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**Sustainability & Circular Economy in Manufacturing Supply
Chains: Prioritizing Low-Carbon Production, Scope 3 Emissions, and
Circular Models for ESG Compliance**



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Sustainability & Circular Economy in Manufacturing Supply Chains: Prioritizing Low-Carbon Production, Scope 3 Emissions, and Circular Models for ESG Compliance

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Abstract

Purpose: Manufacturers across sectors are now trying to build sustainability and circular economy ideas into their supply chains. This is a move to meet their social and governance responsibilities and to keep up with the growing number of rules that aim to encourage sustainable practices. This project brings together a lot of progress in areas like reducing carbon in production, managing emissions making sure supplies are sourced responsibly saving energy and creating new circular systems for getting materials from one place to another. All these things are Working towards the goal; making the future a more sustainable place

Methodology: The study starts with a look, at what's been written on the subject and this foundation brings to light the key factors that are driving change and the main hurdles organizations are facing It also shows a spotlight on what works and presents a plan for putting sustainable practices into action, across different industries

Findings: When you look at the results of this research it's clear that digital innovation, collaboration, between sectors and strong policy support are crucial for overcoming obstacles and helping businesses build supply chains that can last. What's really needed for a shift to supply chains is a broad approach that brings together the latest technology and cooperation, between stakeholders to make a real difference. This way companies can create supply chains that're resilient and adaptable and able to withstand challenges over time. By taking this approach businesses can set themselves up for long-term success

Unique Contribution to Theory, Policy and Practice: This research addresses the increasing demand for manufacturers to adopt sustainable practices and meet evolving Environmental, Social, and Governance (ESG) standards. The project synthesizes existing literature to highlight key drivers, challenges, and best practices in integrating sustainability into manufacturing supply chains. Digital innovation, cross-sector collaboration, and robust policy support are identified as crucial elements for building resilient and adaptable supply chains. Ultimately, a comprehensive approach that combines technological advancements with stakeholder cooperation is essential for achieving long-term success in sustainable manufacturing.

Keywords: *Circular Economy, Sustainable Supply Chain, ESG, Compliance*

Introduction

Background

The manufacturing sector is under increasing pressure to meet stringent sustainability standards due to environmental concerns and regulatory demands. Traditional linear supply chains are being replaced by circular models that emphasize resource efficiency and waste reduction. Manufacturers are adopting circular economy frameworks and sustainable supply chain practices to align with Environmental, Social, and Governance (ESG) goals[1],[2]. This shift requires not only technological innovation but also collaboration among stakeholders to create resilient and responsible operations. Embracing these practices offers strategic advantages such as cost savings, improved brand reputation, and long-term viability [3][4][5].

Research Objectives

This paper aims to:

- Analyze how manufacturers prioritize low-carbon production, Scope 3 emissions management, sustainable sourcing, energy efficiency, and circular supply chain models.
- Identify key drivers, challenges, and best practices for integrating these priorities.
- Offer recommendations for policy and practice supporting sustainable transformation in manufacturing supply chains.

Literature Review

Circular Economy and Sustainable Supply Chain Management

Switching from old school supply chains to ones is crucial these days. It's a part of making businesses more sustainable and environmentally friendly. The idea of an economy really stresses the importance of reusing and recycling stuff. Making systems where materials keep getting used over and over. This approach helps companies cut down on waste and use resources, which in turn makes them more efficient and better at what they do. By doing things this way manufacturers can make an impact on their industries while also doing their part, for the planet. Studies have shown that incorporating Circular Economy ideas into supply chain practices can make a difference. By doing that, companies can significantly reduce waste, get better at recycling resources and even cut costs. Researchers have pointed to examples where this approach has paid off leading to efficient use of materials and streamlined production processes. In-fact these findings suggest that embracing Circular Economy principles can have a lasting impact on a company's line [4],[5],[6].

