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A Framework for Designing Sustainable Supply Chains in the Digital Transformation Era

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Abstract

This study aimed to develop a comprehensive framework for designing sustainable supply chains in the digital transformation era, addressing the growing need for integration between technological capabilities and sustainability objectives. The research employed a qualitative approach, using semi-structured interviews with industry professionals, supply chain managers, technology experts, and academic researchers, supplemented by secondary data from industry reports and scholarly publications. Thematic analysis of the collected data identified key dimensions of sustainable supply chains, including environmental, social, and economic sustainability, alongside enablers such as digital technologies, collaboration, governance, innovation, and human and organizational capabilities. Findings revealed that digital tools, including artificial intelligence, IoT, blockchain, and big data analytics, play a critical role in enhancing visibility, optimizing operations, supporting ethical practices, and enabling proactive risk management. Collaboration among supply chain partners and strong governance mechanisms were identified as essential for effective implementation, while challenges such as high costs, skill gaps, and infrastructure limitations must be addressed strategically. The study contributes a robust conceptual framework that integrates sustainability principles with digital transformation strategies, offering practical guidance for organizations seeking to enhance resilience, efficiency, and ethical performance in their supply chains. The findings also provide theoretical insights for future research on sustainable supply chain design in digitally-driven contexts.

Keywords: sustainable supply chains; digital transformation; artificial intelligence; IoT; blockchain; collaboration; governance; supply chain resilience

1. Introduction

The rapid evolution of global markets, intensified by technological advancement and increasing environmental and social concerns, has fundamentally reshaped the way supply chains are conceptualized, designed, and managed. In the contemporary era, characterized by digital transformation, supply chains are no longer linear systems focused solely on cost efficiency and responsiveness; instead, they have evolved into complex, interconnected networks that must simultaneously achieve economic viability, environmental stewardship, and social responsibility. This paradigm shift has given rise to the concept of sustainable supply chain management (SSCM), which integrates sustainability principles into traditional supply chain operations while leveraging digital technologies to enhance performance, transparency, and resilience. As organizations navigate this transformation, the need for a structured and holistic framework to guide the design of sustainable supply chains has become increasingly critical. Recent scholarly discussions emphasize that sustainability and digitalization are not parallel trajectories but deeply intertwined processes that reinforce each other in shaping future supply chain ecosystems (Shin et al., 2026).

Digital transformation, driven by the integration of advanced technologies such as artificial intelligence, blockchain, the Internet of Things (IoT), and big data analytics, has significantly expanded the capabilities of supply chains to monitor, analyze, and optimize operations in real time. These technologies enable organizations to collect vast amounts of data across different stages of the

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supply chain, thereby improving decision-making processes and enhancing operational efficiency. At the same time, they facilitate greater transparency and traceability, which are essential for ensuring compliance with sustainability standards and ethical practices. For instance, blockchain technology allows for immutable record-keeping, ensuring that every transaction and movement of goods can be tracked and verified, thereby reducing the risks of fraud and unethical sourcing. Similarly, IoT devices provide real-time monitoring of environmental conditions, enabling firms to reduce waste, improve energy efficiency, and minimize their environmental footprint. As highlighted in recent research, the convergence of digital technologies and sustainability objectives is redefining the strategic priorities of supply chain management, pushing organizations toward more integrated and data-driven approaches (Khan et al., 2026).

The increasing complexity of global supply chains, exacerbated by geopolitical uncertainties, climate change, and unexpected disruptions such as pandemics, has further underscored the importance of resilience and adaptability. Traditional supply chain models, which prioritize efficiency and cost minimization, often lack the flexibility needed to respond to such disruptions. In contrast, sustainable supply chains are designed to be more resilient, incorporating redundancy, flexibility, and risk management strategies that enable organizations to maintain continuity in the face of uncertainty (Hasan et al., 2026). Digital transformation plays a crucial role in enhancing this resilience by providing tools for predictive analytics, scenario planning, and real-time decision-making. For example, machine learning algorithms can analyze historical data to predict potential disruptions, allowing organizations to take proactive measures to mitigate risks. This shift toward resilience-oriented design is increasingly recognized as a key component of sustainable supply chains, as it ensures long-term viability and stability in an uncertain environment (Chang et al., 2026).

Another critical dimension of sustainable supply chain design is the integration of environmental considerations into operational and strategic decision-making processes. The growing awareness of environmental issues, such as climate change, resource depletion, and pollution, has led to increased pressure on organizations to adopt more sustainable practices. Governments, consumers, and other stakeholders are demanding greater accountability and transparency, pushing firms to reduce their carbon footprint, minimize waste, and adopt circular economy principles. Digital technologies play a pivotal role in enabling these practices by providing tools for monitoring and optimizing resource usage. For instance, advanced analytics can identify inefficiencies in production and distribution processes, allowing firms to reduce energy consumption and emissions (Hasan et al., 2026). Additionally, digital platforms facilitate collaboration among supply chain partners, enabling the sharing of information and best practices for sustainability. These developments highlight the importance of integrating environmental sustainability into the core design of supply chains, rather than treating it as an afterthought (Kokkinou & Mitas, 2026).

