

# **DECARBONISING SUPPLY CHAINS IN EMERGING ECONOMIES: A MULTILEVEL ANALYSIS OF REGULATION, ESG, AND DIGITISATION**

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## **ABSTRACT**

As global efforts to combat climate change intensify, the decarbonisation of supply chains has become a strategic imperative, yet little is known about how this transition unfolds in emerging economies. This study investigates the complex interplay between regulatory frameworks, ESG (Environmental, Social, and Governance) practices, and digitisation in driving supply chain decarbonisation within Nigeria's carbon-intensive sectors. Drawing on a multilevel analytical lens, we develop and empirically test 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; regulatory enforcement, rather than formal existence, is the true catalyst for sustainable transitions. ESG-driven strategies show strong mediating effects yet are significantly constrained by firm-level challenges such as cost, technical know-how, and infrastructural limitations. Notably, digital innovations, particularly in the form of blockchain, AI, and IoT, emerge as critical enablers of carbon transparency and traceability, offsetting some of the institutional voids that characterise emerging economies. This study offers a rare, data-driven perspective on supply chain decarbonisation in the Global South, contributing 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, ESG Integration, Digital Transformation, Emerging Economies, Sustainability Governance.

## 1. INTRODUCTION

The imperative to decarbonise supply chains has emerged as a defining challenge for contemporary sustainability efforts, yet its implementation in emerging economies remains fraught with structural, regulatory, and technological complexities (Kumar et al., 2024; Appiah et al., 2023; Bulkeley et al., 2022; Adom & Matsui, 2024). Nigeria's supply chains, particularly within extractive industries, exert significant environmental pressures as a resource-driven economy, with carbon-intensive operations undermining global sustainability commitments (Chidolue et al., 2024). However, while existing literature predominantly examines decarbonisation 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, Environmental, Social, and Governance (ESG) adoption, and digital transformation in emerging economies exacerbates this knowledge gap (Daggash & Mac Dowell, 2021).

The dominant discourse on supply chain sustainability often treats regulatory frameworks, corporate ESG integration, and digital transformation as discrete elements rather than interdependent drivers of decarbonisation (Hlali & Gfasi, 2024). However, in emerging economies such as Nigeria, these dimensions interact within a volatile institutional environment where economic pragmatism frequently overrides 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, Amaeshi & Nakajima, 2013). This paradox underscores the necessity of a multilevel analytical approach that accounts for macro-level regulatory constraints, meso-level corporate ESG strategies, and micro-level technological enablers in facilitating decarbonisation 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 decarbonisation (Kamble et al., 2023). Technologies such as blockchain, artificial intelligence (AI), and the Internet of Things (IoT) are increasingly recognised for enhancing supply chain transparency, compliance, and efficiency (Adu et al., 2023). 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 digitalisation 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 decarbonisation 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, Sarkis & Lai, 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: (1) How do existing regulatory frameworks in Nigeria facilitate or constrain supply chain decarbonisation efforts? (2) To what extent do firms integrate ESG principles into supply chain management, and what are the key drivers and barriers to adoption? (3) What role does digital transformation, specifically blockchain, AI, and IoT, play in enhancing transparency, compliance, and efficiency in sustainable supply chain practices? (4) How can regulatory mechanisms, corporate ESG strategies, and digital

innovation be aligned to create a synergistic model for effective decarbonisation in emerging economies?

This study contributes novel insights into supply chain sustainability in emerging markets by bridging regulatory, corporate, and technological dimensions. Employing a multilevel analytical framework, the research elucidates the systemic constraints that hinder ESG-driven decarbonisation while demonstrating how digital transformation can be a critical enabler in overcoming governance and operational limitations. The findings offer an empirically grounded foundation for integrating regulatory frameworks with corporate sustainability strategies, advancing a pragmatic approach to decarbonisation that is contextually relevant and theoretically rigorous.

The remainder of this paper is structured as follows: Section 2 outlines the theoretical background and develops the research hypotheses. Section 3 details the research methodology, including data collection and analytical techniques. Section 4 presents the study's findings, and Section 5 discusses the study's findings. Finally, Section 6 discusses the study's conclusions, practical implications, and limitations, providing directions for future research.

