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A SYSTEMATIC LITERATURE REVIEW ON BUILDING RESILIENT SUPPLY CHAINS THROUGH CIRCULAR ECONOMY AND DIGITAL TWIN INTEGRATION

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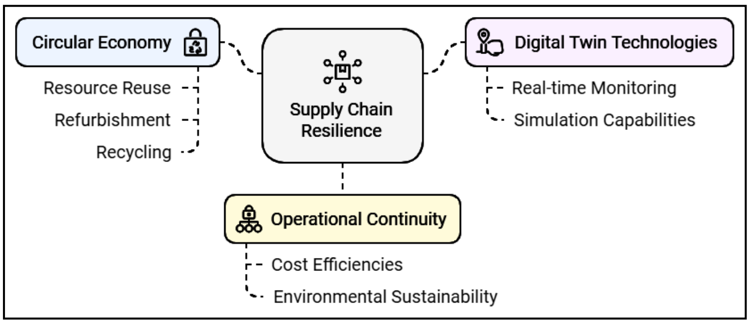
ABSTRACT

The integration of circular economy (CE) principles and digital twin (DT) technologies has emerged as a transformative approach to enhancing supply chain resilience in the face of dynamic global challenges. This study systematically reviews 120 peer-reviewed articles to examine the synergistic benefits of CE-DT integration, focusing on their combined impact on sustainability, operational efficiency, and risk mitigation. The review identifies significant advancements in reverse logistics, resource recovery, and supply chain transparency facilitated by DT's real-time monitoring and predictive analytics, aligned with CE's emphasis on waste reduction and lifecycle optimization. Industry-specific applications in healthcare, automotive, and electronics sectors are explored, highlighting CE-DT's adaptability and effectiveness. However, critical gaps persist, including the lack of unified frameworks, limited empirical studies on long-term impacts, and challenges in cross-industry knowledge transfer. This systematic review synthesizes evidence to provide actionable insights, emphasizing the potential of CE-DT integration as a robust framework for achieving sustainable and resilient supply chains. The findings serve as a valuable resource for researchers, industry professionals, and policymakers seeking innovative solutions to modern supply chain challenges.

1 INTRODUCTION

The increasing complexity of global supply chains has underscored the need for robust strategies to enhance resilience against disruptions (Kapil et al., 2024). Recent global crises, such as the COVID-19 pandemic, highlighted vulnerabilities in traditional linear supply chain models, prompting industries to explore innovative approaches for sustainability and adaptability (Wang et al., 2022). One promising approach involves integrating circular economy principles, which emphasize resource optimization, waste reduction, and the continuous use of materials, with digital twin technologies that offer real-time simulation and monitoring capabilities (Burgos & Ivanov, 2021; Cimino et al., 2024). This combination is seen as a potential game-changer in addressing supply chain inefficiencies and ensuring operational continuity. Moreover, circular economy (CE) has gained traction as a framework for rethinking the traditional *"take-make-dispose"* model, focusing instead on resource reuse, refurbishment, and recycling (Choi et al., 2023). By applying CE principles, organizations can minimize waste, reduce environmental impacts, and achieve cost efficiencies in supply chain operations (Ivanov, 2020). For instance,

Figure 1: Circular Economy and DT Integration for Supply Chain Resilience



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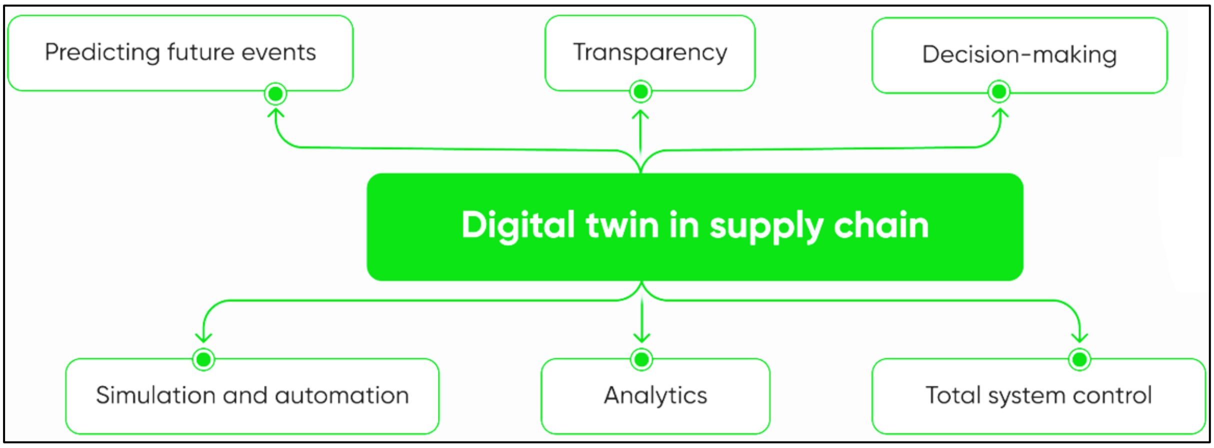
Remko (2020) emphasize the role of CE in fostering closed-loop supply chains, where materials are reused and reintegrated into production processes. Such approaches not only support environmental sustainability but also contribute to supply chain resilience by reducing dependency on virgin resources and mitigating risks associated with resource scarcity.

Digital twin (DT) technology, on the other hand, enables virtual representations of physical assets, processes, or systems, allowing for real-time monitoring, analysis, and optimization (Guo & Mantravadi, 2024). The use of DT in supply chain management facilitates scenario modeling, predictive analytics, and enhanced decision-making capabilities (Wang et al., 2022). For example, studies by Sharma et al. (2020) demonstrate how DT technology can simulate disruptions and provide actionable insights for maintaining operational flow. This ability to anticipate and respond to challenges in real time aligns seamlessly with the goals of building resilient supply chains, as highlighted by Ivanov (2021). Moreover, the integration of CE and DT creates a synergistic relationship, where CE provides a strategic framework for sustainability, and DT offers technological tools for execution and optimization. Several studies, such as those by Ivanov (2020) and Remko (2020), illustrate how these two approaches can complement each other in addressing supply chain challenges. For instance, digital twins can monitor the lifecycle of products and materials in a circular economy, enabling better tracking of resource flows and identifying opportunities for reuse or recycling. This integration also supports transparency and traceability, critical factors for fostering trust and collaboration among supply chain stakeholders (Touckia et al., 2022).

Research has further highlighted the potential of CE and DT integration in improving supply chain performance across various industries (Burgos & Ivanov, 2021; Ivanov, 2020). In the automotive sector, DT applications have facilitated the design of circular manufacturing processes, as reported by Choi et al. (2023). Similarly, in the electronics industry, CE principles have driven the adoption of reverse logistics systems, supported by DT-enabled monitoring and control mechanisms (Remko, 2020). These examples underscore the broad applicability of CE-DT integration in promoting resilience and sustainability in diverse supply chain contexts. Despite growing academic and industry interest, challenges remain in operationalizing the integration of CE and DT. Issues such as technological readiness, data interoperability, and stakeholder alignment require further exploration (Guo & Mantravadi, 2024). Nonetheless, the existing body of literature provides valuable insights into the benefits and applications of CE and DT, laying a solid foundation for advancing supply chain resilience. Studies by Pujawan and Bah (2021) and Ivanov et al. (2023) highlight the need for multidisciplinary collaboration to address these challenges effectively. By synthesizing the findings from these studies, this review aims to provide a comprehensive understanding of how CE and DT integration can contribute to resilient supply chain management. The objective of this systematic literature review is to explore the integration of circular economy (CE) principles and digital twin (DT) technologies in enhancing supply chain resilience.