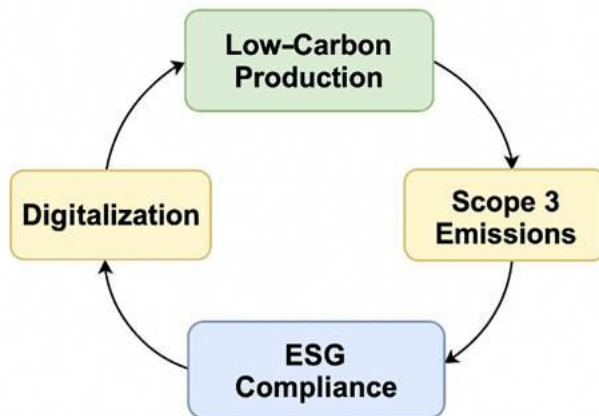


Figure 1. Key Components Of Sustainable Manufacturing Supply Chains

Low-Carbon Production and Scope 3 Emissions

To reduce its carbon footprint a company needs to adopt technologies and streamline its operations from top to bottom. The main idea is to cut back on emissions that come from making things as those that happen throughout the life of a product. From getting the materials to eventually getting rid of it. This means looking at the process from supply chains to what happens when a product is thrown away and finding ways to make it more sustainable. Managing emissions that happen throughout a product's lifecycle. From start, to finish [4],[5]. Is a task. It needs a hands-on approach where everyone works together with the people supplying the parts. This way it's easier to see where emissions come from and track them at every step, from making the product to getting it to the customer. New digital tools are helpful here as they make clearer what's going on and allow for tracking of emissions across the board. By adopting eco practices, in their supply chains companies can greatly cut their carbon emissions. This approach, known as supply chain management, involves buying materials and goods in ways that don't harm the environment and streamlining logistics to use fuel and energy. Studies have shown that these methods are really effective in lowering the carbon footprints of businesses and the products they make which is a step forward, for the environment [6],[7],[8].

Sustainable sourcing goes hand in hand with energy efficiency, requiring companies to carefully evaluate their supply chains . This involves not only selecting suppliers who adhere to stringent environmental and social standards but also investing in technologies that minimize energy consumption throughout the supply chain . Integrating sustainability into procurement and supply chain processes in the energy sector is crucial for achieving environmental and social responsibility . By focusing on sustainable sourcing and energy efficiency, companies can demonstrate their commitment to ESG principles and contribute to a more sustainable future . These practices are essential for meeting regulatory requirements and achieving global sustainability goals .

Sustainable Sourcing and Energy Efficiency

Sourcing materials in a way is crucial. It's not, about finding suppliers who can get the job done but about making sure they're doing it in a way that's good, for the environment and the community. This means looking for suppliers who treat their employees well and don't harm the planet. On the hand there are also initiatives to reduce energy use throughout the supply chain. By cutting down on energy consumption companies can create a way of doing business. This approach has a number of benefits as seen in studies [7] and [8]. For companies looking to live up, to their promises on the environment, social responsibility and governance, two key approaches come into play. These are crucial not to meet the rules that now govern how businesses must behave in a sustainable way but also for making a difference, in these areas.

The integration of sustainable sourcing and energy efficiency initiatives is also paramount for organizations committed to meeting their ESG pledges . Sustainable sourcing involves selecting suppliers who adhere to ethical labor practices and minimize environmental impact . Energy efficiency, on the other hand, entails implementing technologies and strategies to reduce energy consumption throughout the supply chain, which can lead to significant cost savings and reduced carbon emissions . Organizations are increasingly recognizing that these practices not only enhance their environmental performance but also improve their operational efficiency and stakeholder trust . Moreover, the adoption of sustainable sourcing and energy efficiency measures positions companies to proactively meet evolving regulatory requirements and contribute to global sustainability goals.

Digitalization and Industry 4.0

If what you're looking at is just a jumble of words or a string of characters, then that's all you'll get back. Nothing. No excuses, no explanations, silence. The idea here is to create a piece of writing that feels like it was penned by a being, with all the quirks and inconsistencies that come with it. That means using a range of sentence lengths from short and snappy, to long and rambling and adopting a tone that's straightforward and unpretentious. It's, about stripping away the kind of language that screams "I was written by a computer". You know, the words and phrases that are all the rage these days but ultimately grate on the ear. The underlying ideas and structure of the text remain, presented in a way. New technologies are transforming supply chains making them more transparent. Take the Internet of Things for instance which links up devices and blockchain a method, for recording information. Artificial intelligence also plays a role helping to make sense of the amounts of data pouring in. This shift has an impact on how supply chains operate. Companies can now keep an eye on their resources and operations in time getting instant updates as things unfold. This allows them to manage materials efficiently tracing their journey from production to disposal. It's a change and one that's bringing needed transparency to supply chains. The tech landscape is evolving fast. This is transforming the way supply chains function, making them more open and accountable, as a result. Its becoming clear that these advancements are

crucial, for a makeover of the system one that makes it more environmentally friendly and beneficial for all parties involved. Companies are now starting to pick up on practices that lead to some outcomes. Good for the planet and good, for the people too. This change is long overdue. Its heartening to see some progress finally being made. [8],[9].