## **2. THEORETICAL BACKGROUND AND HYPOTHESES DEVELOPMENT**

### **2.1 Theoretical Foundation**

This study is underpinned by two less frequently applied yet highly relevant theoretical perspectives: Complexity Theory and Structuration Theory (see figure 1). Complexity Theory posits that organisations operate within nonlinear, adaptive systems where interactions among multiple variables create unpredictable outcomes (Amoah & Eweje, 2022). In the context of supply chain decarbonisation, Nigerian firms operate within a regulatory environment characterised by overlapping mandates, fragmented enforcement, and inconsistent sustainability policies (Adegbite, Amaeshi & Nakajima, 2013). These factors create a complex and often chaotic compliance landscape where firms must continuously adjust their ESG strategies to respond to shifting institutional and market pressures (Alaburo & Gbadebo, 2024). This theoretical lens also explains the challenges of digital adoption for ESG compliance. While blockchain, AI, and IoT enhance transparency and sustainability reporting, their effectiveness is contingent upon stable regulatory and infrastructural conditions (Kamble et al., 2023). In developed economies, where digital ecosystems are mature and regulatory enforcement is predictable, firms can seamlessly integrate technology into sustainability strategies (Wiredu et al., 2024). However, in Nigeria, weak governance, financial constraints, and infrastructural gaps create unpredictable technological adoption patterns, requiring firms to develop adaptive strategies to align with ESG mandates (Ufua et al., 2021). Complexity Theory thus provides an explanatory framework for understanding how firms navigate the nonlinearity of regulatory and technological environments when implementing sustainability initiatives.

Structuration Theory (Giddens, 2014) offers a perspective on the interaction between institutional structures and corporate agencies in sustainability adoption. Unlike static institutional perspectives that assume firms merely respond to regulatory pressures, this theory posits that firms actively shape and are shaped by the regulatory and economic systems in which they operate (Chu, P.-Y. et al., 2017). In Nigeria, where regulatory inconsistencies and enforcement weaknesses undermine ESG adoption, firms engage in strategic adaptations, sometimes circumventing regulatory inefficiencies through voluntary sustainability commitments and private governance mechanisms (Adegbite & Nakajima, 2022). This perspective is particularly relevant to digital sustainability adoption. While regulatory pressures may encourage firms to integrate AI, blockchain, and IoT for enhanced transparency, their successful deployment depends on internal corporate strategies and external structural enablers (Xu et al., 2023). Nigerian firms, constrained by financial and infrastructural barriers, often leverage informal networks, private sustainability standards, and partnerships with multinational stakeholders to fill regulatory and institutional gaps (Brookings Institution, 2023). Structuration Theory thus highlights the bidirectional influence between institutional structures and corporate agency, demonstrating that firms are not merely passive recipients of regulatory change but active participants in shaping sustainability transitions.