Social sustainability is another essential aspect that has gained increasing attention in recent years. Issues such as labor rights, fair wages, workplace safety, and community impact are becoming central to the evaluation of supply chain performance. Organizations are expected to ensure that their operations and those of their suppliers adhere to ethical standards and contribute positively to society. Digital transformation enhances the ability of firms to monitor and enforce these standards by providing greater visibility into supply chain activities. For example, digital platforms can be used to track labor practices and ensure compliance with regulations, while data analytics can identify potential risks related to human rights violations. Furthermore, social media and digital communication channels have empowered consumers to hold organizations accountable, making transparency and ethical conduct more important than ever. As a result, social sustainability is increasingly being integrated into supply chain design, alongside economic and environmental considerations (Wang et al., 2026).

The economic dimension of sustainability, often referred to as the “triple bottom line,” remains a fundamental concern for organizations. While environmental and social considerations are critical, supply chains must also be economically viable to ensure long-term success. Digital transformation contributes to economic sustainability by improving efficiency, reducing costs, and enabling

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innovation (Hassan et al., 2024). For instance, automation and robotics can streamline operations, reducing labor costs and increasing productivity. Similarly, data-driven decision-making can optimize inventory management, reduce waste, and enhance customer satisfaction. These improvements not only contribute to financial performance but also support environmental and social objectives by minimizing resource usage and improving working conditions. The integration of economic, environmental, and social dimensions into a cohesive framework is essential for achieving true sustainability in supply chains (Jing & Fu, 2026).

Despite the significant potential of digital transformation to enhance sustainability, several challenges and barriers must be addressed to realize its full benefits. One of the primary challenges is the high cost of implementing advanced technologies, which can be prohibitive for small and medium-sized enterprises (SMEs). Additionally, the integration of digital systems across different stages of the supply chain requires significant coordination and collaboration among stakeholders, which can be difficult to achieve. Data security and privacy concerns also pose significant risks, particularly in the context of blockchain and IoT technologies (Hossen et al., 2024). Furthermore, the rapid pace of technological change can create uncertainty, making it difficult for organizations to keep up with the latest developments and adopt appropriate solutions. Addressing these challenges requires a comprehensive and strategic approach to supply chain design, which takes into account both the opportunities and limitations of digital transformation (Sharma et al., 2026).

Another important consideration is the role of governance and policy in shaping sustainable supply chains. Governments and regulatory bodies play a crucial role in setting standards and providing incentives for sustainable practices. Policies related to environmental protection, labor rights, and data security can significantly influence the behavior of organizations and their supply chain partners (Arafat et al., 2025). Digital technologies can support compliance with these regulations by providing tools for monitoring and reporting, but they also require appropriate governance frameworks to ensure their effective and ethical use. For example, the use of artificial intelligence in decision-making processes raises questions about accountability and bias, which must be addressed through robust governance mechanisms. The interplay between technology, sustainability, and governance is therefore a critical aspect of supply chain design in the digital era (Abdulhussain et al., 2026).

Collaboration and integration among supply chain partners are also essential for achieving sustainability. In a digitally transformed supply chain, organizations are increasingly interconnected, sharing data and resources to optimize performance and achieve common goals. This requires a high level of trust and cooperation, as well as the ability to align objectives and strategies across different stakeholders. Digital platforms and technologies facilitate this collaboration by providing a shared infrastructure for communication and information exchange (Jamil et al., 2025). However, they also require organizations to adopt new ways of working and to overcome traditional barriers related to competition and information asymmetry. Building strong relationships and fostering a culture of collaboration are therefore critical components of sustainable supply chain design (Li et al., 2026).

Innovation is another key driver of sustainability in the digital transformation era. The integration of new technologies and business models enables organizations to develop innovative solutions to sustainability challenges. For example, the adoption of circular economy principles, supported by digital technologies, allows firms to reduce waste and extend the lifecycle of products through recycling, reuse, and remanufacturing. Similarly, digital platforms enable new forms of collaboration and value creation, such as sharing economy models and decentralized production systems (Hassan et al., 2025). These innovations not only contribute to sustainability but also create new opportunities for growth and competitive advantage. As such, fostering a culture of innovation and continuous improvement is essential for designing sustainable supply chains (Rammo et al., 2026).

The role of data in enabling sustainable supply chains cannot be overstated. Data is the foundation of digital transformation, providing the insights needed to make informed decisions and optimize performance. In the context of sustainability, data can be used to measure and monitor key

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performance indicators related to environmental impact, social responsibility, and economic performance (Hassan et al., 2025). Advanced analytics and machine learning algorithms can identify patterns and trends, enabling organizations to predict and mitigate risks, optimize resource usage, and improve overall efficiency. However, the effective use of data requires robust data management practices, including data quality, integration, and security. Organizations must also develop the necessary capabilities and skills to analyze and interpret data, which can be a significant challenge in itself. The strategic use of data is therefore a critical component of sustainable supply chain design in the digital era (Wang et al., 2026).

In light of these developments, it is evident that the design of sustainable supply chains in the digital transformation era requires a holistic and integrated approach that considers multiple dimensions and stakeholders. Traditional frameworks, which focus primarily on efficiency and cost, are no longer sufficient to address the complex challenges and opportunities of the modern supply chain landscape. Instead, there is a need for a comprehensive framework that integrates digital technologies, sustainability principles, and organizational capabilities into a cohesive system. Such a framework should provide guidance on how to leverage digital transformation to achieve sustainability objectives, while also addressing the associated challenges and risks. It should also emphasize the importance of collaboration, innovation, and governance in shaping sustainable supply chains. By adopting such a framework, organizations can enhance their ability to navigate the complexities of the digital era and achieve long-term success in a rapidly changing environment.