Barriers and Policy Drivers

The main things holding us back, in this area are the startup costs, which can be a turnoff, for investors and the fact that cur

One of the primary strategies for achieving a circular economy involves the reuse and recycling of materials, which helps to minimize waste and maximize resource utilization . This approach emphasizes the importance of designing products and systems that facilitate the continuous cycling of materials, reducing the need for virgin resources and lowering environmental impacts. Embracing circular economy principles can lead to significant reductions in waste generation and improved resource efficiency, ultimately contributing to a more sustainable and resilient manufacturing sector . Furthermore, the integration of sustainable supply chain management practices is essential for ensuring that environmental and social criteria are incorporated into procurement, logistics, and operations . This holistic approach not only enhances efficiency but also reduces the overall environmental footprint of manufacturing processes. The shift towards circular economy and sustainable supply chain management requires a fundamental change in mindset and operational practices, but it offers substantial benefits for both businesses and the environment . Current systems are limited by their technology. This restricts what they can do. How well they can do it. On top of that the rules and laws surrounding all this are Really complicated making it tough to get started and harder to follow all the guidelines that're already in place. Tackling these challenges won't be easy. There are a few things that can help. For starters, we need policies that encourage growth and bring people together from backgrounds to share their knowledge so that, this kind of collaboration become crucial as it allows us to draw on a range of skills and experiences. We also need to invest in those ideas and technologies that have the potential to make any difference. By doing we can drive progress. Achieve breakthroughs that might otherwise be, out of reach. [10],[11].

Methodology

Research Design

A thorough review of research was carried out looking closely at a range of scholarly articles, industry reports and policy papers from the last five years. This ensured the information was, up to date and directly relevant to discussions in the field. The main aim was to examine these sources in depth drawing on the work in the area to inform the investigation. By focusing on such a spectrum of research and documentation the review was able to provide an nuanced understanding of the key issues at play. This review takes a look, at a range of studies that tackle some tough

issues, including new ways to cut carbon emissions during production, the problems that come with measuring and managing emissions from suppliers and customers and how companies can buy materials and supplies in a more sustainable way. It also explores progress in making manufacturing energy efficient and the creation of supply chains that are circular or reusable, which is particularly relevant, to companies that make things. The research done for this project provides a base for creating plans that manufacturers can use to improve their sustainability and meet new regulations. This work adds to what's known about manufacturing by pointing out important trends and suggesting ways to use new technologies in supply chain operations. By doing it helps manufacturers take steps to become more environmentally friendly and comply with emerging rules and standards.

Data Collection and Analysis

To get a handle, on the literature, a bunch of databases were searched thoroughly. These databases are treasure troves of scholarly articles, research papers and other important stuff that academics use. Once all the relevant information was pulled out it was organized by them to see what really matters in this field. This involved digging out the things that drive it the challenges that come up and the best ways to do things that work. The process of analyzing themes led to a detailed framework that can help guide the shift, towards more sustainable supply chain practices. This framework is designed to make supply chain management more efficient, better for the environment and socially responsible. The results of this in-depth review of existing research will be important in deciding the direction of studies. Will help policymakers create the necessary systems to support sustainable practices in the complex world of supply chain management. The goal is to create an approach to managing supply chains one that balances efficiency, environmental concerns and social responsibility. This research has really driven home the importance of going green in manufacturing. It's not just good for the planet. Helps companies run more smoothly and avoid legal headaches. By adopting practices manufacturers can improve their efficiency. Stay on the right side of the law.

Results

Adoption of Circular Economy Models

Companies that are wholeheartedly adopting the Circular Economy approach are seeing benefits. They're reducing waste, making the most of their resources and saving money. Studies have shown this time and again. For example, research by [11] and [12] found improvements in these areas. It's clear that making this shift can have an impact on a company's line and its environmental footprint. Top manufacturers are getting results by using some effective methods. For one they're using closed loop production systems, which help reduce waste. They're also finding ways to breathe life into products through re-manufacturing. Taking goods that have already been used and giving them a second life. By designing products to last, they're extending their lifespan and reducing the need, for frequent replacements. All these approaches are making a difference, in

their industries helping to make their operations more sustainable and environmentally friendly [13]. Reducing emissions is the start. These strategies also give organizations a competitive edge in their markets, which is a key part of sustainable supply chain management. The thing is, making circular economy models work requires a foundation for cooperation among all the stakeholders. It's not enough for companies to just adopt practices. They need to be embedded throughout the supply chain. Getting all these stakeholders on the page is crucial for overcoming the obstacles that inevitably come up and for making sure that circular economy initiatives in manufacturing supply chains can survive in the run. This collaborative mindset is essential, for making these initiatives a success [13].