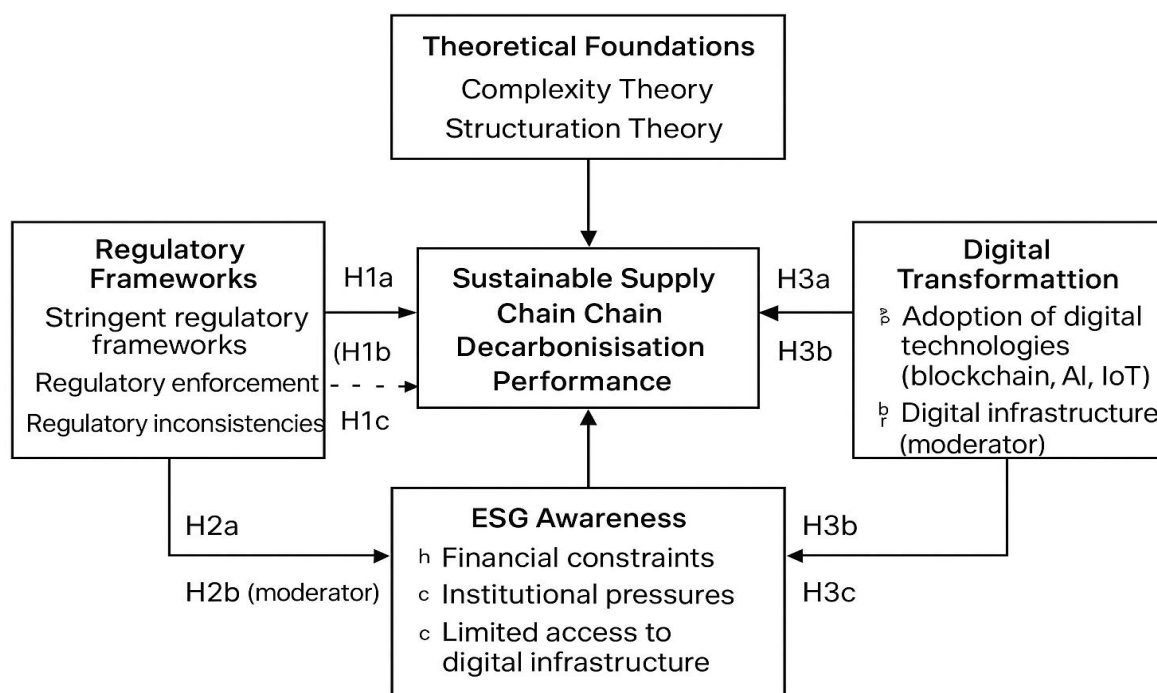


Figure 1: Conceptual framework of the study (Source: Author)

## 2.2 Regulatory Frameworks and Supply Chain Decarbonization

Regulatory frameworks 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 strengthen environmental governance and drive decarbonisation efforts (Brookings Institution, 2023). These regulations provide an institutional foundation for sustainable business practices, yet their effectiveness depends on enforcement mechanisms and corporate adherence (Noah et al., 2021). However, while these regulations provide a foundation for corporate environmental responsibility, their effectiveness remains uncertain due to persistent enforcement challenges (Adegbite & Nakajima, 2022; Brookings Institution, 2023).

Despite regulatory stringency, compliance is often inconsistent in developing economies. Research in Ghana and Nigeria indicates that firms generally respond to environmental regulations, yet disparities in enforcement efficiency, corruption, and informal networks hinder consistent adoption (Amoah & Eweje, 2022). While some perspectives suggest 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 prioritise short-term survival over long-term sustainability (Udeagha & Ngepah, 2023).

Furthermore, comparative studies suggest that stringent environmental policies improve corporate compliance in 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, regulatory enforcement 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.

Moreover, regulatory inconsistencies contribute to policy fragmentation, complicating compliance and escalating firm costs. Without a coherent regulatory framework, companies must allocate additional resources to navigate conflicting policies. Studies on sustainable procurement in Nigeria reveal that weak policy coordination significantly hampers the adoption of sustainability initiatives (Oyewobi & Jimoh, 2022). While some viewpoints attribute regulatory fragmentation to systemic unpredictability, they often lack actionable solutions. Meanwhile, perspectives emphasising cost minimisation overlook corruption and weak governance as primary barriers to compliance (Amoah & Eweje, 2022). Addressing these structural deficiencies requires an integrated regulatory approach considering economic, political, and institutional constraints.

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

- **H1a:** Stringent regulatory frameworks positively influence corporate adoption of supply chain decarbonisation.
- **H1b:** Regulatory enforcement mediates the relationship between policy existence and compliance.
- **H1c:** Regulatory inconsistencies hinder sustainable supply chain implementation in Nigeria.

### **2.3 ESG Awareness and Decarbonization Integration in Supply Chains**

The integration of Environmental, Social, and Governance (ESG) principles into corporate strategies is increasingly recognised as a key driver of supply chain decarbonisation (Amoah & Eweje, 2022). Firms with strong ESG awareness are expected to adopt sustainable practices due to their understanding of environmental and social impacts and the role of governance in mitigating negative outcomes (Adegbite, Amaeshi & Nakajima, 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 firms' ability to embed ESG-driven operational models.

