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Decarbonizing Supply Chains in Emerging Economies: A Multilevel Analysis of Regulation, ESG, and Digitalization

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Abstract

As global efforts to combat climate change intensify, the decarbonization of supply chains has become a strategic imperative; yet, little is known about how this transition unfolds in emerging economies. This study examines the intricate relationship between regulation, environmental, social, and governance (ESG) practices, and digitisation in driving supply chain decarbonization within Nigeria's carbon-intensive sectors. Drawing on a multilevel analytical lens, we developed and empirically tested a structural equation model using survey data from 306 supply chain professionals across manufacturing, construction, energy, and logistics industries. Our findings reveal that regulatory stringency alone is insufficient in weak institutional environments; rather, regulatory enforcement, rather than the formal existence of regulations, is the true catalyst for sustainable transitions. ESG-driven strategies exhibit strong mediating effects but are significantly constrained by firm-level challenges, including costs, technical expertise, and infrastructure limitations. Notably, digital innovations, particularly blockchain, AI, and IoT, emerge as critical enablers of carbon transparency and traceability, helping offset some of the institutional voids that characterise emerging economies. This study presents a rare, data-driven perspective on supply chain decarbonization in the Global South, making a significant contribution to sustainability theory and managerial practice. It provides actionable insights for policymakers, sustainability officers, and technology innovators seeking to align economic development with climate resilience in rapidly industrialising regions.

Keywords

Supply chain decarbonization, regulatory frameworks, environmental, social, and governance integration, digital transformation, emerging economies

JEL Classification

Q54, Q56, M14, O13, O55

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Introduction

The imperative to decarbonize supply chains has emerged as a defining challenge for current sustainability efforts, but implementing these changes in emerging economies remains fraught with structural, regulatory, and technological complexities (Adom & Matsui, 2024; Appiah et al., 2023; Bulkeley et al., 2022; Kumar et al., 2024). Nigeria's supply chains, particularly in extractive industries, place a significant environmental burden on the resource-dependent economy, with carbon-intensive activities undermining global sustainability commitments (Chidolue et al., 2024). Although much of the existing literature focuses on decarbonization strategies within developed economies (Cordonnier & Saygin, 2023), their direct applicability to emerging markets remains underexplored, given the region-specific institutional voids and regulatory inefficiencies that hinder the seamless integration of sustainability principles into corporate operations (Onuoha et al., 2024). The scarcity of empirical research addressing the interdependencies between regulatory enforcement (RE), environmental, social, and governance (ESG) adoption, and digital transformation in emerging economies exacerbates this knowledge gap (Daggash & MacDowell, 2021).

The dominant discourse on supply chain sustainability often treats regulatory stringencies, corporate ESG integration, and digital transformation as discrete elements rather than interconnected drivers of decarbonization (Hlali & Gfasi, 2024). However, in emerging economies such as Nigeria, these dimensions interact within a volatile institutional environment, where economic pragmatism frequently takes precedence over environmental commitments (Brookings Institution, 2023). Regulatory inefficiencies, weak enforcement mechanisms, and conflicting mandates create an implementation paradox, as firms are expected to comply with sustainability policies without institutional support structures (Adegbite et al., 2013). This paradox highlights the need for a comprehensive analytical approach that encompasses macro-level regulatory constraints, meso-level corporate ESG strategies, and micro-level technological enablers in facilitating decarbonization efforts (Amoah & Eweje, 2022).

A critical limitation in existing research is the insufficient exploration of digital transformation as a catalyst for overcoming regulatory and operational barriers to supply chain decarbonization (SCD) (Kamble et al., 2023). Technologies such as blockchain, artificial intelligence (AI), and the Internet of Things (IoT) are increasingly recognized for enhancing supply chain transparency, compliance, and efficiency (Peprah Adu et al., 2024). However, their deployment within emerging markets is constrained by infrastructural deficits, financial limitations, and digital literacy gaps (Ufua et al., 2021). Furthermore, prevailing sustainability discourses in Nigeria remain fixated on corporate social responsibility and environmental compliance, overlooking the transformative role of digitalization in embedding sustainability within core supply chain operations (Egeruoh-Adindu, 2022). By framing digital innovation as a strategic lever for regulatory alignment and ESG integration, this study advances an alternative perspective on decarbonization pathways within emerging economies.

Nigeria, Africa's largest economy and a pivotal actor in global supply networks, provides an ideal context for examining the interplay between governance, corporate sustainability, and technological innovation (Zhu et al., 2019). Despite its economic prominence, Nigeria's supply chains remain constrained by systemic inefficiencies, regulatory fragmentation, and limited ESG adoption (Ahmed et al., 2023). Understanding how firms navigate these constraints to implement sustainability transitions is critical for informing policy frameworks and corporate strategies that extend beyond conventional regulatory compliance (Oluwakoya, 2024).

This study addresses these critical gaps by investigating four interrelated research questions: (a) How do existing regulations in Nigeria facilitate or constrain SCD efforts? (b) To what extent do firms integrate ESG principles into supply chain management, and what are the key drivers and barriers to

adoption? (c) What role does digital transformation, specifically blockchain, AI, and IoT, play in enhancing transparency, compliance, and efficiency in sustainable supply chain practices? (d) How can regulatory mechanisms, corporate ESG strategies, and digital innovation be aligned to create a synergistic model for effective decarbonization in emerging economies?

This study enhances the theoretical understanding by integrating regulatory dynamics, corporate ESG adoption, and digital transformation into a multilevel framework for analyzing SCD in emerging economies. It broadens the sustainability scholarship by demonstrating how digital technologies, blockchain, AI, and IoT can serve as strategic levers to address institutional gaps and regulatory inefficiencies typical of contexts such as Nigeria (Kamble et al., 2023; Ufua et al., 2021). The proposed evidence-based model aligns regulatory strictness with corporate strategy and technological innovation, providing policymakers and business leaders with a practical basis for integrating sustainability within constrained infrastructure and governance environments (Amoah & Eweje, 2022; Egeruoh-Adindu, 2022). Conceptually, the study contributes to complexity theory by revealing the nonlinear interaction between regulatory and technological contexts, which encourages firms to adapt ESG strategies dynamically (Adegbite & Nakajima, 2022). It also extends structuration theory by illustrating the reciprocal shaping of institutional structures and corporate agency, demonstrating how firms in fragmented regulatory landscapes employ private governance mechanisms and technological innovations to both comply with and influence evolving sustainability norms (Tetteh et al., 2025). This challenges deterministic views of regulatory compliance and highlights firm agency in shaping sustainability trajectories under institutional voids. Practically, the findings emphasize the need for adaptive strategies that integrate ESG principles, digital capabilities, and resilient compliance systems to handle regulatory ambiguity and infrastructural deficits (Wiredu et al., 2024). Firms should invest in digital transformation while expecting uneven returns due to infrastructural limitations, and engage proactively with stakeholders, investors, consumers, and community actors to compensate for the lack of comprehensive institutional support for decarbonization (Chu et al., 2017; Ufua et al., 2021).

The rest of the article is structured as follows. The next section outlines the theoretical background and develops the research hypotheses. A discussion of the research methodology, including data collection and analytical techniques, follows this. The subsequent section presents the study's findings, while the following section provides a discussion of these findings. The final section concludes the article by highlighting the practical implications, outlining the study's limitations, and suggesting directions for future research.