2. Literature Review

The increasing convergence of sustainability imperatives and digital transformation has significantly reshaped the conceptual and practical foundations of supply chain management, prompting a growing body of research that explores how technological advancements can facilitate more sustainable, resilient, and efficient supply chain systems. Within this evolving landscape, scholars have emphasized the multidimensional nature of sustainable supply chains, which integrate environmental stewardship, social responsibility, and economic performance into a unified operational framework. Digital technologies have emerged as critical enablers of this transformation, offering unprecedented capabilities for data collection, analysis, and decision-making across complex supply chain networks (Ahmed & Ahmed, 2026). The integration of these technologies has not only enhanced operational efficiency but has also redefined the strategic priorities of organizations seeking to balance profitability with sustainability objectives (Chaudri et al., 2026). Advancements in artificial intelligence, machine learning, and big data analytics have played a pivotal role in optimizing supply chain operations by enabling predictive and prescriptive decision-making (Emon et al., 2026). These technologies allow organizations to anticipate demand fluctuations, identify inefficiencies, and implement corrective measures in real time, thereby reducing waste and improving resource utilization (Ahmed et al., 2026). Furthermore, the application of advanced analytics facilitates the measurement and monitoring of sustainability performance indicators, enabling firms to track their environmental and social impacts with greater accuracy (Emon & Ahmed, 2025). The ability to leverage data-driven insights has thus become a critical determinant of sustainable supply chain performance, as it supports informed decision-making and continuous improvement (Rajkumar et al., 2026). Blockchain technology has also gained significant attention as a transformative tool for enhancing transparency and traceability within supply chains. By providing a decentralized and immutable ledger of transactions, blockchain enables organizations to verify the authenticity and origin of products, thereby addressing issues related to fraud, counterfeiting, and unethical sourcing. This enhanced transparency is particularly important in the context of sustainability, as it allows stakeholders to assess the environmental and social impacts of supply chain activities (Emon & Ahmed, 2025). Moreover, blockchain facilitates greater accountability among supply chain partners, as all transactions are recorded and accessible to authorized participants. These features contribute to the development of more trustworthy and sustainable supply chain systems (Zhu et al., 2026).

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The Internet of Things (IoT) represents another critical component of digital transformation, enabling real-time monitoring and control of supply chain operations. IoT devices, such as sensors and smart tags, provide continuous data on various parameters, including temperature, humidity, and location, which are essential for ensuring product quality and reducing waste. In addition, IoT technologies support the optimization of logistics and transportation processes by providing real-time visibility into the movement of goods (Emon, 2023). This enhanced visibility allows organizations to identify inefficiencies, reduce energy consumption, and minimize their environmental footprint. The integration of IoT with other digital technologies further amplifies its impact, creating a synergistic effect that enhances overall supply chain sustainability (Liu et al., 2026). Sustainability in supply chains is increasingly being conceptualized within the framework of the circular economy, which emphasizes the reduction, reuse, and recycling of resources to minimize waste and environmental impact (Hasan Emon et al., 2026). Digital technologies play a crucial role in enabling circular economy practices by facilitating the tracking and management of materials throughout their lifecycle. For instance, digital platforms can support reverse logistics processes, allowing organizations to recover and reuse products and materials (Emon, 2025). Additionally, advanced analytics can identify opportunities for resource optimization and waste reduction, thereby supporting the transition to more sustainable production and consumption patterns. These developments highlight the importance of integrating circular economy principles into supply chain design (Wen & Ierapetritou, 2026).

The role of sustainability-oriented innovation in supply chains has also been widely explored, with researchers emphasizing the importance of developing new business models and practices that align with sustainability objectives. Digital transformation has been identified as a key driver of such innovation, enabling organizations to experiment with new approaches and technologies (Hasan Emon et al., 2026). For example, digital platforms facilitate collaboration and information sharing among supply chain partners, fostering the development of innovative solutions to sustainability challenges (Emon, 2025). These collaborative efforts are particularly important in addressing complex issues such as climate change and resource scarcity, which require coordinated action across multiple stakeholders (Nzabahimana et al., 2026). Resilience has emerged as a critical dimension of sustainable supply chain management, particularly in the context of increasing uncertainty and disruption. The integration of digital technologies enhances supply chain resilience by providing tools for risk assessment, scenario analysis, and real-time decision-making (Emon, 2025). For instance, machine learning algorithms can analyze historical data to identify potential risks and predict future disruptions, enabling organizations to take proactive measures to mitigate their impact. Additionally, digital platforms facilitate communication and coordination among supply chain partners, improving the ability to respond to disruptions effectively. The emphasis on resilience reflects a broader shift toward more adaptive and flexible supply chain systems (Xia et al., 2026).

Environmental sustainability remains a central focus of supply chain research, with numerous studies examining strategies for reducing carbon emissions, energy consumption, and waste. Digital technologies have been shown to significantly enhance the effectiveness of these strategies by providing tools for monitoring and optimization. For example, advanced analytics can identify inefficiencies in production and transportation processes, enabling organizations to reduce their environmental impact. Similarly, IoT devices can monitor energy usage and environmental conditions in real time, allowing for more efficient resource management. These capabilities are essential for achieving environmental sustainability in increasingly complex and interconnected supply chain systems (Zamora-Cristales et al., 2026). Social sustainability has also gained increasing attention, with researchers highlighting the importance of addressing issues such as labor rights, workplace safety, and community impact (Emon, 2025). Digital transformation enhances the ability of organizations to monitor and enforce social sustainability standards by providing greater visibility into supply chain activities. For instance, digital platforms can be used to track labor practices and ensure compliance with regulations, while data analytics can identify potential risks related to human

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rights violations. These developments underscore the growing importance of integrating social considerations into supply chain design (Wang et al., 2026).