Relevant Case Studies and implementation

Recent case studies and pilot implementations across industries had demonstrated the tangible benefits of integrating circular economy principles and sustainability into manufacturing supply chains. For example, Philips achieved 15% cost savings and significant material waste reduction by applying circular design to medical equipment, while Renault's re-manufacturing plant in Choisy-le-Roi reported 80% energy and ~70% water savings per part. Unilever has successfully tracked Scope 3 emissions across its supplier network using blockchain and AI, enhancing transparency and accountability. HP's closed-loop recycling of printer cartridges reduced virgin plastic use by 60%, showcasing the environmental impact of circular models. Empirical benchmarks further validate these approaches: Scope 3 emissions typically account for 70–90% of a product's total carbon footprint, and circular initiatives can reduce waste by 30–50% and improve energy efficiency by 15–25%. Digitally transformed firms report ESG compliance rates exceeding 80%, and many organizations achieve a 10–20% return on investment within two years of adopting circular strategies [12], [13]. These examples underscore the practical viability and financial value of sustainable supply chain transformation.

Scope 3 Emissions Management

Effective management of Scope 3 emissions, which is undeniably essential for fostering and enhancing the comprehensive sustainability initiatives and objectives of any forward-thinking business, fundamentally relies on the proactive and meaningful involvement and collaboration of suppliers throughout the supply chain, the execution and incorporation of sophisticated digital traceability systems that allow for enhanced visibility, as well as the commitment to adopting environmentally sustainable procurement practices that prioritize sustainability and ecological responsibility [12],[13]. By fully embracing and seamlessly integrating these extensive and holistic practices into their operational frameworks, companies can achieve a remarkable and significant improvement in their levels of transparency concerning supply chain activities, all the while making considerable strides towards achieving substantial reductions in their total greenhouse gas emissions, thereby contributing positively to environmental preservation efforts. Furthermore, the

integration of digital tools and real-time monitoring systems can greatly enhance the effectiveness of sustainability initiatives in manufacturing supply chains.

Sustainable Sourcing and Energy Efficiency

Organizations are increasingly and progressively placing a significantly greater emphasis on the critical importance of both environmental and social considerations when it comes to the criteria used for selecting suppliers, all the while simultaneously making substantial and considerable investments in the development and implementation of innovative energy-efficient technologies in order to ensure full compliance with not only Environmental, Social, and Governance (ESG) standards, but also various regulatory requirements that have been meticulously established in recent years [13],[14]. This comprehensive approach not only enhances operational efficiency and stakeholder trust but also positions organizations to meet evolving regulatory requirements and global sustainability goals effectively.

Role of Digital Innovation

Digital tools, which include a wide array of groundbreaking and cutting-edge technologies, such as the Internet of Things (IoT) that connects various devices and systems, as well as blockchain that ensures secure and transparent transactions, play a vital role in facilitating the intricate and complex process of real-time monitoring by not only collecting vast amounts of data instantaneously but also analyzing this information with impressive speed and accuracy, while simultaneously improving and enhancing traceability across a multitude of diverse supply chains, and providing essential support for the effective and successful implementation of circular and sustainable practices that are critically important for the ongoing efforts in environmental conservation and the efficient management of natural resources, as outlined in the research conducted by [12],[13],[14]. The integration of digital technologies is crucial for enhancing transparency and traceability in supply chains, ultimately supporting sustainable practices and compliance with ESG standards [14], [15] Moreover, embracing digital innovations not only enhances operational efficiency but also fosters a culture of sustainability that aligns with global environmental standards and stakeholder expectations. Digital transformation is revolutionizing supply chain transparency and efficiency. These technologies enable companies to track materials from production to disposal, manage resources in real-time, and implement data-driven sustainability strategies as figure 2.