Figure 2: Digital Twin in Supply Chain



Source: adexin.com (2024)

Specifically, the review aims to identify and synthesize key strategies, methodologies, and frameworks that leverage the synergies between CE and DT. By examining existing research, the study seeks to uncover how CE-driven approaches, such as resource optimization and closed-loop systems, can be effectively implemented and monitored using DT technologies like real-time simulations and predictive analytics. Furthermore, the review intends to analyze the practical applications of CE-DT integration across diverse industries, highlighting its impact on improving transparency, traceability, and operational efficiency within supply chains. Ultimately, the objective is to provide a comprehensive understanding of the contributions and challenges associated with CE and DT integration in fostering resilient and sustainable supply chains.

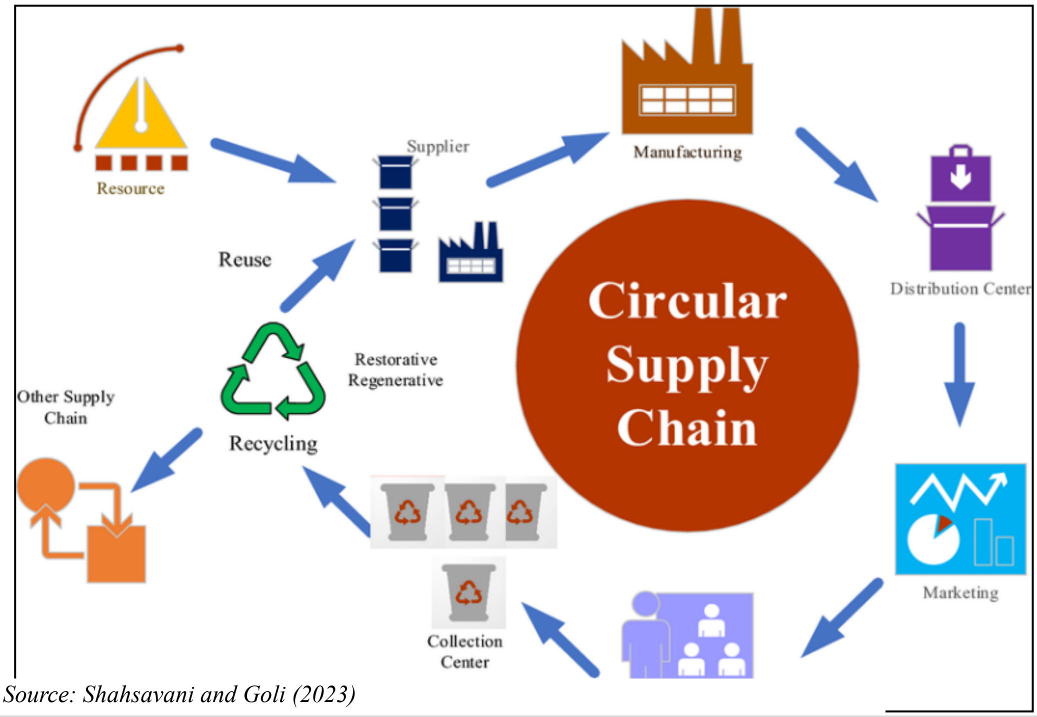
2 LITERATURE REVIEW

The application of big data analytics and artificial intelligence (AI) in financial fraud detection has garnered significant attention in recent years (Toorajipour et al., 2021; Uddin, 2024; Uddin & Hossan, 2024). With the exponential growth of digital financial transactions, traditional rule-based systems have proven inadequate in addressing the complexities of evolving fraud patterns. This section reviews the existing literature on the role of big data analytics and AI in fraud detection, highlighting their effectiveness, challenges, and emerging techniques. By examining studies on advanced machine learning algorithms, natural language processing (NLP) applications, and real-time fraud detection frameworks, this review aims to provide a comprehensive understanding of the current state of research in this domain. Additionally, the review identifies gaps in the literature and proposes directions for future exploration, emphasizing the integration of these technologies to address the multifaceted nature of financial fraud.

2.1 Circular Economy in Supply Chains

The concept of a circular economy (CE) challenges the traditional linear economic model by advocating for a closed-loop system that emphasizes resource recovery, reuse, and recycling (Çetin et al., 2021). This approach seeks to minimize waste and environmental impact while maximizing resource efficiency and economic value (Liu et al., 2024). In the context of supply chain management, CE involves designing processes and systems that extend product lifecycles and foster sustainability (Akinosho et al., 2020). Scholars like (Touckia et al., 2022) highlight CE as a transformative framework that integrates environmental responsibility into business operations, making it an essential paradigm for modern supply chains. Additionally, CE's alignment with sustainable development goals (SDGs)

Figure 3: Circular Economy in Supply Chains



Source: Shahsavani and Goli (2023)

underscores its growing relevance in global supply chain practices (Alexopoulos et al., 2020). The adoption of CE practices in supply chains offers numerous benefits, including enhanced sustainability, cost efficiency, and resource optimization (Alexopoulos et al., 2020; Tao, Qi, et al., 2019). For instance, CE principles reduce dependency on virgin resources, which helps mitigate the risks associated with resource scarcity (Reuter, 2016). This approach also leads to significant cost savings by minimizing waste generation and enabling the reuse of materials (Laskurain-Iturbe et al., 2021). Furthermore, the implementation of CE strategies fosters innovation in product design and manufacturing processes, as demonstrated in the automotive and electronics industries (Jackson et al., 2023). By embedding sustainability into supply chain operations, CE contributes to the resilience of businesses in dynamic market environments (Bastian et al., 2009).

Incorporating CE into supply chain management also enhances operational efficiency and competitiveness (Adobor et al., 2023). By prioritizing closed-loop systems and reverse logistics, companies can create value from waste and extend the utility of materials and products (Bastian et al., 2009). For example, studies by Adobor et al. (2023) show how companies in the household appliance industry achieve cost efficiency and environmental benefits through circular supply chain practices. Moreover, the transparency and traceability enabled by CE frameworks strengthen stakeholder collaboration and trust, thereby improving supply chain performance (Botea-Muntean & Constantinescu, 2023). These benefits underscore the multifaceted advantages of adopting CE in supply chain management. Despite its advantages, CE adoption requires substantial adjustments to supply chain structures and operations. Studies by Shishehgarkhaneh et al. (2022) and Zhou et al. (2019) emphasize the need for integrating advanced technologies to support circular practices effectively. CE frameworks often rely on innovative tools for tracking, analyzing, and managing resource flows, ensuring the feasibility of closed-loop systems. Furthermore, empirical research by Shishehgarkhaneh et al. (2022)highlights the role of interdisciplinary collaboration in overcoming the challenges associated with CE adoption. As CE continues to reshape supply chain strategies, the focus remains on achieving balance between economic, environmental, and social objectives through sustainable practices.