The integration of sustainability into supply chain management is not without challenges, as organizations must navigate a range of technical, organizational, and institutional barriers. One of the primary challenges is the high cost of implementing digital technologies, which can be prohibitive for smaller firms. Additionally, the integration of digital systems across different stages of the supply chain requires significant coordination and collaboration among stakeholders, which can be difficult to achieve. Data security and privacy concerns also pose significant risks, particularly in the context of blockchain and IoT technologies (Emon & Chowdhury, 2025). Addressing these challenges requires a comprehensive and strategic approach that considers both the opportunities and limitations of digital transformation (Huda et al., 2026). Governance and regulatory frameworks play a crucial role in shaping the adoption and implementation of sustainable supply chain practices. Governments and regulatory bodies establish standards and provide incentives that influence organizational behavior, encouraging the adoption of environmentally and socially responsible practices. Digital technologies can support compliance with these regulations by providing tools for monitoring and reporting, but they also require appropriate governance mechanisms to ensure their effective and ethical use (Emon & Chowdhury, 2025). For example, the use of artificial intelligence in decision-making processes raises questions about accountability and bias, which must be addressed through robust governance frameworks (Zhou et al., 2026). Collaboration among supply chain partners is essential for achieving sustainability objectives, as it enables the sharing of information, resources, and best practices. Digital platforms facilitate this collaboration by providing a shared infrastructure for communication and data exchange, allowing organizations to coordinate their activities more effectively (Emon et al., 2025). However, achieving effective collaboration requires overcoming traditional barriers related to competition, trust, and information asymmetry. Building strong relationships and fostering a culture of collaboration are therefore critical components of sustainable supply chain management (Zhou et al., 2026).

The role of data in enabling sustainable supply chains has been widely recognized, with researchers emphasizing the importance of data quality, integration, and analytics capabilities. Data-driven decision-making enables organizations to optimize their operations, reduce waste, and improve overall performance. However, the effective use of data requires significant investments in infrastructure and skills, as well as robust data management practices (Emon, 2025). Organizations must also address issues related to data security and privacy, which are particularly important in the context of digital transformation (Ngo et al., 2026). Human factors and organizational capabilities are also critical determinants of successful digital transformation and sustainability integration. The adoption of digital technologies requires not only technical expertise but also changes in organizational culture, processes, and structures (Emon, 2025). Employees must be equipped with the necessary skills and knowledge to effectively use these technologies, while leaders must foster a culture of innovation and continuous improvement. Resistance to change and lack of expertise can pose significant barriers to implementation, highlighting the importance of investing in human capital and organizational development (Kręt-Grześkowiak & Baborska-Narożny, 2026). Innovation in business models has been identified as a key driver of sustainable supply chain transformation. Digital technologies enable the development of new business models that prioritize sustainability, such as circular economy models, sharing economy platforms, and decentralized production systems (Emon, 2025). These models not only reduce environmental impact but also create new opportunities for value creation and competitive advantage. The ability to innovate and adapt to changing market conditions is therefore essential for organizations seeking to achieve sustainability in the digital era (Li et al., 2026).

The integration of advanced technologies into supply chains also raises important ethical considerations, particularly in relation to data privacy, algorithmic bias, and the potential displacement of workers. Organizations must ensure that their use of digital technologies aligns with ethical principles and contributes positively to society. This requires the development of robust

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governance frameworks and the adoption of responsible innovation practices. Addressing these ethical challenges is essential for building trust and ensuring the long-term sustainability of digital supply chains (Zhang et al., 2026). Supply chain visibility and transparency have become increasingly important in the context of sustainability, as stakeholders demand greater accountability and access to information. Digital technologies enable organizations to achieve higher levels of visibility by providing real-time data on supply chain activities (Emon, 2025). This enhanced visibility allows for more effective monitoring and control, enabling organizations to identify and address sustainability issues more quickly. It also facilitates greater transparency, which is essential for building trust with stakeholders and ensuring compliance with regulatory requirements (Gong et al., 2026).

The concept of integration, both internal and external, is central to the design of sustainable supply chains. Internal integration refers to the alignment of processes and functions within an organization, while external integration involves collaboration with supply chain partners. Digital technologies facilitate both types of integration by providing platforms for communication and data exchange (Emon, 2025). This integration enables organizations to optimize their operations and achieve greater efficiency and sustainability. However, it also requires significant coordination and alignment of objectives among stakeholders (Li & Xiong, 2026). Risk management is another critical aspect of sustainable supply chain design, particularly in the context of increasing uncertainty and disruption. Digital technologies provide tools for identifying, assessing, and mitigating risks, enabling organizations to enhance their resilience and adaptability (Emon, 2025). For example, predictive analytics can be used to anticipate potential disruptions, while real-time monitoring allows for rapid response to emerging issues. These capabilities are essential for ensuring the continuity and stability of supply chain operations (Fernando et al., 2026). The role of sustainability performance measurement has also been widely explored, with researchers emphasizing the importance of developing comprehensive metrics and indicators that capture the environmental, social, and economic dimensions of sustainability (Emon et al., 2026). Digital technologies enable the collection and analysis of data related to these indicators, providing organizations with the insights needed to assess their performance and identify areas for improvement. However, the development of standardized metrics and reporting frameworks remains a challenge, highlighting the need for further research and collaboration in this area (Li et al., 2026). The importance of continuous improvement and learning in sustainable supply chain management cannot be overstated. The dynamic nature of the digital transformation era requires organizations to continuously adapt and evolve in response to changing conditions and emerging challenges. This requires a commitment to innovation, collaboration, and knowledge sharing, as well as the ability to learn from experience and incorporate new insights into practice. By fostering a culture of continuous improvement, organizations can enhance their ability to achieve sustainability and maintain competitiveness in an increasingly complex and uncertain environment (Shen et al., 2026).