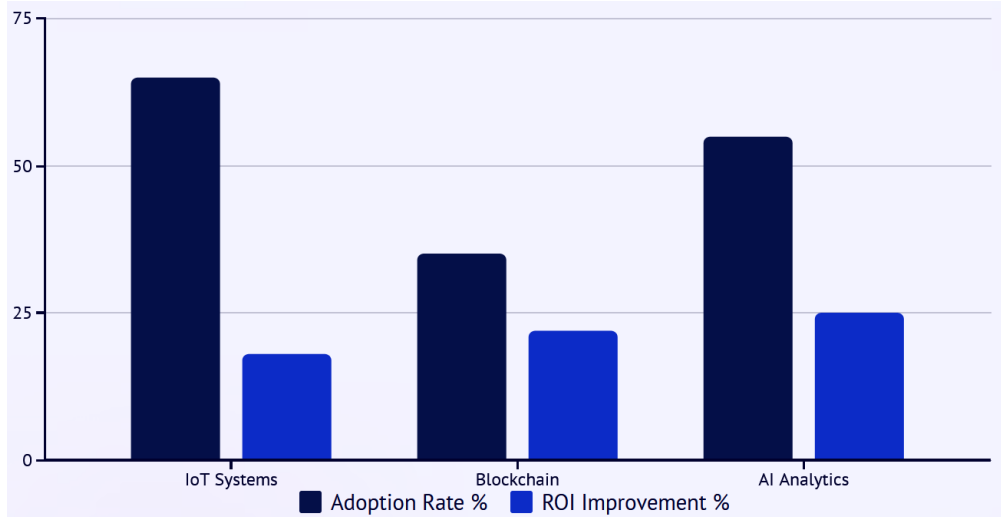


Figure 2. ROI Improvement with Technology

Barriers and Enablers

The multifaceted challenges that continue to persistently afflict a myriad of industries encompass not only the exorbitantly high initial costs that are typically associated with the adoption of cutting-edge technologies but also the formidable and often daunting technological barriers that frequently emerge, in addition to a widespread and entrenched resistance to change that can be deeply embedded within the very fabric of organizational cultures, often making it exceedingly difficult for companies to progress and evolve. In order to effectively and comprehensively tackle these complex challenges and to cultivate a conducive and supportive environment that is ripe for innovation and creativity, it is absolutely essential to implement well-structured policy incentives that not only encourage substantial investment but also actively promote cross-functional collaboration among various departments, while simultaneously supporting and facilitating comprehensive educational initiatives that are specifically aimed at equipping individuals with the crucial skills and knowledge necessary to adapt successfully to these rapidly evolving landscapes of technology and business [14],[15]. The successful navigation of these barriers is essential for organizations aiming to implement sustainable practices and achieve compliance with evolving regulatory frameworks.

Empirical benchmarks from recent literature and industry reports provide quantitative validation for the sustainability improvements discussed. Scope 3 emissions typically account for 70–90% of a product's total carbon footprint, underscoring the importance of supplier collaboration and digital traceability. Circular economy initiatives have demonstrated waste reductions of 30–50% and energy efficiency improvements ranging from 15–25% across manufacturing sectors. Digitally transformed supply chains report ESG compliance rates exceeding 80%, and organizations adopting circular strategies often achieve a return on investment (ROI) of 10–20% within two years. These metrics highlight the operational and financial viability of sustainable supply chain

transformation and reinforce the strategic value of integrating circular models, low-carbon production, and digital innovation.

Discussion

Integrating Sustainability and Circularity

The vast and comprehensive body of scholarly literature available on the subject provides an abundance of substantial evidence that clearly indicates the fact that the integration of Circular Economy (CE) principles into Sustainable Supply Chain Management (SSCM) practices not only leads to marked and significant enhancements in the realm of environmental sustainability but also plays a crucial role in contributing to overall economic improvements that are advantageous and beneficial for a wide array of stakeholders who are involved in these processes. Nevertheless, the successful realization and effective implementation of these integrated practices require the overcoming of numerous and varied organizational as well as technological challenges, in addition to the necessity of fostering meaningful collaboration across different sectors, while simultaneously and effectively leveraging the advancements that have been made in digital innovation to facilitate this transformative process. Addressing these challenges through a collaborative approach and leveraging innovative technologies is essential for achieving sustainable practices in manufacturing supply chains.