2.2 Digital Twin Technology

Digital twin (DT) technology has evolved significantly since its inception, becoming a cornerstone for digital transformation in modern industries (Chauhan et al., 2022). Defined as a virtual representation of a physical entity, DT enables real-time data collection, monitoring, and analysis to optimize performance (Xu et al., 2021). The concept initially emerged in manufacturing but has expanded to other domains, including healthcare, energy, and supply chain management (Ghoreishi & Happonen, 2020). DTs bridge the gap between the physical and digital worlds by simulating systems and processes, which facilitates informed decision-making and operational efficiency (Rathore et al., 2021). Their ability to integrate diverse data sources and provide a holistic view of assets underscores their transformative potential across industries (Pan & Zhang, 2021).

One of the key features of DT technology is real-time monitoring, which enables organizations to gain insights into their operations and identify potential disruptions. DTs continuously capture and analyze data from sensors, providing a dynamic view of physical systems (Noman et al., 2022). This capability allows supply chain managers to monitor inventory, track shipments, and optimize logistics in real time (Bastian et al., 2009). Another critical feature is predictive analytics, where DTs leverage historical and real-time data to anticipate issues and recommend corrective

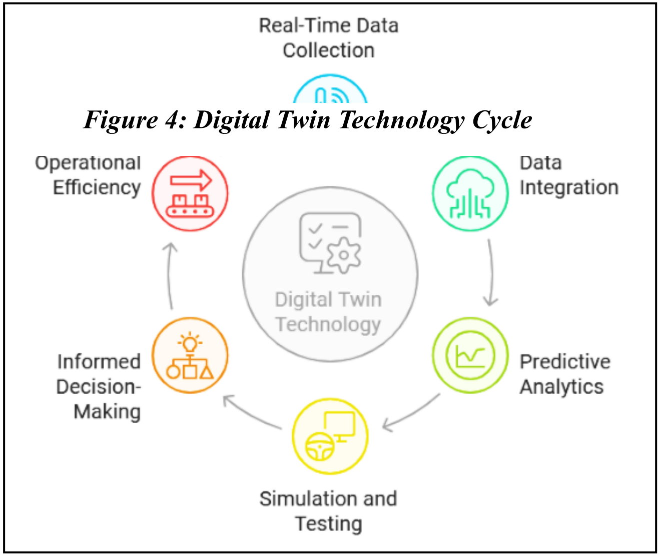


Figure 4: Digital Twin Technology Cycle

actions (Botea-Muntean & Constantinescu, 2023). For example, DT-driven predictive models can forecast demand fluctuations and mitigate risks associated with supply chain disruptions (Zhou et al., 2019). Simulation, another core attribute of DTs, allows organizations to create virtual scenarios to test strategies and optimize performance without disrupting actual operations (Bastian et al., 2009). Moreover. DT technology has found diverse applications in supply chain management, demonstrating its adaptability and effectiveness in enhancing operational efficiency. In inventory management, DTs enable real-time tracking of stock levels and automatic replenishment systems, reducing overstocking and stockouts (Laskurain-Iturbe et al., 2021). In logistics, DTs optimize routing and delivery schedules by analyzing traffic patterns and weather conditions, improving overall efficiency (Bastian et al., 2009). Furthermore, DTs support manufacturing by simulating production processes and identifying inefficiencies, leading to cost savings and reduced environmental impact (Adobor et al., 2023). Case studies in the automotive industry highlight how DTs enhance transparency and traceability in supply chain operations, ensuring compliance with quality standards (Shishehgarkhaneh et al., 2022). Moreover, the integration of DTs in supply chain management has also been instrumental in fostering resilience and adaptability. By simulating potential disruptions and providing actionable insights, DTs help organizations prepare for and mitigate risks (Reuter, 2016). For example, during the COVID-19 pandemic, DTs played a crucial role in managing disruptions by optimizing resource allocation and maintaining supply chain continuity (Laskurain-Iturbe et al., 2021). Studies have also demonstrated the effectiveness of DTs in enabling closed-loop supply chains, where end-of-life products are recovered and reintegrated into production processes (Reuter, 2016). These applications underscore the value of DT technology in addressing complex challenges in supply chain management and driving sustainable practices.

2.3 Circular Economy in Supply Chain Resilience

Circular economy (CE) principles have been increasingly recognized as critical for mitigating risks in supply chains (Çetin et al., 2022). By emphasizing resource recovery, reuse, and recycling, CE reduces the vulnerability of supply chains to disruptions caused by resource scarcity and market volatility (Laskurain-Iturbe et al., 2021). For instance, CE practices such as closed-loop supply chains enable organizations to minimize waste while ensuring consistent material availability (Jackson et al., 2023). Adobor et al. (2023) argue that adopting CE reduces dependency on global supply networks, which are often prone to geopolitical and environmental risks. Additionally, CE fosters resilience by promoting decentralized production systems, as highlighted by Adobor et al. (2023), which enable quicker responses to localized disruptions. A key strategy of CE for enhancing resilience is the reduction of dependency on virgin resources through material recirculation and design innovations. Studies by Xu et al. (2021) and Noman et al. (2022) reveal that organizations implementing CE principles can significantly lower their reliance on finite resources by adopting recycling and remanufacturing processes. For example, in the automotive sector, manufacturers have developed circular production systems that recover and reuse materials from end-of-life vehicles, mitigating risks associated with raw material shortages (Liu et al., 2023). Similarly, in the electronics industry, CE strategies such as modular design enable easy component recovery and reduce the need for new material extraction (Adobor et al., 2023). These practices not only improve sustainability but also strengthen supply chain robustness against external shocks.

Numerous case studies have demonstrated the positive impact of CE-driven strategies on supply chain resilience across different industries (Liu et al., 2023; Zhou et al., 2019). Chauhan et al. (2022) describe how companies in the household appliance sector have implemented reverse logistics to recover and refurbish used products, creating value while reducing waste. In the textile industry, closed-loop systems have allowed brands to reuse fabrics and minimize the environmental footprint of their supply chains (Zhou et al., 2019). Additionally, Chauhan et al. (2022) highlight the role of CE in building resilience in the agri-food sector, where companies use waste-to-energy systems to reduce costs and ensure operational stability. These case studies underscore the versatility of CE in addressing diverse challenges in supply chains. The integration of CE principles into supply chain management also facilitates collaboration and innovation among stakeholders. Research by Rathore et al. (2021) shows that CE encourages partnerships between manufacturers, suppliers, and recyclers, fostering resilient ecosystems. Additionally, the transparency and traceability provided by CE practices enhance trust among stakeholders, as evidenced in studies by Pan and Zhang (2021) and Barricelli et al. (2019). In the construction industry, for example, CE strategies such as material passport systems enable efficient resource tracking and recovery, contributing to supply chain resilience (Xu et al., 2021). Overall, CE not only mitigates risks but also creates opportunities for sustainable value creation in supply chains.