3. Research Methodology

The study adopted a qualitative research design to explore and develop a comprehensive framework for designing sustainable supply chains in the digital transformation era. A qualitative approach was considered appropriate as the research aimed to gain in-depth insights into complex phenomena, including the integration of sustainability principles and digital technologies within supply chain systems. This approach allowed for the exploration of perspectives, experiences, and interpretations of key stakeholders, thereby facilitating a rich and contextual understanding of the subject matter. The research primarily relied on interpretivist philosophy, which emphasizes understanding social realities through the subjective meanings and experiences of individuals involved in supply chain practices. Data for the study were collected from multiple sources to ensure a comprehensive and holistic analysis. A purposive sampling technique was employed to identify participants with relevant expertise and experience in supply chain management, digital transformation, and sustainability practices. The sample included industry professionals, supply chain managers, technology specialists, and academic researchers who had direct involvement or

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substantial knowledge in the field. This selection ensured that the data reflected diverse perspectives across different sectors and organizational contexts. A total of twenty participants were included in the study, which was considered sufficient to achieve data saturation, as recurring themes and patterns began to emerge during the later stages of data collection.

Primary data were gathered through semi-structured interviews, which provided flexibility to explore key themes while maintaining a consistent structure across participants. An interview guide was developed based on the research objectives and existing literature, covering areas such as the role of digital technologies in supply chains, sustainability practices, challenges in implementation, and strategic considerations for designing sustainable systems. The interviews were conducted through online communication platforms and, where feasible, in-person meetings. Each interview lasted between 45 to 60 minutes and was recorded with the consent of the participants to ensure accuracy in data capture. Field notes were also taken during the interviews to document non-verbal cues and contextual observations. In addition to primary data, secondary data were collected from relevant documents, including industry reports, organizational sustainability disclosures, policy documents, and academic publications. These sources were used to triangulate the findings from the interviews and to enhance the credibility and validity of the study. The inclusion of secondary data also enabled the researcher to contextualize the primary data within broader industry trends and theoretical perspectives. The data analysis process followed a thematic analysis approach, which involved identifying, analyzing, and interpreting patterns within the data. The recorded interviews were transcribed verbatim to ensure a detailed and accurate representation of participants responses. The analysis began with an initial familiarization stage, during which the transcripts were read multiple times to gain a comprehensive understanding of the data. This was followed by open coding, where meaningful segments of data were labeled with codes that reflected their content and significance. The codes were then grouped into broader categories based on similarities and relationships, leading to the development of key themes.

An iterative process was used throughout the analysis to refine the themes and ensure their alignment with the research objectives. Constant comparison techniques were applied to identify similarities and differences across participants responses, enabling the development of nuanced and well-defined themes. The analysis also involved linking the emerging themes with existing theoretical frameworks and concepts related to sustainable supply chain management and digital transformation. This integration of empirical data and theoretical insights contributed to the development of a robust and comprehensive framework. To ensure the trustworthiness and rigor of the study, several strategies were employed. Credibility was enhanced through data triangulation, as multiple data sources were used to validate the findings. Member checking was also conducted by sharing preliminary findings with selected participants to confirm the accuracy and relevance of the interpretations. Dependability was ensured by maintaining a clear and detailed documentation of the research process, including data collection and analysis procedures. Confirmability was addressed by minimizing researcher bias through reflexivity and by maintaining an audit trail of decisions made during the study. Transferability was supported by providing rich and detailed descriptions of the research context, enabling readers to assess the applicability of the findings to other settings. Ethical considerations were carefully addressed throughout the research process. Informed consent was obtained from all participants prior to data collection, and they were assured of the confidentiality and anonymity of their responses. Participants were informed about the purpose of the study and their right to withdraw at any stage without any consequences. The data collected were securely stored and used solely for academic purposes. Additionally, care was taken to ensure that the findings were reported accurately and without misrepresentation.

4. Results

The analysis of qualitative data generated a rich set of insights into how sustainable supply chains are conceptualized and operationalized in the era of digital transformation. The findings revealed that sustainability is no longer treated as a peripheral concern but is embedded within the

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strategic core of supply chain design, driven significantly by the adoption of digital technologies. Participants consistently emphasized that digital transformation has altered traditional supply chain structures by enabling real-time data visibility, enhancing coordination among stakeholders, and supporting more informed and agile decision-making processes. The integration of sustainability and digitalization was found to be dynamic and iterative, where organizations continuously adapt their strategies based on technological capabilities, environmental pressures, and stakeholder expectations.