External pressures also shape corporate ESG adoption. Some perspectives suggest that firms align with investor, consumer, and regulatory expectations 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, P.-Y. et al., 2017).

Empirical evidence highlights the need for systemic support. Adu et al. (2023) found that firms in Ghana with high ESG awareness pursued green supply chain practices, though technical and financial limitations constrained implementation. Likewise, Ufua et al. (2021) observed that while Nigerian firms expressed interest in decarbonisation, poor infrastructure and regulatory gaps impeded execution. These findings reinforce the need for institutional support and tailored policies that address local constraints.

Financial limitations remain a fundamental barrier to ESG-driven decarbonisation, particularly in emerging economies. Implementing sustainability strategies requires significant capital investments in

technology, process redesign, and workforce development costs that many firms struggle to absorb (Wiredu et al., 2024). A global study across 51 countries found that financial constraints significantly hinder 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 yielded lower returns, reducing firms' willingness to commit to sustainability.

Funding gaps remain substantial. The Landscape of Climate Finance in Nigeria (2024) estimates that USD 1.9 trillion is required for Nigeria's energy transition by 2060, yet existing financial mechanisms remain 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 like 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 regulatory inconsistencies, weak enforcement, and limited financial incentives reduce firms' motivation to integrate decarbonisation strategies (Chu, P.-Y. et al., 2017). Although investor demands and consumer preferences are rising, corporate ESG adoption remains in its early stages, influenced by market maturity, economic instability, and regulatory uncertainty (Adu et al., 2023).

The effectiveness of external pressures varies across economies. In developed markets, stringent enforcement and standardised sustainability frameworks ensure compliance, whereas in Nigeria, weak institutional support and fragmented governance structures limit ESG effectiveness (Udeagha & Ngepah, 2023). Studies suggest that while investor expectations influence corporate behaviour, regulatory inconsistencies reduce firms' responsiveness to sustainability mandates (Adegbite, Amaeshi & Nakajima, 2013). Chu, P.-Y. et al. (2017) found that while government, customer, and competitor pressures shaped sustainable practices, weak institutional frameworks reduced top management support for ESG. Similarly, Wiredu et al. (2024) noted that while green supply chain initiatives improved corporate environmental performance, external pressures alone were insufficient, with leadership commitment and sustainability culture playing a more direct role in ESG adoption.

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

- **H2a:** Firms with higher ESG awareness are more likely to integrate decarbonisation strategies into their supply chain operations.
- **H2b:** Financial constraints negatively impact the adoption of ESG-driven decarbonisation practices in Nigeria.
- **H2c:** Institutional pressures (e.g., investor demand and consumer preferences) significantly influence the extent of ESG integration in Nigerian supply chains.

## 2.4 Digital Transformation and Sustainable Supply Chains

The adoption of blockchain, artificial intelligence (AI), and the Internet of Things (IoT) is increasingly recognised as a driver of transparency in sustainability reporting (Amoah & Eweje, 2022). Blockchain's decentralised ledger enhances data integrity, reducing information asymmetry and fostering 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, overlooking challenges in emerging markets such as Nigeria (Adegbite, Amaeshi & Nakajima, 2013). Limited infrastructure, low digital literacy, and organisational resistance hinder the adoption of digital sustainability reporting tools (Brookings Institution, 2023). Additionally, assuming a direct link between technology adoption and transparency neglects the role of corporate culture and stakeholder engagement, which can either facilitate or obstruct digital reporting initiatives (Chu, P.-Y. et al., 2017). Addressing these gaps requires context-specific research considering institutional and socio-economic factors shaping transparency outcomes in developing economies.