Theoretical Background and Hypotheses Development

Theoretical Foundation

This study is supported by two less commonly used yet highly relevant theoretical perspectives: complexity theory and structuration theory (Figure 1). Complexity theory suggests that organizations function within nonlinear, adaptable systems where interactions among multiple variables lead to unpredictable outcomes (Amoah & Eweje, 2022). In the context of SCD, Nigerian firms operate in a regulatory environment characterized by overlapping mandates, fragmented enforcement, and inconsistent sustainability policies (Adegbite et al., 2013). These factors create a complex and often chaotic compliance landscape, requiring firms to continually refine their ESG strategies to respond to shifting institutional and market pressures (Alaburo & Gbadebo, 2024). This theoretical perspective also sheds light on the difficulties of digital adoption for ESG compliance. While blockchain, AI, and IoT boost transparency

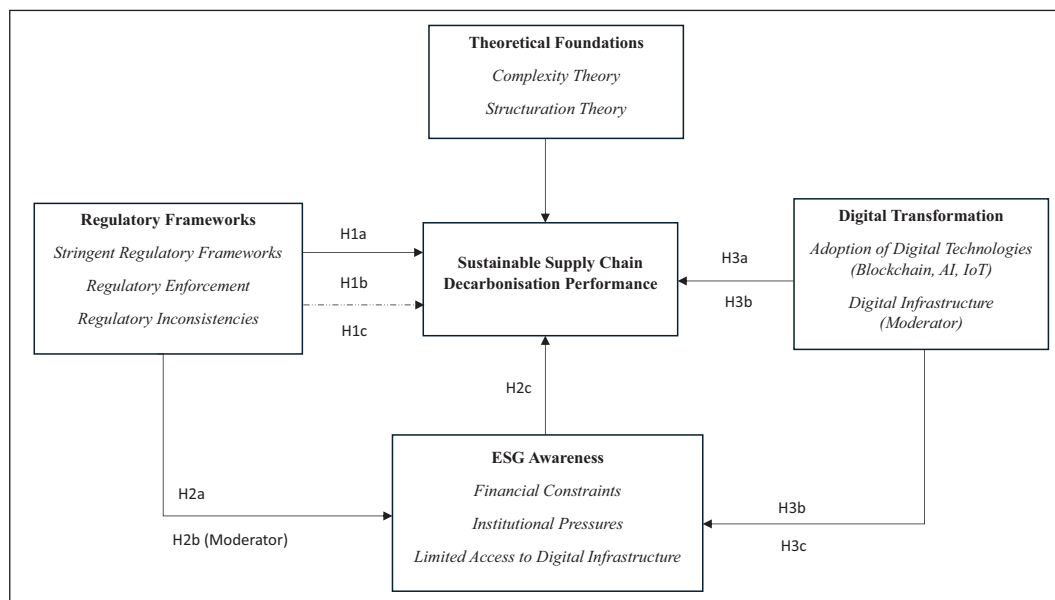


Figure 1. Conceptual Framework of the Study.

and sustainability reporting, their effectiveness hinges on stable regulatory and infrastructural conditions (Kamble et al., 2023). In developed economies, where digital ecosystems are advanced and RE is reliable, firms can integrate technology smoothly into their sustainability strategies (Wiredu et al., 2024). However, in Nigeria, weak governance, financial constraints (FC), and infrastructural gaps lead to unpredictable patterns of technological adoption, necessitating firms to develop adaptive strategies aligned with ESG mandates (Ufua et al., 2021). Complexity theory thus offers an explanatory framework for understanding how firms navigate the nonlinearity of regulatory and technological environments when implementing sustainability initiatives.

Structuration theory (Giddens, 2014) provides a perspective on how institutional structures and corporate agencies interact in adopting sustainability. Unlike static institutional theory that view firms merely as responding to regulatory pressures, this theory proposes that firms actively influence and are influenced by the regulatory and economic systems within which they operate (Chu et al., 2017). In Nigeria, where regulatory inconsistencies (RI) and weak enforcement hinder ESG adoption, firms adapt strategically, sometimes bypassing regulatory shortcomings through voluntary sustainability commitments and private governance mechanisms (Adegbite & Nakajima, 2022). This perspective is particularly relevant to the adoption of digital sustainability. While regulatory pressures may motivate firms to implement AI, blockchain, and IoT for greater transparency, the effective deployment of these technologies relies on both internal corporate strategies and external structural enablers (Xu et al., 2023). Nigerian firms, limited by financial and infrastructural challenges, often rely on informal networks, private sustainability standards, and partnerships with multinational stakeholders to bridge regulatory and institutional gaps (Brookings Institution, 2023). Thus, structuration theory emphasizes the reciprocal influence between institutional structures and corporate agency, showing that firms are not just passive recipients of regulation but actively participate in shaping sustainability practices transitions.

Regulatory Frameworks and SCD

Regulations are fundamental to corporate sustainability, as they establish environmental standards and mandate compliance obligations (Adegbite & Nakajima, 2022). In Nigeria, key policies, such as the National Environmental Standards and Regulations Enforcement Agency (NESREA) Act and the Climate Change Act of 2021, aim to enhance environmental governance and promote decarbonization efforts (Brookings Institution, 2023). These regulations provide an institutional foundation for sustainable business practices; however, their success depends on the effective enforcement of these mechanisms and corporate compliance (Noah et al., 2021). While these regulations form the foundation for corporate environmental responsibility, their effectiveness remains uncertain due to persistent enforcement challenges (Adegbite & Nakajima, 2022; Brookings Institution, 2023).

Despite regulatory stringency (RS), compliance is often inconsistent in developing economies. Research in Ghana and Nigeria suggests that firms generally respond to environmental regulations; however, disparities in enforcement efficiency, corruption, and informal networks hinder consistent adoption (Amoah & Eweje, 2022). While some perspectives suggest that firms comply with regulations to maintain legitimacy (DiMaggio & Powell, 2000), others argue that external pressures influence corporate sustainability decisions (Pfeffer & Salancik, 2015). However, these explanations overlook financial and operational constraints that drive firms to prioritize short-term survival over long-term sustainability (Udeagha & Ngepah, 2023).

Furthermore, comparative studies suggest that stringent environmental policies improve corporate compliance in Organization for Economic Co-operation and Development (OECD) nations and across global supply chains. However, assuming uniform enforcement capacity across jurisdictions limits the applicability of these findings to emerging economies. In Nigeria, overlapping regulatory mandates, weak institutional coordination, and policy uncertainty create a complex compliance landscape (Onuoha et al., 2024). Consequently, conflicting federal and state regulations result in inefficiencies, selective enforcement, and increased transaction costs, deterring firms from investing in sustainable supply chain practices (Ufua et al., 2021).

Additionally, RE is crucial in transforming policy into tangible corporate action. However, in Nigeria, enforcement remains compromised by corruption, inadequate funding, and limited technical capacity within regulatory agencies (University of the West of England, 2023). While some frameworks assume regulators operate independently and impartially, practical realities in developing economies highlight political interference and regulatory capture (Noah et al., 2021). This underscores the need for a more context-sensitive enforcement model that acknowledges governance weaknesses.

Furthermore, RI leads to policy fragmentation, making compliance more difficult and raising costs for firms. Without clear regulation, companies need to spend extra resources to manage conflicting policies. Research on sustainable procurement in Nigeria reveals that inadequate policy coordination significantly hinders the adoption of sustainability initiatives (Oyewobi & Jimoh, 2022). While some believe that regulatory fragmentation is caused by systemic unpredictability, they often lack practical solutions. At the same time, views that focus on cost reduction often overlook corruption and weak governance as key barriers to compliance (Amoah & Eweje, 2022). Addressing these structural issues requires a unified regulatory approach that considers economic, political, and institutional challenges.