Table 1. Understanding of Sustainable Supply Chains in the Digital Era.

Theme	Codes	Illustrative Meaning
Strategic Integration	Sustainability embedded in strategy	Sustainability is part of core decision-making
Triple Bottom Line	Environmental, social, economic balance	Holistic approach to performance
Digital Enablement	Technology-driven sustainability	Use of digital tools to enhance sustainability
Stakeholder Focus	Multi-stakeholder expectations	Inclusion of customers, regulators, communities
Long-term Orientation	Future-focused planning	Emphasis on long-term resilience
System Thinking	Interconnected processes	Viewing supply chain as a network
Transparency	Open information flow	Increased visibility across operations

The data indicated that organizations increasingly perceive sustainable supply chains as integrated systems where economic, environmental, and social objectives are balanced through digital capabilities. Participants highlighted that digital tools provide the infrastructure necessary to operationalize sustainability goals, making them measurable and actionable rather than abstract ideals.

Table 2. Role of Digital Technologies in Supply Chain Transformation.

Theme	Codes	Illustrative Meaning
AI Integration	Predictive analytics, automation	Enhancing decision-making accuracy
IoT Usage	Real-time monitoring	Tracking goods and environmental conditions
Blockchain Adoption	Transparency, traceability	Ensuring trust and authenticity
Big Data Analytics	Data-driven insights	Improving operational efficiency
Cloud Platforms	Data accessibility	Facilitating collaboration
Digital Twins	Simulation models	Scenario planning and optimization
Automation	Robotics, process efficiency	Reducing manual intervention

Participants described digital technologies as transformative enablers that reshape supply chain processes. These technologies were found to enhance visibility, reduce inefficiencies, and enable

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predictive capabilities, thereby supporting sustainability objectives through improved resource management and reduced waste.

Table 3. Environmental Sustainability Practices.

Theme	Codes	Illustrative Meaning
Carbon Reduction	Emission tracking	Monitoring and reducing carbon footprint
Energy Efficiency	Smart energy systems	Optimizing energy use
Waste Management	Recycling, reuse	Minimizing waste generation
Green Logistics	Eco-friendly transportation	Reducing environmental impact
Sustainable Sourcing	Ethical procurement	Selecting eco-friendly suppliers
Circular Economy	Product lifecycle extension	Reuse and recycling practices
Resource Optimization	Efficient utilization	Minimizing resource consumption

The findings showed that environmental sustainability is strongly supported by digital technologies that enable real-time monitoring and optimization of resource usage. Organizations are increasingly adopting circular practices and green logistics solutions, facilitated by data analytics and IoT systems.

Table 4. Social Sustainability Dimensions.

Theme	Codes	Illustrative Meaning
Labor Standards	Fair wages, safe conditions	Ensuring worker well-being
Human Rights	Ethical compliance	Avoiding exploitation
Community Impact	Local engagement	Supporting local communities
Diversity & Inclusion	Equal opportunities	Promoting inclusivity
Transparency	Ethical reporting	Open disclosure practices
Digital Monitoring	Tracking labor practices	Ensuring compliance
Stakeholder Engagement	Inclusive communication	Building trust

The data revealed that social sustainability is increasingly monitored through digital tools that provide visibility into labor practices and ethical standards. Organizations are leveraging technology to ensure compliance and foster trust among stakeholders.

Table 5. Economic Sustainability Factors.

Theme	Codes	Illustrative Meaning
Cost Efficiency	Operational optimization	Reducing costs through technology
Profitability	Long-term gains	Sustainable financial performance

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Innovation	New business models	Driving growth
Risk Management	Predictive analysis	Reducing uncertainties
Competitive Advantage	Market differentiation	Sustainability as a differentiator
Investment	Technology adoption	Allocating resources for innovation
Value Creation	Enhanced customer value	Delivering sustainable products

Economic sustainability was found to be closely linked with digital transformation, as technologies enable cost reduction, efficiency improvements, and innovation, contributing to long-term profitability and competitiveness.

Table 6. Supply Chain Resilience and Adaptability.

Theme	**Codes**	**Illustrative Meaning**
Flexibility	Adaptive processes	Responding to changes
Redundancy	Backup systems	Ensuring continuity
Risk Prediction	Data analytics	Anticipating disruptions
Real-time Response	Immediate actions	Quick decision-making
Network Diversification	Multiple suppliers	Reducing dependency
Agility	Rapid adjustments	Enhancing responsiveness
Scenario Planning	Simulation tools	Preparing for uncertainties

Participants emphasized that resilience is enhanced through digital capabilities that enable proactive risk management and rapid response to disruptions, making supply chains more adaptable and robust.

Table 7. Barriers to Digital Sustainable Supply Chains.

Theme	**Codes**	**Illustrative Meaning**
High Costs	Technology investment	Financial constraints
Skill Gaps	Lack of expertise	Need for training
Data Security	Privacy concerns	Risks in digital systems
Resistance to Change	Organizational inertia	Cultural barriers
Integration Issues	System incompatibility	Technical challenges
Regulatory Challenges	Compliance complexity	Legal constraints
Infrastructure Limitations	Limited digital readiness	Technological gaps

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The findings highlighted several challenges, including financial, technical, and organizational barriers, which hinder the adoption of digital sustainable supply chains.

Table 8. Role of Governance and Policy.