Furthermore, firms with advanced digitalisation capabilities are better positioned to comply with ESG regulations due to enhanced data analytics, automated compliance monitoring, and improved decision-making (Wiredu et al., 2024). Digital tools enable real-time ESG performance tracking, aligning corporate operations with regulatory standards and stakeholder expectations (Udeagha & Ngepah, 2023). AI-driven risk detection and IoT-based environmental monitoring ensure firms meet sustainability benchmarks (Adeleke et al., 2022). However, research often assumes regulatory uniformity, failing to reflect the fragmented regulatory landscape in developing economies (University of the West of England, 2023). Nigeria's weak enforcement mechanisms and inconsistent sustainability policies reduce the efficacy 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 financial constraints and institutional gaps affect digital adoption is critical for designing effective sustainability policies.

The success of digital technologies in driving decarbonisation also depends on the availability of reliable digital infrastructure. While developed economies benefit from seamless technological integration, enabling substantial emissions reductions, infrastructure deficits in Nigeria, such as unreliable electricity, poor internet connectivity, and limited technical expertise, undermine the effectiveness of digital sustainability solutions (Amoah & Eweje, 2022). Existing studies often examine the direct effects of digital adoption on decarbonisation but neglect the moderating role of infrastructure, a critical omission given the technological deployment challenges 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 requires coordinated efforts, including policy reforms, private-sector investment, and cross-sector partnerships to enhance digital infrastructure and maximise technology's impact on decarbonisation (Chu, P.-Y. et al., 2017).

Comparative analyses reveal divergent pathways for digital sustainability adoption across economic contexts. In developed markets, stringent ESG regulations and advanced technological ecosystems drive transparency, compliance, and decarbonisation (Wiredu et al., 2024). However, developing economies face institutional voids, financial limitations, and infrastructure challenges, constraining digital adoption at scale (Adegbite, Amaeshi & Nakajima, 2013). Nigeria exemplifies these challenges, where despite increasing interest in digital transformation, supply chain inefficiencies, corruption, and regulatory inconsistencies weaken digital adoption's impact 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 hypothesises that:

- **H3a:** The adoption of digital technologies (blockchain, AI, IoT) positively correlates with transparency in supply chain sustainability reporting.
- **H3b:** Firms with higher levels of digitalisation demonstrate stronger compliance with ESG-related supply chain regulations.

- **H3c:** Limited access to digital infrastructure moderates the relationship between technological adoption and decarbonisation outcomes.

### 3. METHODOLOGY

#### 3.1 Research Design

This study employs a quantitative, cross-sectional survey to examine the influence of regulatory frameworks, ESG integration, and digital transformation on supply chain decarbonisation in Nigeria. This method ensures empirical data collection from firms engaged in supply chain operations, aligning with sustainability research in emerging markets (Zhu, Sarkis & Lai, 2019; Adeleke et al., 2022).

#### 3.2 Sampling Strategy

This study targets firms with at least 100 employees across manufacturing, oil and gas, logistics, and agriculture, key sectors in Nigeria's carbon-intensive supply chains. These industries were selected due to their environmental impact and strategic role in sustainability transitions (Brookings Institution, 2023; Appiah et al., 2023). The sampling frame was sourced from the Nigerian Corporate Affairs Commission (CAC) and NACCIMA directories. Using stratified random sampling, 180 firms were contacted, with 162 providing 324 responses (two per firm), yielding a response rate of 90%, consistent with sustainability research in emerging economies (Amoah & Eweje, 2022). Industries such as finance, telecommunications, and retail were excluded due to their comparatively lower direct environmental impact within supply chain operations. While these sectors engage in sustainability reporting, they do not significantly contribute to carbon-intensive supply chain processes, making them less relevant to this study's objectives.

