation of Supply Chain Maturity*

Another important implication of TSIM is the development of a multidimensional framework for evaluating supply chain transformation. Existing research often measures organizational progress primarily through technological sophistication or environmental performance indicators. TSIM broadens this evaluative perspective by demonstrating that supply chain maturity depends on the simultaneous development of technological, sustainability, organizational, and governance capabilities. This creates a more comprehensive analytical basis for examining long-term sustainable transformation within global fashion supply chains (Ahmed et al., 2025; Sarker et al., 2021).

E. *Providing a New Analytical Lens for Future Research*

Finally, TSIM contributes a flexible analytical architecture for future supply chain research by enabling comparative analysis across different transformation pathways. The quadrant structure of the model allows researchers to classify organizations according to varying levels of technological and sustainability maturity, thereby supporting a more systematic examination of structural differences across supply chain systems. As a result, the model establishes a stronger conceptual foundation for future empirical, interdisciplinary, and longitudinal research on intelligent circular supply chains (Chiappetta Jabbour et al., 2020; Kazancoglu et al., 2023; Tsolakis et al., 2022).

Operationalising the Technology–Sustainability Integration Model in Practice

The TSIM provides a pragmatic framework for facilitating sustainable transformation in FSCs by highlighting the congruence between digital capabilities and sustainability goals. It serves as a diagnostic tool to assess organizational standing in terms of technical and sustainability maturity factors. Research indicates that several organizations now function inside technology-oriented but sustainability-deficient frameworks, whereby digital investments emphasize efficiency rather than sustainability results (Zamani et al., 2022; Samuels, 2024). The methodology allows managers to recognize misalignments and design focused initiatives that include sustainability factors into digital infrastructures.

- ***Embedding Lifecycle Intelligence into Digital Decision Systems***

A key application of this framework lies in the incorporation of lifecycle assessment (LCA) metrics into AI-driven decision-making systems. Despite LCA offering comprehensive methods for assessing environmental consequences (Ahmed et al., 2025; Niinimäki et al., 2020), its integration into real-time operating systems is still constrained. Integrating lifetime indicators into AI-driven planning, sourcing, and forecasting processes allows organizations to enhance both efficiency and environmental performance (Tsolakis et al., 2022; Zhang et al., 2025).

- ***Aligning AI Capabilities with Circular Resource Flows***

The framework further supports aligning AI-driven optimisation with CE practices, particularly in demand forecasting, inventory control, and reverse logistics. While AI has demonstrated potential to improve responsiveness and reduce waste (Ahmed et al., 2023; Liu et al., 2024), its integration into circular systems remains underdeveloped. The model facilitates the transition toward closed-loop supply chains by linking technological maturity with circular resource management strategies (Parnell et al., 2025; Sharma et al., 2025).

- ***Integrating Transparency with Governance and Accountability***

Digital technologies such as blockchain and IoT enhance traceability and visibility across complex supply chains (Hong & Xiao, 2024; Zrelli & Rejeb, 2024). However, transparency alone does not ensure accountability or ethical compliance (Lopes de Sousa Jabbour et al., 2025). The model emphasises the need to embed these technologies within governance frameworks that include regulatory alignment, stakeholder oversight, and performance accountability mechanisms, thereby translating data visibility into actionable sustainability outcomes.

- ***Advancing Social Sustainability Integration***

F. The framework also tackles the inadequate representation of social sustainability in current supply chain procedures. Although environmental factors predominate contemporary research, aspects such as labor conditions, ethical sourcing, and equality are inadequately included (Sarker et al., 2021). Integrating social indicators into digital monitoring and decision-making systems fosters a more holistic and equitable approach to sustainability.

- ***Enabling Strategic Transition Toward Integrated Circular Systems***

From a strategic perspective, the model provides guidance on transitioning between maturity levels, supporting the shift from fragmented or efficiency-driven systems toward fully integrated, intelligent circular supply chains. This transition requires not only technological adoption but also organisational capability development, cross-functional integration, and stakeholder collaboration (Chiappetta Jabbour et al., 2020; Kazancoglu et al., 2023). Ultimately, the framework reinforces that sustainable transformation is a socio-technical process in which meaningful outcomes emerge from the alignment of technology, sustainability practices, and governance structures. As illustrated in Figure 5, the Technology–Sustainability Integration Model provides a structured pathway for aligning digital capabilities with sustainability objectives in FSCs.