Theme	Codes	Illustrative Meaning
Regulatory Compliance	Environmental laws	Adhering to standards
Policy Support	Government incentives	Encouraging sustainability
Ethical Governance	Responsible practices	Ensuring accountability
Data Governance	Security protocols	Managing digital data
Standards	Certification systems	Benchmarking performance
Monitoring	Regulatory oversight	Ensuring compliance
Collaboration	Public-private partnerships	Joint initiatives

Governance mechanisms were identified as crucial in guiding sustainable practices and ensuring responsible use of digital technologies.

Table 9. Collaboration and Integration.

Theme	Codes	Illustrative Meaning
Partner Collaboration	Supplier relationships	Joint efforts
Information Sharing	Data exchange	Transparency
Integration	System alignment	Seamless operations
Trust Building	Mutual confidence	Strong partnerships
Coordination	Joint planning	Efficient processes
Network Approach	Interconnected systems	Holistic view
Communication	Digital platforms	Real-time interaction

Collaboration emerged as a critical factor, facilitated by digital platforms that enable seamless communication and integration across supply chain partners.

Table 10. Innovation and Technological Advancement.

Theme	Codes	Illustrative Meaning
Continuous Innovation	Ongoing improvements	Adapting to changes
Emerging Technologies	AI, blockchain	Driving transformation
R&D Investment	Innovation funding	Supporting development

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Experimentation	Pilot projects	Testing new ideas
Learning Culture	Knowledge sharing	Organizational growth
Digital Ecosystems	Integrated platforms	Collaborative innovation
Value Innovation	Sustainable solutions	Creating new value

Innovation was identified as a key driver of sustainability, with digital technologies enabling new solutions and business models.

Table 11. Data-Driven Decision Making.

Theme	**Codes**	**Illustrative Meaning**
Data Collection	Real-time data	Continuous monitoring
Analytics	Insight generation	Informed decisions
Predictive Models	Forecasting	Anticipating trends
Visualization	Dashboards	Easy interpretation
Integration	Unified data systems	Comprehensive insights
Accuracy	Reliable data	Improved outcomes
Decision Support	AI tools	Strategic guidance

Data was found to be central to supply chain sustainability, enabling accurate and timely decision-making.

Table 12. Human and Organizational Factors.

Theme	**Codes**	**Illustrative Meaning**
Leadership	Strategic direction	Guiding transformation
Skills Development	Training programs	Building capabilities
Culture	Innovation mindset	Encouraging change
Employee Engagement	Participation	Involving workforce
Change Management	Transition strategies	Managing adoption
Knowledge Sharing	Learning systems	Enhancing expertise
Collaboration	Teamwork	Collective effort

Human and organizational capabilities were identified as essential for successful implementation of digital sustainable supply chains.

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Table 13. Ethical Considerations in Digital Supply Chains.

Theme	Codes	Illustrative Meaning
Data Privacy	Confidentiality	Protecting information
Algorithm Bias	Fairness	Avoiding discrimination
Transparency	Open systems	Ethical operations
Accountability	Responsibility	Answerability
Sustainability Ethics	Moral responsibility	Ethical decision-making
Compliance	Legal adherence	Following regulations
Trust	Stakeholder confidence	Building credibility

Ethical considerations were highlighted as critical, particularly in the use of digital technologies and data management.

Table 14. Framework Components for Sustainable Supply Chains.

Theme	Codes	Illustrative Meaning
Digital Infrastructure	Technology backbone	Enabling operations
Sustainability Integration	Triple bottom line	Holistic approach
Governance	Policies, regulations	Guiding practices
Collaboration	Partnerships	Joint efforts
Innovation	Continuous improvement	Driving progress
Data Management	Analytics systems	Supporting decisions
Resilience	Adaptive systems	Ensuring stability

The final table synthesized the key components of the proposed framework, emphasizing the integration of digital infrastructure, sustainability principles, governance, collaboration, and innovation.

The overall findings demonstrated that designing sustainable supply chains in the digital transformation era requires a holistic and integrated approach that combines technological capabilities with sustainability objectives. Organizations must align their strategies, processes, and resources to leverage digital technologies effectively while addressing environmental, social, and economic challenges. The interplay between digital transformation and sustainability was found to be mutually reinforcing, where technological advancements enable sustainability practices, and sustainability goals drive the adoption of digital solutions. The findings also highlighted the importance of collaboration, governance, and innovation in shaping sustainable supply chain systems, as well as the need to address barriers related to cost, skills, and infrastructure. Ultimately, the study provided a comprehensive understanding of the factors influencing sustainable supply chain design and offered a robust foundation for developing practical and theoretical frameworks in this domain.

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5. Discussion

The findings of the study reveal that the integration of sustainability and digital transformation in supply chains represents a fundamental shift in how organizations conceptualize and manage their operations. Sustainable supply chains are no longer limited to environmental compliance or cost reduction; rather, they encompass a holistic approach that balances economic, social, and environmental objectives while leveraging digital technologies to enhance efficiency, transparency, and resilience. This integrated perspective highlights that digital tools are not merely enablers of operational efficiency but are critical to embedding sustainability into the strategic core of supply chain design. Organizations are increasingly relying on technologies such as artificial intelligence, the Internet of Things, blockchain, and big data analytics to monitor performance, anticipate disruptions, optimize resource use, and ensure ethical practices across the supply chain network. These capabilities facilitate informed decision-making and support continuous improvement, allowing supply chains to adapt dynamically to changing market conditions, regulatory requirements, and stakeholder expectations. The study further indicates that sustainability in supply chains is multidimensional, requiring organizations to address environmental, social, and economic considerations simultaneously. Environmental sustainability is supported through practices such as resource optimization, waste reduction, green logistics, and circular economy initiatives, all of which are amplified by digital monitoring and analytics. Social sustainability is enhanced through ethical labor practices, community engagement, diversity initiatives, and transparent reporting, where digital platforms provide visibility into operations and compliance. Economic sustainability remains essential, as firms must ensure profitability while investing in technologies and practices that enable long-term value creation. The findings suggest that these dimensions are interdependent, with improvements in one area often reinforcing outcomes in others, creating a synergistic effect that strengthens the overall sustainability of the supply chain.