Building on these insights, this study proposes the following hypotheses:

- H_{1a} : RS positively influences corporate adoption of SCD.
- H_{1b} : RE mediates the relationship between policy existence and compliance.
- H_{1c} : RI hinders sustainable supply chain implementation in Nigeria.

ESG Awareness and Decarbonization Integration in Supply Chains

The integration of ESG principles into corporate strategies is increasingly recognized as a key driver of SCD (Amoah & Eweje, 2022). Firms with strong ESG awareness are expected to adopt sustainable practices due to their understanding of environmental and social impacts, as well as the role of governance in mitigating negative outcomes (Adegbite et al., 2013). In Nigeria, ESG-aligned firms have demonstrated leadership in sustainability initiatives, linking ESG commitments to long-term business growth (Brookings Institution, 2023).

However, awareness alone does not translate into implementation. Limited technical expertise, inadequate infrastructure, and weak regulatory incentives hinder the transition from knowledge to action (Adeleke et al., 2022). Adom and Matsui (2024) identified major barriers to sustainability reporting in Nigeria, including insufficient integration of ESG metrics and weak stakeholder engagement. Similarly, Oyewobi and Jimoh (2022) found that, while green supply chain management enhances environmental performance, financial viability depends on a firms' ability to embed ESG-driven operational models.

External pressures also shape corporate ESG adoption. Some perspectives suggest that firms align with the expectations of investors, consumers, and regulators to maintain legitimacy (DiMaggio & Powell, 2000). In Nigeria, international investors and global supply chain partners increasingly drive ESG engagement (Udeagha & Ngepah, 2023). However, regulatory pressures play an equally significant role. While structured policy environments can reinforce ESG commitments, Nigeria's weak enforcement mechanisms and regulatory ambiguities often diminish corporate adherence (Chu et al., 2017).

Empirical evidence highlights the need for systemic support. Adu et al. (2023) found that firms in Ghana with high ESG awareness tend to pursue green supply chain practices, although technical and financial limitations constrained their implementation. Likewise, Ufua et al. (2021) observed that while Nigerian firms expressed interest in decarbonization, poor infrastructure and regulatory gaps impeded execution. These findings underscore the importance of institutional support and targeted policies that address local constraints.

Financial limitations remain a significant barrier to ESG-driven decarbonization, particularly in emerging economies. Implementing sustainability strategies requires considerable capital investments in technology, process redesign, and workforce development, which many firms struggle to absorb (Wiredu et al., 2024). A global study across 51 countries has found that FC significantly hinders firms' ability to reduce carbon footprints, underscoring the universal challenge of resource limitations (Alaburo & Gbadebo, 2024).

Nigeria's financial landscape further complicates these challenges. Limited access to affordable financing, high borrowing costs, and economic volatility discourage firms from investing in sustainability (Amoah & Eweje, 2022). The absence of green financial instruments, such as sustainability-linked loans and green bonds, further constrains ESG investment. Alaburo and Gbadebo (2024) found that while social investing correlated positively with financial performance in Nigerian energy firms, environmental investments yield lower returns, reducing firms' willingness to commit to sustainability.

Funding gaps remain significant. The Landscape of Climate Finance in Nigeria (2024) estimates that \$1.9 trillion is required for Nigeria's energy transition by 2060, yet existing financial mechanisms are inadequate. Institutional constraints and macroeconomic instability limit access to international climate finance, further restricting ESG adoption (Ufua et al., 2021). Some perspectives suggest that firms require financial capital, technical expertise, and infrastructure to integrate sustainability initiatives (Barney, 1991). However, resource-constrained environments, such as Nigeria, lack the necessary conditions for widespread ESG adoption.

Institutional frameworks also influence corporate sustainability investments. While structured policies and stakeholder expectations shape ESG commitments, Nigeria's RI, weak enforcement, and limited financial incentives reduce firms' motivation to integrate decarbonization strategies (Chu et al., 2017). Although investor demands and consumer preferences are increasing, corporate ESG adoption remains at its early stages, influenced by factors such as market maturity, economic instability, and regulatory uncertainty (Adu et al., 2023).

The effectiveness of external pressures varies across economies. In developed markets, strict enforcement and standardized sustainability frameworks ensure compliance, whereas in Nigeria, weak institutional support and fragmented governance structures limit the effectiveness of ESG (Udeagha & Ngepah, 2023). Studies suggest that while investor expectations influence corporate behavior, RI reduces firms' responsiveness to sustainability mandates (Adegbite et al., 2013). Chu et al. (2017) found that government, customer, and competitor pressures shape sustainable practices; however, weak institutional frameworks reduce top management support for ESG. Similarly, Wiredu et al. (2024) noted that while green supply chain initiatives have improved corporate environmental performance, external pressures alone were insufficient; leadership commitment and a culture of sustainability played a more direct role in the adoption of ESG.

Based on these findings, this study proposes the following hypotheses:

- H_{2a} : Firms with higher ESG awareness are more likely to integrate decarbonization strategies into their supply chain operations.
- H_{2b} : FC negatively impacts the adoption of ESG-driven decarbonization practices in Nigeria.
- H_{2c} : Institutional pressures (IP) (e.g., investor demand and consumer preferences) significantly influence the extent of ESG integration in Nigerian supply chains.

Digital Transformation and Sustainable Supply Chains

The adoption of blockchain, AI, and the IoT is increasingly recognized as a driver of transparency in sustainability reporting (Amoah & Eweje, 2022). Blockchain's decentralized ledger enhances data integrity, reduces information asymmetry, and fosters trust among stakeholders (Adu et al., 2023). AI-powered analytics and IoT-enabled real-time monitoring further improve compliance by automating data collection and ensuring adherence to sustainability metrics (Ufua et al., 2021). However, existing research largely focuses on developed economies with robust digital infrastructure (DI), overlooking the challenges faced by emerging markets such as Nigeria (Adegbite et al., 2013). Limited infrastructure, low digital literacy, and organizational resistance hinder the adoption of digital sustainability reporting tools (Brookings Institution, 2023). Additionally, assuming a direct link between technology adoption and transparency neglects the influence of corporate culture and stakeholder engagement, which can either facilitate or obstruct digital reporting initiatives (Chu et al., 2017). Addressing these gaps requires context-specific research that considers institutional and socio-economic factors shaping transparency outcomes in developing economies.

Furthermore, firms with advanced digitalization capabilities are better equipped to comply with ESG regulations due to improved data analytics, automated compliance monitoring, and enhanced decision-making (Wiredu et al., 2024). Digital tools allow real-time ESG performance monitoring, aligning corporate operations with regulatory standards and stakeholder expectations (Udeagha & Ngepah, 2023). AI-driven risk detection and IoT-based environmental monitoring help ensure firms meet sustainability benchmarks (Adeleke et al., 2022). However, research often assumes regulatory uniformity, failing to capture the fragmented regulatory landscape in developing economies (University of the West of

England, 2023). Nigeria's weak enforcement mechanisms and inconsistent sustainability policies hinder the effectiveness of digital compliance tools (Alaburo & Gbadebo, 2024). Additionally, high implementation costs create disparities between large corporations and small- and medium-sized enterprises (SMEs), limiting SME access to ESG-compliant digital solutions (Ufua et al., 2021). Understanding how FC and institutional gaps influence digital adoption is vital for developing effective sustainability policies.