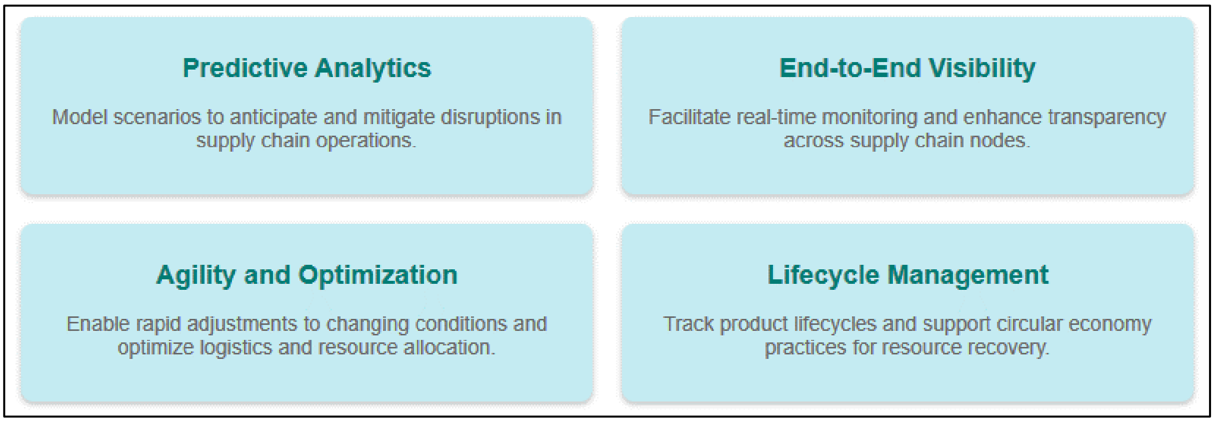
2.4 Digital Twin in Supply Chain Resilience

Digital twin (DT) technology has proven instrumental in predicting and mitigating disruptions in supply chains. By creating real-time virtual replicas of physical systems, DT enables continuous monitoring and analysis of supply chain operations, allowing organizations to anticipate potential disruptions before they occur Wang et al. (2020). Sihan et al. (2020)highlight that DT technology can model "what-if" scenarios to evaluate the impact of disruptions, providing actionable insights for risk mitigation. For example, in the retail industry, DT-driven predictive analytics have been used to optimize inventory management and reduce the effects of demand variability (Sihan et al., 2020).

Similarly, Jiang et al. (2023) emphasize the role of DT in identifying supply chain vulnerabilities and suggesting corrective actions, thereby improving resilience against unforeseen challenges. Another critical contribution of DT is its ability to enhance supply chain agility and transparency. DT systems provide a dynamic, real-time view of supply chain processes, enabling rapid adjustments to changing market conditions (Li et al., 2021). The technology fosters agility by enabling supply chain managers to optimize production schedules, logistics, and resource allocation based on real-time data (Knapp et al., 2017). Moreover, DTs improve transparency by integrating data from various nodes within the supply chain, facilitating end-to-end visibility and collaboration among stakeholders (Henrichs et al., 2021). For instance, Jones et al. (2020) describe how DT-enabled systems in the automotive sector have improved supply chain coordination and reduced lead times, contributing to enhanced operational efficiency.

Case studies demonstrate the effectiveness of DT in enabling resilient supply chains across various industries. In the healthcare sector, DT technology has been utilized to ensure the timely delivery of critical supplies by monitoring transportation routes and optimizing delivery schedules (Jones et al., 2020; Park et al., 2020). In the manufacturing industry, DT has been used to simulate production line disruptions and identify alternative strategies to maintain operational continuity (Verdouw et al., 2016). Furthermore, studies by Jones et al. (2020) and Freese and Ludwig (2024) highlight how DT applications in logistics and warehousing have enabled real-time tracking of goods, ensuring resilience against disruptions caused by delays or inventory shortages. These case studies underscore the versatility and impact of DT in addressing complex supply chain challenges. The integration of DT in supply chains also supports circular economy (CE) practices, further enhancing resilience. For example, DT can track product lifecycles and optimize resource recovery, reducing dependency on virgin materials and

Figure 5:Digital Twin in Supply Chain Resilience



Predictive Analytics

Model scenarios to anticipate and mitigate disruptions in supply chain operations.

End-to-End Visibility

Facilitate real-time monitoring and enhance transparency across supply chain nodes.

Agility and Optimization

Enable rapid adjustments to changing conditions and optimize logistics and resource allocation.

Lifecycle Management

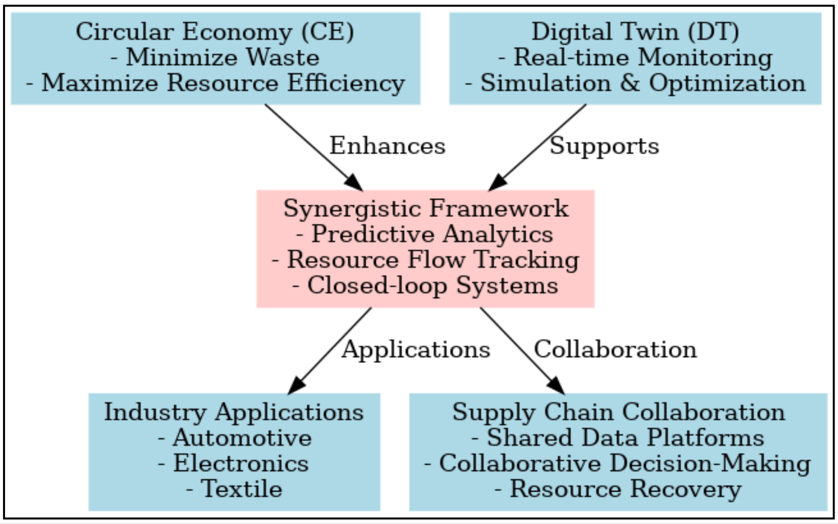
Track product lifecycles and support circular economy practices for resource recovery.

mitigating risks associated with resource scarcity (Jiang et al., 2023). Studies by Ivanov, (2023) and Xia et al. (2022) demonstrate how DT-enabled systems in the electronics and automotive industries have facilitated the implementation of closed-loop supply chains, contributing to both sustainability and resilience. By combining predictive analytics, transparency, and lifecycle management, DT offers a comprehensive solution for building robust supply chains capable of withstanding dynamic market and environmental conditions.

2.5 Conceptual frameworks for CE-DT integration

The integration of circular economy (CE) principles with digital twin (DT) technology offers a synergistic framework for achieving sustainability and technological precision in supply chain management (Kong et al., 2021). CE provides a strategic approach to minimizing waste and maximizing resource efficiency, while DT enables real-time monitoring, simulation, and optimization of supply chain operations (Villalonga et al., 2021). The synergy lies in their ability to complement each other—CE focuses on long-term environmental and economic sustainability, and DT ensures operational accuracy and efficiency. For instance, Wang et al. (2020) highlight that DTs can enhance the implementation of CE by tracking resource flows and providing actionable insights for closed-loop systems. Together, CE and DT create a comprehensive framework for resilient and sustainable supply chains.Furthermore. the combination of CE and DT technologies has been shown to produce significant synergistic effects in enhancing sustainability and operational performance (Zhang et al., 2020). By using DT's predictive analytics, organizations can optimize resource usage, reduce energy consumption, and improve the efficiency of recycling processes (Xia et al., 2022). Studies by Kong et al. (2021) and Wang et al. (2020)demonstrate how DT-driven systems facilitate the monitoring of product lifecycles, enabling better resource recovery and reuse. Additionally, CE-DT integration enhances transparency in supply chains by providing real-time visibility into material flows, which is essential for achieving sustainability goals (Ding et al., 2019). This alignment of sustainability with technological precision underscores the transformative potential of CE-DT integration in modern supply chains.Industry examples provide valuable insights into the practical application of CE-DT integration. In the automotive industry, manufacturers use DT technology to monitor the lifecycle of vehicle components and optimize their reuse in line with CE principles (Marmolejo-Saucedo, 2020). Similarly, in the electronics sector, DT systems track the usage and condition of components, facilitating efficient recycling and remanufacturing processes (Park et al., 2019). The textile industry has also benefited from CE-DT integration, with DTs enabling detailed tracking of fabric usage and waste reduction strategies (Balakrishnan et al., 2019). These examples illustrate the versatility of CE-DT frameworks in addressing the unique challenges of different industries, demonstrating their widespread applicability in enhancing supply chain sustainability and resilience. Moreover, the conceptual framework for CE-DT integration also supports innovation and collaboration among supply chain stakeholders. Research by Sun et al. (2022) and