#### 3.3 Data Collection

Surveys were distributed via email and in person, with initial telephone contact to encourage participation. Two key informants per firm, Managing Directors (MDs) or Chief Sustainability Officers (CSOs), and Supply Chain or IT Managers, provided perspectives on strategic ESG alignment and operational digitalisation 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. First, we embedded attention-checking questions at different survey sections to ensure participants were focused. Respondents who failed these checks were excluded (Podsakoff et al., 2003). Secondly, responses with missing values were discarded (Hayes et al., 2011). Thirdly, 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 serving as proxies for nonparticipants (Amoah & Eweje, 2022). We used a Mann-Whitney U test to compare early and late responses across demographic variables (age, experience) and key constructs, which showed no significant differences ( $p > 0.05$ ). Thus, we conclude that non-response bias is not a concern in this study. Additionally, we considered the potential for common method bias, as data for both exogenous and endogenous constructs were collected from the same respondents (Podsakoff et al., 2003). To mitigate this, we carefully crafted survey questions using clear, concise language and reliable measures from prior studies and separated endogenous and exogenous constructs within different survey sections. To confirm the absence of common method bias, we conducted a collinearity test, which indicated that all VIF values were below 3.3 (Kumar et al., 2024), suggesting no common method bias in the data.

#### 3.4 Measurement and Operationalization of Variables

Each construct is operationalised through validated multi-item scales adapted from peer-reviewed sources to ensure reliability and validity (Gallardo-Vázquez & Sanchez-Hernandez, 2014; Sarkis et al., 2021).

Regulatory stringency (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 rigour, compliance costs, and the effectiveness of government interventions. Regulatory enforcement (RE) measures the extent of compliance monitoring, penalties for violations, and institutional capacity, drawn from Wiredu et al. (2024). Regulatory inconsistencies (RI) reflect bureaucratic inefficiencies, policy conflicts, and institutional fragmentation, aligning with prior studies on governance effectiveness in emerging markets (Adegbite & Nakajima, 2012).

ESG awareness (ESG) is measured through firms' engagement with sustainability initiatives, employee training, and corporate reporting practices, utilising scales from Gallardo-Vázquez & Sanchez-Hernandez (2014). Financial constraints (FC) assess the availability of capital for ESG investments, following frameworks established by Alaburo & Gbadebo (2024) and the Climate Policy Initiative (2024). Institutional pressures (IP) encompass investor expectations, consumer demand, and global supply chain requirements, drawing from Chu et al. (2017) and Wiredu et al. (2024).

Digital technology adoption (DTA) measures the extent to which firms integrate blockchain, AI, and IoT in their supply chain operations, following methodologies from Sarkis et al. (2021) and Bai et al. (2020). Digitalisation and ESG compliance (DEC) evaluate the role of digital systems in facilitating regulatory compliance and sustainability reporting, adapted from Belhadi et al. (2022). Digital infrastructure (DI) constraints capture limitations in ICT investment, internet connectivity, and technical expertise, as conceptualised in Hlali & Gfasi (2024).

The dependent variable, supply chain decarbonisation (SCD), is operationalised through carbon reduction initiatives (CRI), energy efficiency practices (EE), and circular economy integration (CE), drawing from frameworks proposed by Amankwah-Amoah, Debrah and Anang (2023) and Adom & Matsui (2024). CRI includes emission reduction targets, low-carbon procurement, and logistics optimisation. EE evaluates energy-efficient technologies, consumption audits, and operational sustainability. CE encompasses material recyclability, waste reduction strategies, and reverse logistics adoption (Okoro et al., 2024).

All constructs are 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 convergent and discriminant validity, ensuring the robustness of the measurement model (Chin, 2009). Reliability was confirmed through Cronbach's alpha and composite reliability scores, maintaining thresholds above 0.70 as recommended by Hair et al. (2019).

**Table 1: Summary of all the hypotheses and their corresponding constructs**

| Hypothesis | Relationship                                                           | Constructs Involved    |
|------------|------------------------------------------------------------------------|------------------------|
| H1a        | Regulatory stringency → Supply chain decarbonisation                   | RS → SCD               |
| H1b        | Regulatory enforcement mediates RS → SCD                               | RS → RE → SCD          |
| H1c        | Regulatory inconsistencies → Supply chain decarbonisation              | RI → SCD               |
| H2a        | ESG awareness → Supply chain decarbonisation                           | ESG → SCD              |
| H2b        | Financial constraints → ESG-driven decarbonisation                     | FC → ESG → SCD         |
| H2c        | Institutional pressures → ESG integration                              | IP → ESG               |
| H3a        | Digital technology adoption → Transparency in sustainability reporting | DTA → DEC              |
| H3b        | Digitalisation → ESG compliance                                        | DTA → DEC              |
| H3c        | Digital infrastructure constraints moderate DTA → SCD                  | DI moderates DTA → SCD |