The success of digital technologies in driving decarbonization also depends on the availability of reliable DI. While developed economies benefit from seamless technological integration, enabling significant emissions reductions, infrastructure deficits in Nigeria, such as unreliable electricity, poor internet connectivity, and limited technical expertise, weaken the effectiveness of digital sustainability solutions (Amoah & Eweje, 2022). Existing studies often examine the direct effects of digital adoption on decarbonization but overlook the moderating role of infrastructure, a crucial omission given the challenges of technological deployment in emerging markets (Brookings Institution, 2023). Additionally, socio-economic barriers, including affordability constraints and digital literacy gaps, further restrict firms' ability to implement digital sustainability initiatives (Adu et al., 2023). Closing these gaps demands coordinated efforts, including policy reforms, private-sector investment, and cross-sector partnerships to improve DI and maximize technology's impact on decarbonization (Chu et al., 2017).

Comparative analyses reveal divergent pathways for the adoption of digital sustainability across different economic contexts. In developed markets, stringent ESG regulations and advanced technological ecosystems drive transparency, compliance, and decarbonization (Wiredu et al., 2024). However, developing economies face institutional voids, financial limitations, and infrastructure challenges, which constrain digital adoption at scale (Adegbite et al., 2013). Nigeria exemplifies these challenges, where, despite increasing interest in digital transformation, supply chain inefficiencies, corruption, and RI weaken the impact of digital adoption on sustainability (Udeagha & Ngepah, 2023). Additionally, SMEs, which form the backbone of Nigeria's economy, often lack the financial and technical capacity to implement digital ESG solutions, creating disparities in sustainability performance (Ufua et al., 2021).

Based on these insights, this study hypothesizes that:

- H_{3a} : The adoption of digital technologies (blockchain, AI, IoT) positively correlates with transparency in supply chain sustainability reporting.
- H_{3b} : Firms with higher levels of digitalization demonstrate stronger compliance with ESG-related supply chain regulations.
- H_{3c} : Limited access to DI moderates the relationship between technological adoption and decarbonization outcomes.

Methodology

Research Design

This study employs a quantitative, cross-sectional survey to investigate the impact of RS, ESG integration, and digital transformation on SCD in Nigeria. This method enables the collection of empirical data from firms involved in supply chain operations, aligning with sustainability research in emerging markets (Adeleke et al., 2022; Zhu et al., 2019).

Sampling Strategy

This study focuses on firms with at least 100 employees operating in Nigeria's manufacturing, oil and gas, logistics, and agriculture sectors, industries collectively responsible for over 70% of Nigeria's industrial emissions and contributing approximately 64% of the nation's industrial gross domestic product (GDP) output (Brookings Institution, 2023; Chidolue et al., 2024). These sectors were purposefully selected due to their disproportionately high environmental impact and strategic significance in the national decarbonization agenda (Appiah et al., 2023; Oluwakoya, 2024). The sampling frame was constructed from the Corporate Affairs Commission (CAC) registry and the Nigerian Association of Chambers of Commerce, Industry, Mines, and Agriculture (NACCIMA) directories, both of which comprehensively document registered enterprises segmented by industry and firm size. According to CAC data, approximately 2,500 medium and large enterprises (with 100 or more employees) operate within these targeted sectors nationwide, with manufacturing and oil and gas jointly accounting for roughly 45% of industrial employment and nearly 50% of industrial output value (Brookings Institution, 2023; Okoro et al., 2024).

To ensure statistical representation, a stratified random sampling technique was employed. Firms were stratified by sector and size class (100–249 employees, 250–499 employees, and ≥ 500 employees) in proportion to their distribution within the national industrial structure, aligning with established methodological guidance for survey representativeness in industrial research (Hair et al., 2019). For example, CAC records indicate that enterprises employing between 100 and 249 staff comprise approximately 58% of firms in these sectors, while larger firms constitute the remainder, a distribution reflected in our sample composition (Amoah & Eweje, 2022; Brookings Institution, 2023). Of the 180 contacted firms, 162 agreed to participate, yielding a response rate of 90%. The sample thus captures around 46.5% of Nigeria's total population of medium and large enterprises in these sectors, a proportion consistent with empirical studies employing sector-specific industrial surveys in emerging economies (Chu et al., 2017; Ufua et al., 2021). Furthermore, the aggregate output value of the sampled firms represents an estimated 58% of the combined industrial GDP across the four sectors, reinforcing the economic weight and relevance of the sample (Adom & Matsui, 2024; Brookings Institution, 2023).

To enhance data reliability and mitigate single-respondent bias, two key informants per enterprise were surveyed, typically a senior executive (such as a Managing Director (MD) or Chief Sustainability Officer (CSO)), and an operational manager (e.g., a supply chain or information technology (IT) manager). This dual-informant approach ensures the capture of both strategic perspectives on ESG integration and operational insights into digitalization practices, consistent with methodological recommendations in sustainability research (Amoah & Eweje, 2022; Podsakoff et al., 2003). Industries such as finance, telecommunications, and retail were excluded from the sampling frame because, despite their engagement in sustainability reporting, they account for less than 5% of Nigeria's industrial carbon footprint and do not materially contribute to carbon-intensive supply chain processes central to this study's objectives (Brookings Institution, 2023; Egeruoh-Adindu, 2022). Collectively, the final sample of 162 enterprises constitutes a statistically and economically significant cross-section of Nigeria's high-impact industrial landscape, ensuring that the findings are generalizable to the broader context of SCD in emerging markets characterized by similar institutional and infrastructural constraints (Adegbite & Nakajima, 2022; Amoah & Eweje, 2022).

Data Collection

Surveys were distributed via email and in person, with an initial telephone contact to encourage participation. The survey instrument was administered in English, which is the official language of business and government communication in Nigeria, and is widely used in industrial and professional contexts. Two key informants per firm, including MDs or CSOs, as well as supply chain or IT managers, provided perspectives on strategic ESG alignment and operational digitalization efforts. This dual-response approach enhances internal validity by reducing the risk of single-response bias. To ensure data integrity, rigorous exclusion criteria were applied to ensure the accuracy of the data. First, we embedded attention-checking questions in different survey sections to ensure participants were focused. Respondents who failed these checks were excluded (Podsakoff et al., 2003). Second, responses with missing values were discarded (Hayes et al., 2011). Third, we excluded rapid responders, or those who selected the same answer for all questions (Ufua et al., 2021). After applying these exclusions, we retained 306 responses for the final analysis. Based on Cohen's (1992) statistical power analysis, this sample size is sufficient to test our hypotheses with high confidence.

Non-response bias was assessed by comparing early and late respondents, with late responses as proxies for nonparticipants (Amoah & Eweje, 2022). A Mann–Whitney U test showed no significant differences in demographic variables (age, experience) or key constructs ($p > .05$), indicating no non-response bias. We also examined common method bias, since data for exogenous and endogenous constructs came from the same respondents (Podsakoff et al., 2003). We minimized it by using clear, concise questions and separate survey sections. A collinearity test confirmed no bias, with all variance inflation factor (VIF) values below 3.3 (Kumar et al., 2024).

Measurement and Operationalization of Variables

Each construct was operationalized through validated multi-item scales adapted from peer-reviewed sources to ensure reliability and validity (Gallardo-Vázquez & Sánchez-Hernández, 2014; Sarkis et al., 2021).

In this study, the notion of “regulatory framework” is operationalized as RS, defined as the perceived rigor, comprehensiveness, and clarity of environmental regulations governing supply chain operations. Thus, the terms “regulatory framework” and “regulatory stringency” are used interchangeably for empirical modeling. RS assesses the perceived strictness of environmental policies and enforcement mechanisms. Items were adapted from Kostova and Roth (2002) and Amoah and Eweje (2022), capturing firms' perceptions of policy rigor, compliance costs, and the effectiveness of government interventions. RE measures the extent of compliance monitoring, penalties for violations, and institutional capacity, drawn from Wiredu et al. (2024). RI reflects bureaucratic inefficiencies, policy conflicts, and institutional fragmentation, aligning with prior studies on governance effectiveness in emerging markets (Adegbite & Nakajima, 2012).