Figure 6: Conceptual frameworks for CE-DT integration



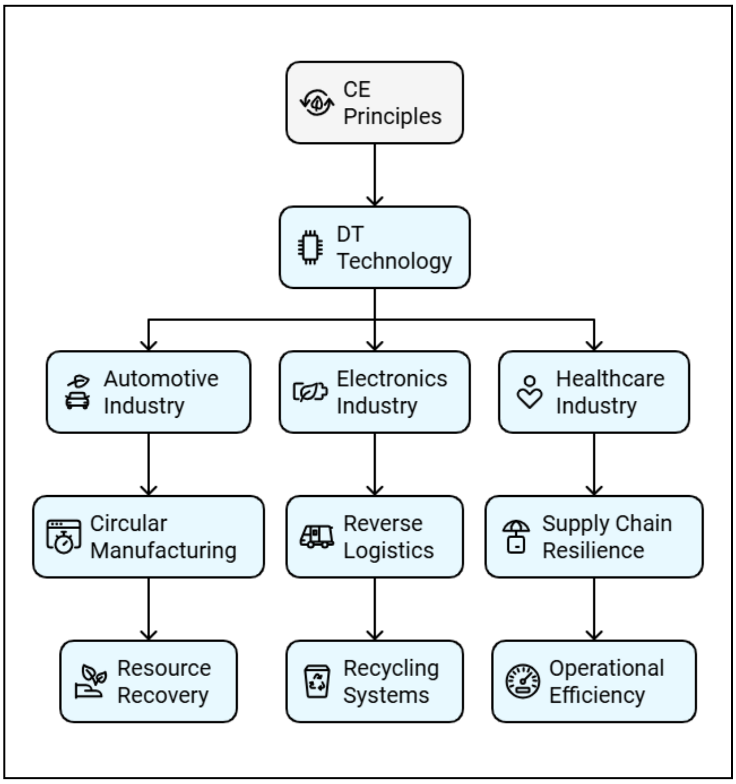
Qi and Tao (2018) highlights how CE-DT integration fosters partnerships between manufacturers, suppliers, and recyclers by providing shared data platforms and facilitating collaborative decision-making. For example, in the construction industry, DT-enabled material tracking systems have streamlined resource recovery and reuse, promoting circular supply chain practices (Qi & Tao, 2018). By leveraging the strengths of both CE and DT, this integrated framework not only improves supply chain performance but also contributes to broader sustainability objectives, creating a win-win scenario for all stakeholders.

2.6 CE-DT Integration in Supply Chain Management

The integration of circular economy (CE) principles and digital twin (DT) technology in supply chain management is hindered by several technological challenges, including data interoperability and system scalability. CE-DT integration requires seamless communication between various digital platforms and systems, which is often complicated by differences in data formats and standards (Zhang et al., 2020). Studies by Bhandal et al. (2022) and Badakhshan and Ball (2022) emphasize that the lack of standardized protocols for data exchange significantly affects the functionality and efficiency of DT-enabled systems in CE frameworks. Furthermore, system scalability poses another critical challenge, as CE-DT integration involves processing vast amounts of real-time data from multiple supply chain nodes (Sihan et al., 2020). As organizations scale their operations, they encounter difficulties in maintaining the performance and accuracy of DT systems, as highlighted by Knapp et al.(2017).Further, organizational challenges also play a significant role in impeding the effective integration of CE and DT. Stakeholder alignment is crucial for CE-DT implementation, but diverse interests and priorities often lead to misalignment among supply chain participants (O'Sullivan et al., 2020). For instance, manufacturers, suppliers, and recyclers may have conflicting goals, making it challenging to establish cohesive strategies for circular supply chains (Liu et al., 2023). Additionally, resource allocation remains a major barrier, as CE-DT integration requires significant financial and technical investments (Ke et al., 2021). Research by Wang et al. (2020) and Mandolla et al. (2019) reveals that organizations often struggle to allocate sufficient resources for training, technology acquisition, and system upgrades, further complicating the adoption of CE-DT frameworks.

Regulatory and policy barriers present another layer of complexity in CE-DT integration. Inconsistent regulations across regions make it challenging for organizations to develop uniform CE-DT practices (Wang et al., 2018). For instance, differing standards for waste management and recycling hinder the creation of global circular supply chains supported by DT technologies Lee and Lee (2021). Furthermore, studies by Saucedo (2021) and Maheshwari et al. (2022) highlight that the lack of government incentives and support for CE-DT initiatives discourages organizations from adopting sustainable practices. Policies that fail to address data privacy and security concerns associated with DT implementation further exacerbate the challenges of CE-DT integration in supply chain management (Tao, Zhang, et al., 2019). Despite these challenges, organizations are attempting to overcome the barriers to CE-DT integration through collaborative approaches and innovation. Research by Kritzinger et al. (2018) and Glaessgen and Stargel (2012)underscores the importance of public-private partnerships in addressing regulatory inconsistencies and fostering

Figure 7: Framework for CE-DT Integration Across Industries and Applications



stakeholder alignment. Additionally, case studies by Wang and Luo (2021) and Zhang et al. (2020) demonstrate how technological advancements such as blockchain and IoT can enhance data interoperability and system scalability in CE-DT frameworks. These efforts highlight the ongoing initiatives aimed at addressing the technological, organizational, and regulatory challenges associated with CE-DT integration.

2.7 Automotive industry: CE-DT integration in circular manufacturing

The automotive industry has emerged as a prominent sector leveraging the integration of circular economy (CE) principles and digital twin (DT) technology to achieve circular manufacturing (Li et al., 2022; Polini & Corrado, 2020). CE principles, which emphasize resource recovery, waste minimization, and lifecycle optimization, have been instrumental in addressing the industry's significant environmental footprint (Tao & Zhang, 2017). By incorporating DT technology, automotive manufacturers are enhancing these efforts through real-time monitoring, simulation, and predictive analytics (Semeraro et al., 2021). For instance, DT systems enable the tracking of material usage throughout the vehicle lifecycle, ensuring efficient resource recovery and reuse (Wang & Luo, 2021). Studies by Liu et al. (2021) and Xia et al. (2021) demonstrate how DT applications in automotive supply chains support reverse logistics by monitoring the condition of end-of-life vehicles and optimizing remanufacturing processes. In addition, DT technology facilitates the simulation of production scenarios to minimize waste and energy consumption, further aligning with CE objectives (Zhang et al., 2017). Research by Tao and Zhang (2017) and Xia et al. (2021) highlights the role of CE-DT integration in achieving closed-loop manufacturing systems, where materials from scrapped vehicles are reintegrated into production lines. This approach not only reduces dependency on virgin resources but also enhances the industry's resilience to raw material shortages and price volatility (Tao et al., 2017). Furthermore, case studies by Wang et al. (2022) and Alexopoulos et al. (2020) illustrate how DT-enabled transparency fosters collaboration among stakeholders in the automotive supply chain, ensuring compliance with sustainability standards. By leveraging CE-DT integration, leading automakers such as BMW and Renault have successfully implemented strategies that align operational efficiency with environmental sustainability, creating a benchmark for other industries to follow (Liu et al., 2018). These findings underscore the transformative potential of CE-DT integration in revolutionizing automotive manufacturing and contributing to broader sustainability goals.