Source: Author's Computation

### 3.5 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 via bootstrapped mediation analysis (Hayes Process Model 4), evaluating whether regulatory enforcement mediates the link between regulatory stringency and decarbonisation (H1b) (Hayes, 2017). Moderation was analysed using hierarchical regression models to determine the effect of digital infrastructure constraints (H3c) on the digitalisation-decarbonization relationship. Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) confirmed construct validity with Cronbach's alpha values between 0.74 and 0.91, ensuring reliability (Hair et al., 2019).

## 4. RESULTS AND FINDINGS

### 4.1 Model Fit and Predictive Power

Assessing model fit and predictive power provides critical insights into the structural model's explanatory strength and practical relevance. The  $R^2$  values indicate the proportion of variance explained in the dependent constructs, demonstrating the model's ability to capture the underlying dynamics of supply chain decarbonisation. Regulatory enforcement (RE) accounts for 28% of the variance ( $R^2 = 0.28$ ), reflecting the significant role of enforcement mechanisms in translating regulatory stringency into actionable decarbonisation strategies (Onuoha et al., 2024). This aligns with prior research emphasising the enforcement gap in emerging economies, where weak institutional capacity often undermines policy effectiveness (Amoah & Eweje, 2022).

ESG awareness (ESG) explains 34% of the variance ( $R^2 = 0.34$ ), highlighting the importance of corporate sustainability consciousness in driving decarbonisation efforts. This finding is consistent with studies that link ESG integration to long-term business growth and environmental performance, particularly in markets where stakeholder pressures complement regulatory frameworks (Adom & Matsui, 2024; Chu et al., 2017). The relatively high  $R^2$  value underscores the potential of ESG-driven strategies to overcome structural barriers in resource-constrained environments.

Digitalisation and ESG compliance (DEC) exhibit the highest explanatory power among the mediating constructs, with an  $R^2$  value of 0.41. This reflects the transformative potential of digital technologies, such as blockchain and IoT, in enhancing transparency and compliance within supply chains (Sarkis et al., 2021; Xu et al., 2023). The strong predictive power of DEC underscores the critical role of digital tools in bridging the gap between regulatory requirements and operational implementation, particularly in contexts characterised by infrastructural deficits (Hlali & Gfasi, 2024).

The dependent variable, supply chain decarbonisation (SCD), achieves an  $R^2$  value of 0.52, indicating that the model explains over half of the variance in decarbonisation outcomes. This explanatory power highlights the synergistic impact of regulatory frameworks, ESG integration, and digital transformation in driving sustainability transitions (Adegbite & Nakajima, 2022). The findings suggest that a multi-level approach, addressing macro (regulatory), meso (corporate), and micro (technological) factors, is essential for achieving meaningful decarbonisation in emerging economies.

The effect size ( $f^2$ ) measures the relative impact of independent constructs on dependent variables. Regulatory enforcement ( $f^2 = 0.12$ ) and ESG awareness ( $f^2 = 0.15$ ) exhibit moderate effect sizes, indicating their substantial but not dominant influence on decarbonisation. In contrast, digitalisation and ESG compliance ( $f^2 = 0.18$ ) demonstrate a stronger impact, reflecting the growing importance of digital tools in enhancing supply chain sustainability (Belhadi et al., 2022). The effect size for SCD ( $f^2 = 0.23$ ) further underscores the cumulative impact of regulatory, ESG, and digital factors in driving decarbonisation.

Predictive relevance ( $Q^2$ ), assessed through the blindfolding procedure, confirms the model's ability to predict outcomes beyond the sample data. All  $Q^2$  values exceed zero, indicating strong predictive relevance. Regulatory enforcement ( $Q^2 = 0.18$ ) and ESG awareness ( $Q^2 = 0.22$ ) demonstrate moderate

predictive power, while digitalisation and ESG compliance ( $Q^2 = 0.25$ ) and SCD ( $Q^2 = 0.31$ ) exhibit higher predictive relevance. This suggests that digital transformation and its alignment with ESG objectives are critical for achieving decarbonization goals, particularly in contexts where regulatory enforcement is inconsistent (Okoro et al., 2024).