ESG awareness (ESG) was measured through firms' engagement with sustainability initiatives, employee training, and corporate reporting practices, utilizing scales from Gallardo-Vázquez and Sánchez-Hernández (2014). FC assesses the availability of capital for ESG investments, following frameworks established by Alaburo and Gbadebo (2024) and the Climate Policy Initiative (2024). IP encompasses investor expectations, consumer demand, and global supply chain requirements, as outlined by Chu et al. (2017) and Wiredu et al. (2024).

Digital technology adoption (DTA) measures the extent to which firms integrate blockchain, AI, and IoT into their supply chain operations, following methodologies established by Sarkis et al. (2021) and Bai et al. (2020). Digitalization and ESG compliance (DEC) evaluate the role of digital systems in

Table 1. Summary of All the Hypotheses and Their Corresponding Constructs.

Hypothesis	Relationship	Constructs Involved
H_{1a}	Regulatory stringency → Supply chain decarbonization	RS → SCD
H_{1b}	Regulatory enforcement mediates RS → SCD	RS → RE → SCD
H_{1c}	Regulatory inconsistencies → Supply chain decarbonization	RI → SCD
H_{2a}	ESG awareness → Supply chain decarbonization	ESG → SCD
H_{2b}	Financial constraints → ESG-driven decarbonization	FC → ESG → SCD
H_{2c}	Institutional pressures → ESG integration	IP → ESG
H_{3a}	Digital technology adoption → Transparency in sustainability reporting	DTA → DEC
H_{3b}	Digitalization → ESG compliance	DTA → DEC
H_{3c}	Digital infrastructure constraints moderate DTA → SCD	DI moderates DTA → SCD

Note: ESG: Environmental, social, and governance.

facilitating regulatory compliance and sustainability reporting, adapted from Belhadi et al. (2022). DI constraints capture limitations in information and communication technology (ICT) investment, internet connectivity, and technical expertise, as conceptualized in Hlali and Gfasi (2024).

The dependent variable, SCD, was operationalized through carbon reduction initiatives (CRI), energy efficiency practices (EEP), and circular economy integration (CEI), drawing from frameworks proposed by Amankwah-Amoah et al. (2023) and Adom and Matsui (2024). CRI includes emission reduction targets, low-carbon procurement, and logistics optimization. EE evaluates energy-efficient technologies, consumption audits, and operational sustainability. CE encompasses material recyclability, waste reduction strategies, and the adoption of reverse logistics (Okoro et al., 2024).

All constructs were measured using a five-point Likert scale (1 = strongly disagree, 5 = strongly agree), ensuring comparability across variables (Hair et al., 2011). The survey instrument was pre-tested with a representative sample to refine item clarity and establish construct validity. Confirmatory factor analysis (CFA) was conducted to assess the convergent and discriminant validity of the measurement model, ensuring its robustness (Chin, 2009). Reliability was confirmed through Cronbach's alpha and composite reliability (CR) scores, which maintained thresholds above 0.70, as recommended by Hair et al. (2019). Table 1 shows the relationship between the hypotheses and their corresponding constructs.

Data Analysis

Structural equation modeling (SEM) using Partial Least Squares SEM (PLS-SEM) in SmartPLS 4.0 was used to examine structural relationships, enabling the assessment of direct and indirect effects. Mediation was tested using bootstrapped mediation analysis (Hayes Process Model 4), evaluating whether RE mediates the relationship between RS and decarbonization (H_{1b}) (Hayes, 2017). Moderation was analyzed using hierarchical regression models to determine the effect of DI constraints (H_{3c}) on the digitalization-decarbonization relationship. Exploratory factor analysis (EFA) and CFA confirmed construct validity with Cronbach's alpha values between 0.74 and 0.91, ensuring reliability (Hair et al., 2019).

Results and Findings

Model Fit and Predictive Power

The SEM model shows strong empirical adequacy across key indices (Table 2). The chi-square ($\chi^2 = 742.15$, $df = 395$) is significant, typical for large samples (Hair et al., 2019). The normed chi-square ($\chi^2/df = 1.88$) is below 3.0, indicating good parsimony. Incremental fit indices are robust—comparative fit index (CFI) (0.936) and Tucker–Lewis index (TLI) (0.924) exceed 0.90, showing improvement over a null model (Adegbite & Nakajima, 2022; Amoah & Eweje, 2022). Residual indices validate the model—root mean square error of approximation (RMSEA) (0.052) is within range (<0.06), and standardized root mean square residual (SRMR) (0.047) indicates minimal discrepancy (Brookings Institution, 2023). These fit measures confirm that the model accurately captures the relationships among RE, ESG, and digital transformation in SCD (Ufua et al., 2021).

The model shows strong explanatory power (Table 3), with R^2 values indicating significant variance explained in key constructs. RE accounts for 28% of the variance ($R^2 = 0.28$), emphasizing effective enforcement in RS (Amoah & Eweje, 2022; Onuoha et al., 2024). ESG awareness explains 34% of variance ($R^2 = 0.34$), highlighting corporate sustainability as a key driver of decarbonization (Adom & Matsui, 2024). DEC has the highest explanatory power ($R^2 = 0.41$), reflecting the critical role of digital tech in transparency and compliance (Sarkis et al., 2021; Xu et al., 2023). SCD is strongly predicted ($R^2 = 0.52$), showing combined impacts of regulatory, ESG, and tech factors (Adegbite & Nakajima, 2022). Effect sizes (f^2) indicate moderate impacts for enforcement (0.12) and ESG awareness

Table 2. Model Fit Indices.

Fit Index	Value	Threshold
Chi-square (χ^2)	742.15	—
Df	395	—
χ^2/df	1.88	<3.00 (Good)
CFI	0.936	>0.90 (Good)
TLI	0.924	>0.90 (Good)
RMSEA	0.052	<0.06 (Good)
SRMR	0.047	<0.08 (Good)

Note: CFI: Comparative fit index; RMSEA: Root mean square error of approximation; SRMR: Standardized root mean square residual; TLI: Tucker–Lewis index.

Table 3. Model Predictive Power.

Construct	R^2	f^2	Q^2
Regulatory enforcement (RE)	0.28	0.12	0.18
ESG awareness (ESG)	0.34	0.15	0.22
Digitalization and ESG compliance (DEC)	0.41	0.18	0.25
Supply chain decarbonization (SCD)	0.52	0.23	0.31

Note: ESG: Environmental, social, and governance.

(0.15), and a stronger effect for DEC (0.18) (Belhadi et al., 2022). Predictive relevance (Q^2) confirms a robust out-of-sample capacity, especially for DEC ($Q^2 = 0.25$) and SCD ($Q^2 = 0.31$), emphasizing digital transformation's role in decarbonization amid enforcement gaps (Okoro et al., 2024).