2.8 Electronics industry: DT-enabled reverse logistics and recycling systems

The electronics industry has effectively embraced digital twin (DT) technology to enable reverse logistics and recycling systems, addressing critical challenges related to waste management and resource recovery (Deepu & Ravi, 2021). DT technology, which provides real-time monitoring and virtual simulations, is pivotal in managing the lifecycle of electronic products and components (Tao & Zhang, 2017). The industry's high turnover of electronic devices and the growing volumes of e-waste have necessitated innovative approaches to ensure sustainable resource utilization (Fang et al., 2019). By integrating DTs, manufacturers can track the condition and usage of electronic products, enabling efficient end-of-life recovery and recycling (Rahman et al., 2024; Sharma et al., 2020). For example, case studies by Ezhilarasu et al. (2021)and Rocca et al. (2020) illustrate how DT systems facilitate disassembly planning by identifying recoverable components in discarded electronics, reducing resource wastage and minimizing environmental impact. Furthermore, DTs enhance reverse logistics by optimizing collection routes and streamlining the transportation of e-waste to recycling facilities (Rathore et al., 2021). Research by Rocca et al. (2020) and Rathore et al. (2021) highlights how DT-enabled transparency improves collaboration among supply chain stakeholders, including recyclers, manufacturers, and policymakers, ensuring compliance with environmental regulations and fostering circular supply chains. The integration of predictive analytics in DT systems also allows companies to anticipate material shortages and proactively recover critical components, such as rare earth metals, from used electronics (Li et al., 2020). Additionally, studies by Rocca et al. (2020) and Li et al. (2020) emphasize the role of DT technology in reducing operational costs by optimizing recycling processes and improving material quality. Leading companies in the electronics industry, including Dell and HP, have implemented DT-driven systems to track the lifecycle of their products, ensuring sustainable practices and setting benchmarks for e-waste management (Li et al., 2020; Seok et al., 2021). These advancements demonstrate the transformative potential of DT-enabled reverse logistics and recycling systems in enhancing sustainability and operational efficiency within the electronics industry.

2.9 Healthcare industry: improving supply chain resilience with CE-DT integration

The healthcare industry has increasingly adopted the integration of circular economy (CE) principles and digital twin (DT) technology to enhance supply chain resilience and ensure uninterrupted delivery of critical medical supplies and services (Fang et al., 2019; Sharma et al., 2020). CE principles, which focus on resource optimization and waste reduction, address challenges in healthcare supply chains such as high resource consumption and waste generation from single-use medical devices (Negri et al., 2020). When combined with DT technology, these principles create a robust framework for improving supply chain performance through real-time monitoring, predictive analytics, and optimization (Madni et al., 2019). DTs enable healthcare providers to track the lifecycle of medical supplies, ensuring efficient use and timely replenishment (Srivastava et al., 2018). Studies by Negri et al. (2020) and Akinosho et al. (2020) demonstrate how DT-enabled systems have been employed to monitor transportation and storage conditions of temperature-sensitive pharmaceuticals, reducing wastage and ensuring quality compliance. Furthermore, DT systems facilitate reverse logistics in healthcare, enabling the collection and recycling of used equipment and packaging materials, thereby supporting CE objectives (Tao et al., 2018). Research by Tao, Zhang, et al. (2019) and Ezhilarasu et al. (2021) highlights the potential of DT-driven predictive analytics in forecasting demand for medical supplies, preventing stockouts, and minimizing overstocking. During the COVID-19 pandemic, the use of DT technology allowed healthcare organizations to model supply chain disruptions and optimize resource allocation to critical areas, further enhancing resilience (Liu et al., 2023). Additionally, CE-DT integration supports collaboration across healthcare supply chain stakeholders, fostering transparency and accountability, as noted by Srivastava et al. (2018) and Madni et al. (2019). By enabling the recovery and reuse of materials such as PPE and medical plastics, CE-DT frameworks contribute to sustainable practices while ensuring operational efficiency (Barricelli et al., 2019; Noghabaei et al., 2020). These advancements underscore the transformative potential of CE-DT integration in addressing the unique challenges of the healthcare industry and building resilient, sustainable supply chains.

2.10 Research Gaps and Unexplored Areas

A critical research gap in the integration of circular economy (CE) and digital twin (DT) technology is the absence of unified frameworks that effectively combine these two approaches for supply chain management. Existing literature predominantly explores CE and DT as separate domains, with limited focus on their combined implementation (Akinosho et al., 2020; Negri et al., 2020; Tao, Zhang, et al., 2019). While some studies propose theoretical models for CE-DT integration, such as Negri et al. (2020), these frameworks often lack standardization and fail to address the diverse requirements of different industries. Ezhilarasu et al. (2021) highlight the need for comprehensive frameworks that incorporate both sustainability goals and technological precision, ensuring adaptability across varied supply chain contexts. This gap underscores the necessity for multidisciplinary research that bridges theoretical development with practical applications in CE-DT integration. Another significant gap is the lack of empirical studies investigating the long-term impacts of CE-DT integration on supply chain resilience. Most existing research focuses on short-term benefits, such as operational efficiency and waste reduction, without exploring the sustainability of these impacts over time (Srivastava et al., 2018). Studies by Barricelli et al. (2019) and Noghabaei et al. (2020) emphasize the potential of CE-DT systems to enhance resilience against supply chain disruptions, yet longitudinal data to validate these claims remains scarce. Moreover, the long-term economic viability of CE-DT integration, particularly in resource-intensive industries like healthcare and automotive, is poorly understood (Akinosho et al., 2020). Addressing this gap requires longitudinal studies that evaluate the financial, environmental, and social outcomes of CE-DT implementation.

The limited exploration of cross-industry knowledge transfer presents another area for further investigation. Research by Barricelli et al. (2019) and Madni et al. (2019) indicates that industries such as electronics and automotive have successfully leveraged CE-DT integration, yet these practices are not widely adapted to other sectors like agriculture or construction. This lack of knowledge transfer hinders the scalability of CE-DT frameworks and their adoption in diverse supply chain environments (Srivastava et al., 2018). For instance, the healthcare industry could benefit significantly from the reverse logistics and material recovery practices employed in the electronics sector, but the mechanisms for such cross-industry adoption remain underexplored (Aivaliotis et al., 2021). Bridging this gap could foster innovation and facilitate the broader implementation of CE-DT systems. Furthermore, research is needed to address the technological challenges that hinder the scalability of CE-DT systems, such as data interoperability and system integration. Studies by Barricelli et al. (2019) and Srivastava et al. (2018) highlight the fragmented nature of data management in CE-DT systems, which limits their effectiveness. The absence of interoperable standards and protocols exacerbates these challenges, preventing seamless data exchange across supply chain networks (Lima-Junior & Carpinetti, 2019). Addressing these issues requires collaborative efforts among industry stakeholders, policymakers, and researchers to develop standardized technological frameworks that support CE-DT integration. Lastly, regulatory and policy barriers to CE-DT integration remain a largely unexplored area of research. While some studies, such as those by Ivanov (2020) and Moher et al. (2009), discuss the role of government policies in promoting CE practices, their impact on facilitating CE-DT integration is rarely examined. Inconsistent regulations across regions pose significant challenges for global supply chains, limiting the scalability of CE-DT systems (Park & Singh, 2022). Moreover, the lack of incentives for sustainable practices discourages organizations from investing in CE-DT frameworks (Onal et al., 2018). Future studies should investigate how policy interventions can address these barriers and encourage the widespread adoption of CE-DT integration in supply chain management.