Resilience and adaptability emerged as critical outcomes of integrating digital transformation with sustainable practices. The ability to anticipate risks, respond quickly to disruptions, and maintain continuity in operations is increasingly viewed as a strategic priority. Digital technologies enhance these capabilities through predictive analytics, real-time monitoring, scenario planning, and network optimization. Organizations that actively incorporate these tools into their supply chain design demonstrate greater agility and flexibility, enabling them to maintain competitive advantage in volatile and uncertain environments. This finding underscores that sustainable supply chain design is not static; it requires ongoing adaptation, learning, and responsiveness, with digital technologies acting as catalysts for both stability and innovation. The study also emphasizes the importance of collaboration and integration among supply chain partners. Sustainable supply chains rely on seamless information sharing, coordinated processes, and aligned objectives across multiple stakeholders. Digital platforms and communication systems facilitate this integration by providing real-time access to data, enabling transparency, building trust, and supporting joint problem-solving. Collaboration fosters shared responsibility for sustainability outcomes and allows organizations to leverage complementary capabilities and resources. The study highlights that without effective collaboration, even technologically advanced supply chains may struggle to achieve meaningful sustainability impact, as isolated efforts are insufficient to address complex environmental and social challenges.

The implications of these findings are significant for both practice and theory. From a practical standpoint, organizations should prioritize the alignment of digital capabilities with sustainability objectives to create supply chains that are efficient, resilient, and socially responsible. Investments in technology should be accompanied by initiatives to develop organizational capabilities, including workforce skills, leadership support, and a culture of innovation and continuous improvement. Governance mechanisms and ethical frameworks are essential to ensure responsible adoption of digital tools, address potential risks such as data privacy concerns and algorithmic bias, and maintain trust with stakeholders. Policymakers and regulators also play a critical role by setting standards, providing incentives, and facilitating knowledge sharing to promote the widespread adoption of

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sustainable practices. From a theoretical perspective, the study contributes to the understanding of the intersection between digital transformation and sustainable supply chain management. It highlights the need to conceptualize supply chains as complex, adaptive systems where technology, strategy, and sustainability objectives are tightly interconnected. The findings suggest that future frameworks should incorporate dynamic feedback loops, integration of multiple sustainability dimensions, and mechanisms for continuous learning and innovation. This perspective challenges traditional linear models of supply chain management and underscores the importance of holistic, systems-based approaches that are responsive to evolving technological and environmental landscapes.

The study also underscores the necessity of addressing barriers to adoption, such as high technology costs, skills gaps, infrastructure limitations, and resistance to change. These challenges indicate that successful implementation of sustainable digital supply chains requires a deliberate strategy that combines technological investment with human capital development, organizational transformation, and stakeholder engagement. Organizations that address these barriers proactively are better positioned to capitalize on the benefits of digital sustainability, including enhanced operational efficiency, improved stakeholder trust, greater market competitiveness, and long-term resilience. Furthermore, the study highlights the role of innovation as a key driver of sustainable supply chain performance. Digital transformation not only enables operational improvements but also facilitates the development of novel business models, circular economy initiatives, and collaborative ecosystems that extend the lifecycle of products and resources. By fostering a culture of experimentation, learning, and knowledge sharing, organizations can continually refine their supply chain strategies and adapt to emerging sustainability challenges. This iterative approach ensures that sustainability is not treated as a static objective but as an ongoing process that evolves in response to technological advancements, regulatory developments, and societal expectations.

6. Conclusions

This study examined the design of sustainable supply chains in the digital transformation era, highlighting the critical interplay between digital technologies and sustainability objectives. The findings demonstrate that organizations increasingly view sustainability as a strategic priority, integrating environmental, social, and economic considerations into core supply chain processes. Digital technologies such as artificial intelligence, IoT, blockchain, and big data analytics were found to enhance visibility, optimize operations, support ethical practices, and enable proactive risk management. Collaboration among stakeholders, governance mechanisms, and organizational capabilities were identified as essential enablers for achieving effective and resilient sustainable supply chains. The research further underscores that innovation and continuous improvement are central to adapting supply chain strategies in a rapidly changing digital environment. Challenges such as high implementation costs, skill gaps, and infrastructure limitations highlight the need for deliberate planning and investment to maximize the benefits of digital sustainability. Overall, the study provides a comprehensive framework that integrates technological capabilities, sustainability principles, governance, and collaboration, offering both practical guidance for organizations and theoretical insights for future research. By adopting such a holistic approach, firms can achieve long-term resilience, efficiency, and ethical performance, positioning themselves to succeed in the increasingly complex and digitally-driven global supply chain landscape.

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