Measurement Model Assessment

The results from the measurement model (Table 4) confirm the reliability and validity of the constructs, ensuring the robustness of the empirical analysis. Convergent validity was established through significant indicator loadings (>0.7), average variance extracted (AVE > 0.5), and composite reliability (CR > 0.7) for all constructs, indicating that the items adequately captured the underlying theoretical dimensions (Chin, 2009; Hair et al., 2019). This aligns with prior studies in emerging markets, where similar metrics have been used to validate constructs related to regulations, ESG practices, and digital transformation (Adegbite & Nakajima, 2022; Amoah & Eweje, 2022). Discriminant validity was confirmed using the Fornell–Larcker criterion and heterotrait–monotrait ratio (HTMT). The square root of AVE for each construct exceeded its correlations with others, and HTMT values stayed below 0.85, ensuring that constructs are distinct (Hair et al., 2019). This is crucial in Nigeria, where overlapping regulatory pressures blur boundaries (Onuoha et al., 2024). The results show that the measurement model effectively differentiates between RS, enforcement, inconsistencies, ESG awareness, FC, and DI limitations.

Reliability was supported by Cronbach's alpha values of over 0.7 for all constructs, indicating high internal consistency (Hair et al., 2019). This aligns with sustainability research, where reliable scales are vital for measuring SCD in resource-limited settings (Adom & Matsui, 2024; Tetteh et al., 2025). High scores for ESG awareness ($\alpha = 0.87$) and SCD ($\alpha = 0.90$) highlight the measurement model's robustness, especially regarding corporate sustainability and regulation in Nigeria. Results highlight the importance of DI constraints ($\alpha = 0.81$) in moderating the link between DTA and decarbonization outcomes. This aligns with studies showing infrastructural barriers in emerging economies, where unreliable electricity

Table 4. Measurement Model Results.

Construct	Cronbach's Alpha (α)	Composite Reliability (CR)	AVE	Fornell–Larcker Criterion	HTMT
Regulatory stringency (RS)	0.85	0.89	0.67	0.82	<0.85
Regulatory enforcement (RE)	0.88	0.91	0.71	0.84	<0.85
Regulatory inconsistencies (RI)	0.79	0.86	0.62	0.79	<0.85
ESG awareness (ESG)	0.87	0.90	0.69	0.83	<0.85
Financial constraints (FC)	0.82	0.88	0.65	0.81	<0.85
Institutional pressures (IP)	0.89	0.92	0.73	0.85	<0.85
Digital technology adoption (DTA)	0.86	0.89	0.68	0.82	<0.85
Digitalization and ESG compliance (DEC)	0.84	0.88	0.66	0.81	<0.85
Digital infrastructure constraints (DI)	0.81	0.87	0.63	0.79	<0.85
Supply chain decarbonization (SCD)	0.90	0.93	0.74	0.86	<0.85

Note: AVE: Average variance extracted; ESG: Environmental, social, and governance; HTMT: Heterotrait–monotrait ratio.

and limited expertise hinder the adoption of advanced technologies like blockchain and IoT (Hlali & Gfasi, 2024; Xu et al., 2023). The measurement model offers a basis for assessing how these constraints affect digital tools' role in supply chain transparency and compliance.

The factor loadings (Table 5) also confirm the reliability and validity of the measurement model underpinning the structural analysis of SCD. All indicators load strongly onto their respective latent constructs, with standardized coefficients ranging from 0.74 to 0.86 and highly significant *t*-values (all

Table 5. Factor Loading.

Construct	Indicator	Standardized Loading	<i>t</i> -value	<i>p</i> Value
Regulatory stringency (RS)	RS1	0.76	12.3	<.001
	RS2	0.82	13.5	<.001
	RS3	0.81	13.1	<.001
Regulatory enforcement (RE)	RE1	0.84	14.1	<.001
	RE2	0.79	12.8	<.001
	RE3	0.86	14.5	<.001
Regulatory inconsistencies (RI)	RI1	0.74	11.7	<.001
	RI2	0.77	12.4	<.001
	RI3	0.81	13.2	<.001
ESG awareness (ESG)	ESG1	0.83	13.8	<.001
	ESG2	0.80	13.2	<.001
	ESG3	0.82	13.5	<.001
Financial constraints (FC)	FC1	0.76	12.5	<.001
	FC2	0.79	13.1	<.001
	FC3	0.77	12.8	<.001
Institutional pressures (IP)	IP1	0.85	14.8	<.001
	IP2	0.82	13.9	<.001
	IP3	0.84	14.3	<.001
Digital technology adoption (DTA)	DTA1	0.81	13.1	<.001
	DTA2	0.79	12.7	<.001
	DTA3	0.84	14.0	<.001
Digitalization and ESG compliance (DEC)	DEC1	0.79	12.8	<.001
	DEC2	0.82	13.4	<.001
	DEC3	0.81	13.0	<.001
Digital infrastructure (DI)	DI1	0.77	12.5	<.001
	DI2	0.76	12.2	<.001
	DI3	0.81	13.1	<.001
Supply chain decarbonization (SCD)	SCD1	0.84	14.2	<.001
	SCD2	0.82	13.7	<.001
	SCD3	0.85	14.6	<.001

Notes: All loadings are significant at $p < .001$. ESG: Environmental, social, and governance.

$p < .001$). This surpasses conventional thresholds for construct validity, indicating robust convergent validity across all scales (Hair et al., 2019). Specifically, constructs such as RS, RE, and SCD show high factor loadings, emphasizing how accurately regulatory dynamics and sustainability outcomes are captured in the model (Amoah & Eweje, 2022; Onuoha et al., 2024). Likewise, ESG awareness (ESG) and DTA demonstrate consistently high loadings, affirming their central role in explaining decarbonization efforts (Adom & Matsui, 2024; Sarkis et al., 2021). The consistently significant loadings reinforce the measurement model's robustness and give strong empirical support for subsequent structural analyses, confirming the integrated approach to regulatory, ESG, and digital factors in promoting sustainable supply chain transitions in emerging economies (Adegbite & Nakajima, 2022).

Structural Model Assessment

The structural model assessment (Table 6) reveals significant relationships between the constructs, providing strong empirical support for the hypothesized pathways that drive SCD in Nigeria. Collinearity assessment confirmed the absence of multicollinearity, with VIF values below 5, ensuring the independence of predictor variables (Hair et al., 2019). This is crucial in complex models involving regulatory, ESG, and digital transformation constructs, where overlapping influences could distort outcomes (Adegbite & Nakajima, 2022). The model in Figure 1 demonstrates the interrelationships between regulatory, ESG, and digitalization factors in advancing SCD. The pathways emphasize direct, mediated, and moderated relationships among key constructs.

The bootstrapping analysis using 10,000 subsamples demonstrated significant path coefficients ($p < .05$) for all hypotheses, thus confirming the proposed relationships. RS positively affected SCD ($\beta = 0.32$, $p < .001$), supporting H_{1a} . This aligns with previous research showing that strict environmental policies promote corporate sustainability efforts, especially in emerging markets where regulatory pressure is often the main driver of change (Amoah & Eweje, 2022; Obuobi et al., 2024). However, the indirect effect of RE as a mediator between RS and SCD ($\beta = 0.18$, $p < .001$) highlights the vital role of enforcement mechanisms in turning policy into action (H_{1b}). This result is consistent with studies pointing out the enforcement gap in Nigeria, where weak institutional capacity and corruption often

Table 6. Structural Model Results.