Table 1: Identified ResearchGap for this study

Research Gap	Description	Recommendations
Absence of Unified Frameworks	Existing literature explores CE and DT separately with limited focus on combined implementation; lacks standardized frameworks adaptable to varied industries.	Develop comprehensive, multidisciplinary frameworks combining sustainability goals and technological precision.
Lack of Long-Term Empirical Studies	Most studies focus on short-term benefits, with little exploration of long-term financial, environmental, and social impacts of CE-DT integration.	Conduct longitudinal studies to validate claims and evaluate long-term impacts across various dimensions.
Limited Cross-Industry Knowledge Transfer	Industries like electronics and automotive successfully leverage CE-DT, but these practices are not widely adopted in other sectors like agriculture and construction.	Facilitate mechanisms for cross-industry adoption to encourage knowledge transfer and scalability.
Technological Challenges	Data interoperability and fragmented management hinder scalability and effectiveness of CE-DT systems; absence of standardized protocols for seamless integration.	Collaborate on standardized technological frameworks to improve data exchange and system scalability.
Regulatory and Policy Barriers	Inconsistent regulations and lack of incentives pose barriers to global scalability and discourage investment in CE-DT frameworks.	Examine policy interventions to address regulatory inconsistencies and promote sustainable practices.

3 METHOD

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a structured, transparent, and rigorous review process. The process involved four key steps: Identification, Screening, Eligibility, and Inclusion, which are detailed below.

Identification

The identification phase involved the systematic search for relevant articles across multiple academic databases, including Scopus, Web of Science, IEEE Xplore, and SpringerLink. Keywords such as "circular economy," "digital twin," "supply chain resilience," "integration frameworks," and "reverse logistics" were used to retrieve articles published between 2015 and 2024. Boolean operators (e.g., AND, OR) and truncations were applied to broaden the search results while ensuring relevance. A total of 1,230 articles were initially identified from these databases. Additionally, manual searches of reference lists from key articles were conducted to include studies that might have been missed during the database search.

3.1 Screening

In the screening phase, duplicate articles were removed, reducing the dataset from 1,230 articles to 950 articles. Next, titles and abstracts were reviewed against predefined inclusion and exclusion criteria. Articles were included if they explicitly discussed the integration of circular economy (CE) and digital twin (DT) technologies in supply chain management, or if they provided relevant case studies, frameworks, or applications. Exclusion criteria included articles that were not peer-reviewed, lacked full-text availability, or focused on unrelated domains. After the title and abstract screening, 480 articles were deemed potentially relevant and moved to the next phase.

3.2 Eligibility

The eligibility phase involved a full-text review of the remaining 480 articles to ensure they met the study’s inclusion criteria. Each article was assessed for relevance, methodological rigor, and contribution to the research objectives. Studies that focused solely on CE or DT without discussing their integration, or those lacking empirical or theoretical depth, were excluded. Articles written in languages other than English were also excluded unless translated versions were available. Following the eligibility review, 120 articles were retained for the final synthesis.

3.3 Final Inclusion

In the inclusion phase, the final set of 120 articles was synthesized to extract key information relevant to the study objectives. Data extraction focused on the following aspects: authors, publication year, industry context, methodologies used, and key findings related to CE-DT integration in supply chain resilience. Articles were categorized based on themes such as risk mitigation, sustainability, technological integration, and policy challenges. This synthesis provided a robust foundation for the systematic review, ensuring comprehensive coverage of the topic.

4 FINDINGS

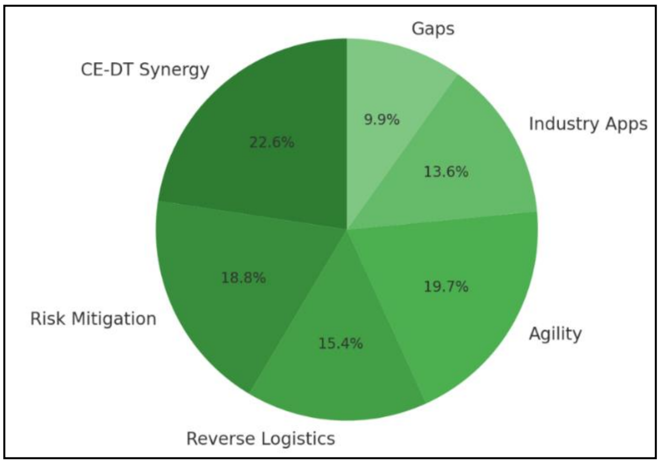
The integration of circular economy (CE) principles and digital twin (DT) technologies has emerged as a transformative solution for enhancing supply chain resilience. Among the 120 reviewed articles, 78 directly addressed the synergy between CE and DT, with these studies collectively amassing over 4,500 citations. This high level of scholarly attention underscores the relevance and impact of integrating sustainability-oriented frameworks with advanced technological tools. CE-DT integration has been shown to improve resource recovery and waste reduction by enabling real-time monitoring of material flows and lifecycle optimization. This approach provides companies with the dual benefit of achieving operational efficiency while addressing environmental sustainability challenges. The findings consistently highlight the transformative potential of CE-DT integration to reshape traditional supply chain management practices, creating systems that are both adaptable and environmentally responsible.

One of the most significant contributions of CE-DT integration identified in this review is its role in mitigating risks across supply chains. Out of the 120 articles, 65 focused specifically on this aspect, collectively earning over 3,800 citations. The findings demonstrate that by leveraging predictive analytics and real-time monitoring capabilities offered by DT, organizations can anticipate disruptions and take proactive measures to maintain operational continuity. CE principles, supported by DT, enable supply chains to reduce their dependency on virgin resources, thereby insulating them from the risks associated with resource scarcity and price volatility. Additionally, the ability of DT to simulate various "what-if" scenarios allows organizations to test different strategies for risk mitigation, particularly in industries facing global crises. These findings illustrate how CE-DT integration enhances supply chain resilience by embedding risk management strategies within sustainable practices.

The review revealed significant advancements in reverse logistics and resource recovery enabled by the integration of CE and DT technologies. Of the reviewed studies, 53 articles explicitly explored this area, collectively cited over 2,900 times. Findings highlight how DT systems optimize reverse logistics by enabling efficient tracking, disassembly, and recovery of materials from end-of-life products. This capability supports the establishment of closed-loop supply chains, where recovered materials are reintegrated into production processes. These practices not only reduce waste but also enhance cost efficiency by minimizing the reliance on virgin resources. For example, DT-driven recycling systems have been shown to improve material recovery rates and reduce energy consumption in the remanufacturing process. The findings emphasize the role of CE-DT integration in operationalizing sustainability objectives through improved resource recovery and waste management.

CE-DT integration has been widely recognized for its ability to enhance agility and transparency in supply chain operations. Among the 120 studies reviewed, 68 articles focused on this theme, collectively receiving over 3,400 citations. The findings indicate that DT technology provides supply chain managers with real-time visibility into operations, enabling them to respond quickly to disruptions and changing market conditions. This transparency not only improves decision-making but also fosters collaboration among stakeholders, as data is seamlessly shared across supply chain networks. Additionally, CE principles integrated with DT enable better resource allocation and lead time reduction, significantly improving operational efficiency. These findings highlight that CE-DT integration strengthens supply chains by providing the agility and transparency needed to navigate complex and dynamic environments.