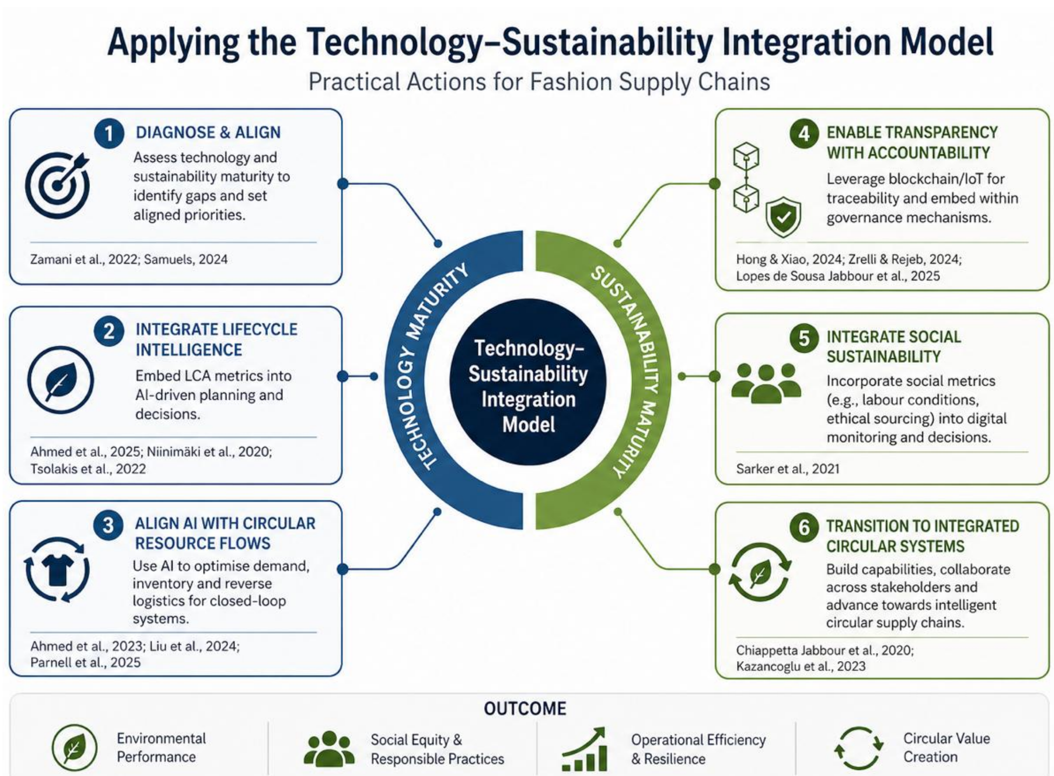

Figure 5. Practical application of the Technology–Sustainability Integration Model in FSCs.

Conclusion

This study provides a structured narrative synthesis of the emerging relationship among AI, CE, and sustainability within FSCs. By reviewing and thematically analyzing 58 interdisciplinary studies published between 2020 and 2026, the paper demonstrates a clear transition in the literature from conventional sustainability-oriented approaches toward digitally enabled and system-level transformation perspectives. Across the reviewed studies, AI increasingly emerges as a strategic enabler of predictive decision-making, operational adaptability, resource optimization, and intelligent circular supply chain management. The thematic synthesis further identifies four major structural disjunctions that continue to constrain sustainable transformation within FSCs: the gap between technological potential and empirical implementation, the dominance of environmental sustainability over social dimensions, the disconnect between transparency and accountability, and the fragmentation between circular practices and digital supply chain systems. These findings indicate that, despite rapid technological advancement, the development of intelligent circular supply chains remains conceptually fragmented and operationally uneven. To address these limitations, the study proposes the TSIM, which conceptualizes sustainable transformation as the co-development of technological maturity and sustainability maturity within a unified socio-technical framework. The model contributes to existing literature by integrating DT, CE, governance, and multidimensional sustainability into a single analytical structure. In doing so, TSIM extends current theoretical perspectives beyond efficiency-centred digitalization and material-centred circularity toward a more systemic understanding of intelligent circular supply chains. The study also highlights several important directions for future research. Greater empirical validation is needed through industry-based case studies, longitudinal investigations, and cross-sector comparative analyses to examine how AI-enabled sustainability systems function in practice. Future research should additionally strengthen the integration of social sustainability, consumer behavior, governance mechanisms, and material innovation within digitally enabled circular supply chain systems. Overall, the findings suggest that sustainable transformation in the fashion industry depends not only on technological advancement but on the capacity to systematically integrate digital capabilities, circular practices, and sustainability objectives across interconnected supply chain ecosystems.

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