Hypothesis	Path	Path Coefficient	t-value	p Value	Result
H_{1a}	RS $\rightarrow$ SCD	0.32	4.56	<.001	Supported
H_{1b}	RS $\rightarrow$ RE $\rightarrow$ SCD	0.18 (Indirect)	3.45	<.001	Supported
H_{1c}	RI $\rightarrow$ SCD	-0.25	3.89	<.001	Supported
H_{2a}	ESG $\rightarrow$ SCD	0.41	5.12	<.001	Supported
H_{2b}	FC $\rightarrow$ ESG $\rightarrow$ SCD	-0.22 (Indirect)	3.78	<.001	Supported
H_{2c}	IP $\rightarrow$ ESG	0.35	4.67	<.001	Supported
H_{3a}	DTA $\rightarrow$ DEC	0.47	5.89	<.001	Supported
H_{3b}	DTA $\rightarrow$ DEC	0.39	4.98	<.001	Supported
H_{3c}	DI moderates DTA $\rightarrow$ SCD	-0.15 (Moderation)	2.89	.004	Supported

Note: DEC: Digitalization and ESG compliance; DI: Digital infrastructure; DTA: Digital technology adoption; ESG: Environmental, social, and governance; FC: Financial constraints; IP: Institutional pressures; RE: Regulatory enforcement; RI: Regulatory inconsistencies; RS: Regulatory stringency; SCD: Supply chain decarbonization.

undermine regulatory effectiveness (Onuoha et al., 2024). Conversely, RI negatively affected decarbonization efforts ($\beta = -0.25, p < .001$), supporting H_{1c} . This reflects the fragmented regulatory environment in Nigeria, where conflicting federal and state policies increase compliance costs and discourage firms from adopting sustainable practices (Brookings Institution, 2023). The findings underscore the importance of coherent and harmonized regulation to support decarbonization in resource-limited economies.

ESG awareness (ESG) showed a strong positive link with decarbonization ($\beta = 0.41, p < .001$), supporting H_{2a} . This confirms that firms with higher ESG awareness are more likely to incorporate sustainability into their supply chains, driven by internal strategic alignment and external stakeholder pressures (Chu et al., 2017; Tetteh et al., 2025). However, FC negatively moderates the relationship between ESG and SCD ($\beta = -0.22, p < .001$), supporting H_{2b} . This highlights the resource limitations faced by firms in emerging economies, where the high capital requirements for sustainability initiatives often outweigh the perceived benefits (Alaburo & Gbadebo, 2024). The findings emphasize the need for financial incentives, such as green bonds and sustainability-linked loans, to close the funding gap for ESG-driven decarbonization. IP, including investor and consumer demands, significantly influences ESG integration ($\beta = 0.35, p < .001$), supporting H_{2c} . This aligns with stakeholder theory, which posits that external pressures influence corporate sustainability practices, especially in markets with weak RE (DiMaggio & Powell, 2000; Wiredu et al., 2024). The results suggest that IP can partly compensate for regulatory shortcomings, encouraging firms to adopt ESG practices even without strict enforcement.

DTA had a positive influence on transparency in sustainability reporting ($\beta = 0.47, p < .001$) and ESG compliance ($\beta = 0.39, p < .001$), supporting H_{3a} and H_{3b} . This finding is consistent with studies that highlight the role of blockchain, AI, and IoT in enhancing supply chain transparency and operational efficiency (Sarkis et al., 2021; Xu et al., 2023). However, DI constraints negatively moderate the relationship between DTA and SCD ($\beta = -0.15, p = .004$), supporting H_{3c} . This reflects the infrastructural deficits in Nigeria, where unreliable electricity and limited internet connectivity hinder the effective deployment of digital tools (Hlali & Gfasi, 2024).

Discussion on Findings

This study's findings demonstrate that RE, ESG integration, and digital transformation within a volatile institutional environment shape the adoption of decarbonization strategies. Unlike prior research that considers these factors in isolation (Amoah & Eweje, 2022; Tetteh et al., 2025), this study integrates them into a multilevel framework, encompassing macro (regulatory), meso (corporate ESG), and micro (technological) dimensions. Findings reveal that DEC exhibits the highest explanatory power ($R^2 = 0.41$), underscoring the transformative role of technology in bridging regulatory gaps, a perspective less emphasized in developed-market studies (Sarkis et al., 2021).

This study offers empirical clarity on the causal dynamics underlying SCD in emerging economies, highlighting the interdependence between regulatory frameworks, ESG integration, and digital transformation. First, while RS shows a significant direct effect on SCD ($\beta = 0.32, p < .001$), the evidence confirms that RS alone does not automatically lead to strict policy enforcement. Instead, RE partly mediates this relationship (indirect effect $\beta = 0.18, p < .001$), suggesting that strict laws can establish institutional expectations but do not guarantee rigorous enforcement unless supported by governance capacity and institutional resources (Amoah & Eweje, 2022; Onuoha et al., 2024). The path coefficients confirm a partial causal link. While stringent regulations set the formal rules of sustainability, enforcement acts as the operational mechanism that turns regulatory intent into corporate action. However, the moderate size of the mediation effect indicates that causality is contingent rather than deterministic, aligning with

structuration theory's assertion that structures influence but do not fully determine agency (Giddens, 2014). Furthermore, RI significantly hinders decarbonization efforts ($\beta = -0.25, p < .001$), demonstrating that fragmented policies raise compliance costs and diminish firms' confidence in the predictability of regulatory outcomes (Brookings Institution, 2023). Thus, regulatory frameworks influence decarbonization through two interconnected mechanisms: the credibility of enforcement and the coherence of policy signals. Firms adjust their sustainability investments not only based on regulatory presence but also on the perceived legitimacy and consistency of institutional regimes (Adegbite & Nakajima, 2022).

Second, ESG integration has a significant positive impact on decarbonization ($\beta = 0.41, p < .001$). This occurs through strategic alignment: companies with high ESG awareness incorporate sustainability goals into operational practices, supply chain governance, and stakeholder engagement (Tetteh et al., 2025). However, this integration faces financial barriers ($\beta = -0.22, p < .001$), underscoring that even strong ESG intentions need sufficient capital to turn strategy into action (Alaburo & Gbadebo, 2024). IP, including investor and consumer expectations ($\beta = 0.35, p < .001$), partly compensate for limited RE, acting as quasi-regulatory forces that drive firms to commit to sustainability despite weak state capacity (Wiredu et al., 2024). Therefore, ESG's effect on decarbonization works through two main channels: internal strategic alignment and external stakeholder influence.

Third, digital transformation significantly promotes decarbonization through two interconnected pathways: enhanced transparency in sustainability reporting ($\beta = 0.47, p < .001$) and improved ESG compliance ($\beta = 0.39, p < .001$). Digital tools such as blockchain, AI, and IoT serve as technological enablers, enabling real-time data collection, traceability, and regulatory reporting, which reduce information asymmetry and compliance costs (Sarkis et al., 2021; Xu et al., 2023). However, this technological mechanism is nonlinear and influenced by context. Infrastructure deficits strongly weaken the link between digital adoption and decarbonization outcomes ($\beta = -0.15, p = .004$), showing that technological advantages are limited in environments with unreliable electricity, low internet access, and limited digital literacy (Hlali & Gfasi, 2024). Therefore, digital transformation impacts decarbonization by improving informational accuracy and process efficiency, but its success depends on infrastructural and institutional support.

This study's findings enhance academic debate by showing that ESG awareness is essential in emerging economies, but it is not enough. FC acts as a significant barrier to transition efforts, revealing a gap in many previous studies, which either overlook or downplay the financial instability faced by firms in resource-limited settings. Unlike Barney's (1991) resource-based view, which emphasizes firm capabilities as internal sources of competitive advantage, these findings suggest that external access to capital, often overlooked in many theoretical models, is crucial in enabling ESG-driven decarbonization in the Global South. IP, especially those from investors and consumers, also plays a key role in driving ESG adoption. While this supports stakeholder theory (DiMaggio & Powell, 2000), it differs from earlier research in that it shows that these pressures partly compensate for the weaknesses in government enforcement. Essentially, market forces act as semi-regulatory agents in environments where governance institutions lack coherence and legitimacy (Ufua et al., 2021). This mechanism has not been sufficiently explored in the ESG literature, particularly in settings where Western compliance models are naively transplanted into institutional voids (Adegbite & Nakajima, 2022).