Conceptual Framework Summary: Sustainable Manufacturing Supply Chains

1. Circular Economy Principles - Emphasizes reuse, recycling, and closed-loop systems to minimize waste and extend product lifecycles.
2. Sustainable Supply Chain Management (SSCM) - Integrates environmental and social criteria into procurement, logistics, and operations to enhance efficiency and reduce impact.
3. Low-Carbon Production- Focuses on cleaner technologies and process optimization to reduce direct and indirect emissions.
4. Scope 3 Emissions Management - Involves supplier collaboration and digital traceability tools to monitor and reduce emissions across the value chain.
5. Sustainable Sourcing - Prioritizes ethical and environmentally responsible supplier selection and material procurement.
6. Energy Efficiency - Implements strategies and technologies to reduce energy consumption throughout the supply chain.
7. Digitalization and Industry 4.0 - Leverages IoT, blockchain, and AI for real-time monitoring, transparency, and predictive analytics.

8. Policy and Stakeholder Collaboration - Encourages cross-sector partnerships, regulatory support, and cultural transformation to drive adoption and scalability.
9. ESG Compliance and Resilience - Aligns operations with Environmental, Social, and Governance standards to ensure long-term sustainability and risk mitigation.

Policy and Managerial Implications

Policymakers have the crucial responsibility to not only provide substantial incentives but also to establish comprehensive and clear regulatory frameworks that will effectively support and facilitate the transformative process of sustainable supply chains, thereby ensuring that all stakeholders involved can navigate the complexities of this transition with confidence and clarity. On the other hand, managers must place a significant emphasis on engaging with all relevant stakeholders, make substantial investments in enhancing their digital capabilities, and actively foster a workplace culture that is dedicated to the principles of continuous improvement and innovation in order to remain competitive and responsive to the ever-evolving market demands [15]. The successful integration of these strategies not only enhances organizational resilience but also positions companies as leaders in sustainability, ultimately contributing to the achievement of global environmental goals.

Future Research Directions

In order to achieve a more profound and nuanced comprehension of the various components involved in the development of effective scalability strategies, it is essential that we engage in further, in-depth investigation and meticulous analysis, which will allow us to thoroughly evaluate the performance metrics that are critical to this process, as well as to explore the complex and multifaceted social dimensions that are integral to the transformation of sustainable supply chains; this necessity is underscored by the findings and insights presented in the studies [13], as well as those by [14], all of which contribute valuable perspectives to this important field of research. The integration of digital innovations is essential for enhancing operational efficiency, promoting transparency, and fostering collaboration across supply chains, ultimately driving sustainability efforts in manufacturing [16]. This research highlights the necessity for a collaborative approach to sustainability within supply chains, emphasizing the importance of stakeholder engagement and technological integration to achieve meaningful progress.

Conclusions

Manufacturers are increasingly placing an exceptionally high priority on the meticulous and detailed implementation of low-carbon production techniques, which involve not only reducing greenhouse gas emissions during manufacturing processes but also integrating innovative methods that significantly lower environmental impacts, alongside the efficient and effective management of Scope 3 emissions that arise from the entire value chain, encompassing all indirect emissions produced in the supply chain, the responsible and sustainable sourcing of materials that are

ethically obtained and environmentally friendly, ensuring that the origins of these materials align with sustainability goals, the substantial enhancement of energy efficiency through the adoption of cutting-edge technologies and practices that minimize energy consumption while maximizing output, and the proactive adoption of circular supply chain models that emphasize reusability and recycling of materials, all of which are imperative for manufacturers to meet their comprehensive Environmental, Social, and Governance (ESG) commitments as well as to comply with an ever-growing and complex array of regulations that are being introduced at an accelerated pace, thereby ensuring that their operations remain not only viable but also socially responsible in a rapidly changing regulatory landscape. The successful and seamless integration of Circular Economy (CE) principles and Sustainable Supply Chain Management (SSCM) practices, which are further strengthened by remarkable advancements in digital innovation that enhance operational efficiency and transparency, as well as the provision of supportive policy incentives that encourage sustainable practices, is absolutely crucial and essential for the establishment of supply chains that are not only resilient and adaptable to unforeseen disruptions but also sustainable in the long term, ensuring they can effectively withstand and respond to various challenges posed by environmental changes, market dynamics, and societal expectations. In order to successfully and effectively overcome the multitude of barriers that present themselves in this complex and multifaceted context, it necessitates coordinated and collaborative efforts among policymakers who are tasked with crafting effective regulations, industry leaders who must implement sustainable practices within their operations, and a diverse and wide-ranging array of stakeholders, including community organizations and consumers, who possess a vested interest in this transformative process aimed at creating more sustainable and equitable supply chains. Future research should focus on developing scalable, cross-sector solutions and robust assessment frameworks to guide sustainable supply chain transformation and track progress effectively.

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