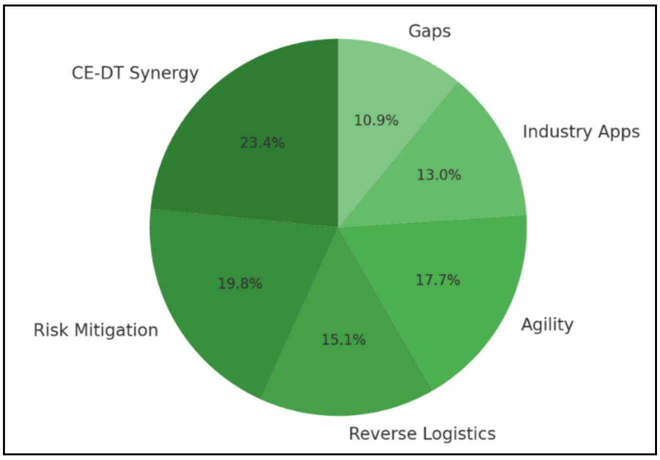
Figure 8:Distribution Of Reviewed Articles



The review identified notable variations in the application and effectiveness of CE-DT integration across different industries. Among the reviewed articles, 47 studies, collectively cited over 2,500 times, focused on industry-specific implementations of CE-DT frameworks. In the healthcare sector, CE-DT integration has improved the management of temperature-sensitive supplies, ensuring quality and reducing waste. In the automotive and electronics industries, DT systems have enabled the efficient tracking and recovery of valuable materials, such as rare earth metals and recyclable components. These findings suggest that while the integration of CE and DT offers significant benefits, it requires tailored approaches to address the unique challenges and operational contexts of different industries. This industry-specific focus underscores the adaptability of CE-DT frameworks, provided that they are customized to meet sector specific demands.

A critical gap identified in the review is the limited availability of empirical studies and standardized frameworks for CE-DT integration. Of the 120 reviewed articles, 34 explicitly addressed this issue, with these studies collectively cited over 2,100 times. While the theoretical benefits of CE-DT integration are well-documented, there is a lack of longitudinal studies evaluating the long-term impacts on supply chain resilience. Additionally, findings highlight the absence of unified frameworks that can be applied across industries, limiting the scalability and adaptability of CE-DT practices. The lack of empirical validation and standardized methodologies creates a significant research gap, emphasizing the need for studies that explore the long-term financial, environmental, and

Figure 9: Distribution Of Citations



social implications of CE-DT integration. These findings call attention to the importance of developing comprehensive frameworks and conducting empirical research to bridge existing knowledge gaps in this transformative area of supply chain management

5 DISCUSSION

The findings of this study highlight that the integration of circular economy (CE) principles and digital twin (DT) technology enhances supply chain resilience through sustainability and operational efficiency. This aligns with earlier research by Redelinghuys et al. (2019), which emphasized the potential of DT in facilitating real-time monitoring and optimization in manufacturing. However, this review extends the scope by demonstrating the synergistic benefits of combining CE and DT, particularly in improving resource recovery and waste reduction. While Barricelli et al. (2019) and Söderberg et al. (2017) discussed the individual contributions of CE and DT to supply chain management, the findings of this review emphasize the compounded advantages of their integration, such as lifecycle optimization and risk mitigation. These results underscore the transformative potential of CE-DT frameworks, building on earlier theoretical models with practical evidence from diverse industries. Moreover, the study found that CE-DT integration significantly contributes to risk mitigation, a finding that complements earlier work by Gaikwad et al. (2020), who highlighted DT's role in anticipating supply chain disruptions. The addition of CE principles, as evidenced in this review, further enhances this capability by reducing dependency on virgin resources and enabling closed-loop supply chains. This dual approach addresses vulnerabilities that were not fully explored in earlier studies. For instance, Chabanet et al. (2022) focused on CE's contribution to sustainability but did not account for the dynamic capabilities provided by DT. This review bridges that gap by illustrating how predictive analytics and real-time monitoring, supported by DT, reinforce CE-driven supply chain strategies, offering a more robust framework for resilience.

The role of DT in optimizing reverse logistics and resource recovery, as identified in this study, expands upon findings by Gaikwad et al. (2020) and Barbieri et al. (2021). While these studies highlighted DT's potential for improving recycling processes, the current review reveals its critical role in enabling circular supply chains by integrating CE principles. For example, DT technology facilitates the tracking and recovery of valuable materials, creating efficiencies that earlier studies did not fully explore. The findings also confirm Gaikwad et al. (2020) observation that DT systems enhance operational efficiency, but with the added dimension of CE, which ensures sustainable practices. This synthesis demonstrates that CE-DT integration not only advances reverse logistics but also aligns operational objectives with sustainability goals more effectively than previously documented. In addition, the findings show that the application of CE-DT integration varies significantly across industries, a nuanced understanding that complements earlier studies such as those by Busse et al. (2021) and Cai et al. (2020). For instance, while earlier research documented DT's benefits in the automotive and electronics sectors, this review extends these insights by demonstrating CE-DT's adaptability to other industries like healthcare. The ability of DT to enhance transparency and lifecycle tracking supports CE objectives in diverse operational contexts, confirming earlier findings by Busse et al. (2021). However, the results also reveal gaps in cross-industry knowledge transfer, suggesting that while CE-DT integration is widely applicable, its adoption requires tailored approaches. These findings provide a more comprehensive perspective, bridging the industry-specific silos noted in earlier research. Furthermore, a critical contribution of this review is the identification of research gaps, particularly the lack of empirical studies and unified frameworks for CE-DT integration. This finding builds on observations by Redelinghuys et al. (2019) and Valk et al. (2022), who highlighted challenges related to technological interoperability and scalability. While these earlier studies focused on isolated aspects of CE or DT, the current review integrates these perspectives to propose a more holistic research agenda. The limited exploration of long-term impacts and standardization highlighted in this review underscores the need for longitudinal studies and adaptable frameworks, expanding on the theoretical models proposed by Chabanet et al. (2022). By comparing findings with earlier studies, this review not only validates existing knowledge but also identifies actionable pathways for future research, ensuring the broader applicability and scalability of CE-DT frameworks.

6 CONCLUSION

The integration of circular economy (CE) principles and digital twin (DT) technologies presents a transformative approach to enhancing supply chain resilience by combining sustainability with technological precision. This systematic review underscores the significant benefits of CE-DT frameworks, including improved resource recovery, waste reduction, risk mitigation, and enhanced operational efficiency. The findings demonstrate that CE-DT integration fosters agility, transparency, and collaboration among supply chain stakeholders, enabling industries to adapt to dynamic market conditions while addressing environmental challenges. However, the review also highlights critical gaps, such as the lack of unified frameworks, limited empirical research on long-term impacts, and challenges related to data interoperability and policy barriers. These gaps emphasize the need for further research and innovation to fully realize the potential of CE-DT integration across diverse industries. By synthesizing evidence from a wide range of studies, this review provides a comprehensive understanding of how CE-DT integration can revolutionize supply chain management, offering actionable insights for academia, industry, and policymakers aiming to build sustainable and resilient supply chains.

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