This study challenges conventional assumptions regarding institutional enforcement (Adegbite & Nakajima, 2022), confirming that RE significantly mediates the effect of RS on decarbonization. It emphasizes that policy effectiveness in emerging markets depends on the presence and enforcement capacity of regulations (Onuoha et al., 2024). The negative effect of RI on decarbonization supports previous research on fragmented governance structures that hinder sustainability efforts (Obuobi et al., 2024). Unlike studies that assume uniform policy effects (Chu et al., 2017), this research shows how

conflicting policies raise compliance costs, discouraging investments in sustainability. In contrast to existing models that treat digital tools as inherently transformative, this study highlights their conditional effectiveness; without stable electricity, reliable internet, and skilled personnel, technologies like blockchain and IoT remain underused. These findings challenge technological determinism and reinforce structuration theory's focus on the organizational agency's mediating role. Nigerian firms display resilience by selectively deploying digital tools to address governance gaps, especially when formal institutions weaken (Brookings Institution, 2023).

The strong link between ESG awareness and decarbonization supports previous research linking sustainability consciousness to better environmental outcomes (Tetteh et al., 2025). However, this study expands the discussion by highlighting FC as a crucial barrier in emerging economies, a factor often ignored in studies focusing on firms with easier access to green financing (Alaburo & Gbadebo, 2024). IP, emerging as key drivers of ESG adoption, reinforces the stakeholder-driven perspective that firms respond to investor and consumer expectations, even in weak regulatory environments (Wiredu et al., 2024). Compared to earlier studies in OECD contexts (e.g., Belhadi et al., 2022; Kamble et al., 2023), which reported linear relationships between digitalization and sustainability performance, this research shows that such conclusions do not apply in low-infrastructure settings. This divergence highlights the danger of applying theories across different contexts without adaptation. Likewise, the dominance of ESG-led models in Western literature overlooks the financial insecurity and institutional gaps faced by firms in countries like Nigeria, thus limiting their practical relevance (Alaburo & Gbadebo, 2024).

Conclusion and Implications

This study offers a comprehensive, empirically grounded analysis of how regulatory frameworks, ESG integration, and digital transformation collectively influence SCD in an emerging economy context. Our findings demonstrate that RE, rather than mere policy existence, is the decisive factor in translating RS into meaningful decarbonization outcomes (Onuoha et al., 2024; University of the West of England, 2023). RI remains a significant barrier, raising compliance costs and discouraging sustainability investments (Brookings Institution, 2023). Furthermore, ESG awareness has emerged as a key driver of decarbonization, reaffirming that sustainability consciousness promotes environmental performance (Chu et al., 2017; Tetteh et al., 2025). However, FC pose a substantial limitation on ESG-led transitions, highlighting the resource dependency of firms operating in capital-scarce environments (Alaburo & Gbadebo, 2024). Digitalization, particularly through blockchain, AI, and IoT, has surfaced as a powerful enabler for improving transparency, regulatory compliance, and operational efficiency (Sarkis et al., 2021; Xu et al., 2023). Yet, systemic infrastructural deficits hinder the scalable deployment of digital sustainability solutions in contexts like Nigeria (Hlali & Gfasi, 2024; Ufua et al., 2021). By integrating macro-level policy factors, meso-level corporate strategies, and micro-level technological tools, this study advances the theoretical understanding of sustainable supply chain management in emerging markets. Unlike prior research that treats these elements in isolation, our multilevel framework emphasizes their mutual dependencies and the need for adaptive firm responses under institutional uncertainty (Adegbite & Nakajima, 2022; Amoah & Eweje, 2022).

Policy Recommendations

To accelerate SCD in emerging economies, we propose the following targeted policy interventions:

1. *Strengthen RE*: Governments must allocate sufficient resources for regulatory agencies to enhance monitoring capacity, reduce corruption, and ensure uniform enforcement across jurisdictions (Brookings Institution, 2023; Onuoha et al., 2024).
2. *Harmonize policy frameworks*: Regulatory coherence is essential to mitigate compliance uncertainties. The harmonization of federal and state regulations will reduce transaction costs and encourage sustainability investments (Adegbite et al., 2013; Ufua et al., 2021).
3. *Expand green financing instruments*: Policymakers should facilitate the development of financial instruments such as green bonds, sustainability-linked loans, and blended finance structures to alleviate capital constraints faced by firms pursuing ESG transitions (Alaburo & Gbadebo, 2024; Cordonnier & Saygin, 2023).
4. *Invest in DI*: Strategic investments in stable electricity, high-speed internet, and digital literacy programs are critical for enabling widespread adoption of digital sustainability solutions, thereby closing the implementation gap in decarbonization initiatives (Amoah & Eweje, 2022; Hlali & Gfasi, 2024).
5. *Incentivize voluntary ESG integration*: Fiscal incentives, such as tax credits, accelerated depreciation on green technologies, and subsidies for sustainability certifications, can encourage firms to embed ESG principles more deeply into their operational models (Brookings Institution, 2023).

Limitations and Suggestions for Further Research

While this study provides valuable insights, its focus on high-impact sectors in Nigeria limits the generalizability of the findings to other industries and regions. The cross-sectional research design limits the ability to capture longitudinal trends in regulatory, corporate, and technological shifts that affect decarbonization (Galeazzi et al., 2024). Future research should employ longitudinal methodologies to assess the evolving impact of regulatory reforms and technological advancements on sustainable supply chain practices. Second, while the study draws on a diverse sample of firms from carbon-intensive industries, it does not incorporate lower-emission sectors, such as finance and telecommunications, which may offer additional insights into ESG integration beyond heavy industry (Tetteh et al., 2025). Expanding the industry scope could enhance the generalizability of findings across different economic sectors. Third, while digital transformation was identified as a key enabler, the study does not account for firm-level variations in technological adoption and capabilities (Ufua et al., 2021). Future research should explore how firm size, digital maturity, and sectoral dynamics influence the effectiveness of digital interventions in supply chain sustainability.

Building on the findings, several directions for future research emerge. First, examining the long-term effects of RE and policy coherence on SCD would offer deeper insights into the sustainability transition process. Comparative studies that assess regulatory consistency across different jurisdictions could identify best practices for harmonizing policy frameworks to support corporate compliance (Adegbite & Nakajima, 2022). Second, future research should investigate the role of financial instruments, such as green bonds and sustainability-linked loans, in alleviating capital constraints that hinder ESG adoption (Alaburo & Gbadebo, 2024). Empirical studies evaluating the effectiveness of financial incentives in promoting sustainability investments could yield practical guidance for policymakers and financial institutions. Third, expanding research on digital transformation by assessing the impact of emerging technologies, such as AI-driven sustainability analytics and blockchain-enabled supply chain transparency, could generate actionable insights for optimizing digital sustainability strategies (Wiredu et al., 2024). Finally, examining the behavioral aspects of corporate sustainability decision-making, especially the influence of organizational culture and leadership commitment on ESG integration, could deepen the understanding of internal drivers shaping decarbonization efforts (Chu et al., 2017). These research

avenues will further enhance the theoretical and practical knowledge of sustainable supply chain management in emerging economies.

Data Availability

The data that support the findings of this study are openly available in Figshare at <https://doi.org/10.6084/m9.figshare.30186337>.

Declaration of Conflicting Interest

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