**Table 2: Model Fit and Predictive Power**

| Construct                               | R <sup>2</sup> | f <sup>2</sup> | Q <sup>2</sup> |
|-----------------------------------------|----------------|----------------|----------------|
| Regulatory Enforcement (RE)             | 0.28           | 0.12           | 0.18           |
| ESG Awareness (ESG)                     | 0.34           | 0.15           | 0.22           |
| Digitalisation and ESG Compliance (DEC) | 0.41           | 0.18           | 0.25           |
| Supply Chain Decarbonization (SCD)      | 0.52           | 0.23           | 0.31           |

Source: Author's Computation

## 4.2 Measurement Model Assessment

The result from the measurement model (Table 1) confirms 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 capture the underlying theoretical dimensions (Hair et al., 2019; Chin, 2009). This aligns with prior studies in emerging markets, where similar metrics have been used to validate constructs related to regulatory frameworks, 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 the AVE for each construct exceeded its correlations with other constructs, and HTMT values remained below the 0.85 threshold, ensuring that the constructs are distinct and non-redundant (Hair et al., 2019). This is particularly critical in the Nigerian context, where overlapping regulatory and institutional pressures often blur the boundaries between constructs (Onuoha et al., 2024). The results suggest that the measurement model effectively differentiates between regulatory stringency, enforcement, and inconsistencies, as well as between ESG awareness, financial constraints, and digital infrastructure limitations.

Reliability was further supported by Cronbach's alpha values exceeding 0.7 for all constructs, indicating high internal consistency (Hair et al., 2019). This is consistent with findings in sustainability research, where reliable measurement scales are essential for capturing the multifaceted nature of supply chain decarbonisation in resource-constrained environments (Adom & Matsui, 2024; Tetteh et al., 2025). The high-reliability scores for constructs such as ESG awareness ( $\alpha = 0.87$ ) and supply chain decarbonisation ( $\alpha = 0.90$ ) underscore the robustness of the measurement model, particularly in capturing the interplay between corporate sustainability practices and regulatory frameworks in Nigeria.

The results also highlight the critical role of digital infrastructure constraints ( $\alpha = 0.81$ ) in moderating the relationship between digital technology adoption and decarbonisation outcomes. This finding aligns with recent studies that emphasise the infrastructural barriers to digital transformation in emerging economies, where unreliable electricity and limited technical expertise hinder the adoption of advanced technologies like blockchain and IoT (Hlali & Gfasi, 2024; Xu et al., 2023). The measurement model thus provides a good foundation for examining how these constraints influence the efficacy of digital tools in enhancing supply chain transparency and compliance.

**Table 3: Measurement Model Results**

| Construct                   | Cronbach's Alpha ( $\alpha$ ) | 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 |

| Construct                               | Cronbach's Alpha ( $\alpha$ ) | Composite Reliability (CR) | AVE  | Fornell-Larcker Criterion | HTMT  |
|-----------------------------------------|-------------------------------|----------------------------|------|---------------------------|-------|
| 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 |
| Digitalisation 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 |

Source: Author Computation

### 4.3 Structural Model Assessment

The structural model assessment (table 2) reveals significant relationships between the constructs, providing robust empirical support for the hypothesized pathways driving supply chain decarbonization in Nigeria. Collinearity assessment confirmed the absence of multicollinearity, with Variance Inflation Factor (VIF) values below 5, ensuring the independence of predictor variables (Hair et al., 2019). This is critical in complex models involving regulatory, ESG, and digital transformation constructs, where overlapping influences could distort results (Adegbite & Nakajima, 2022). The model in Figure 1 illustrates the interrelationships between regulatory, ESG, and digitalisation factors in driving supply chain decarbonisation (SCD). The pathways highlight direct, mediated, and moderated relationships among key constructs.

The bootstrapping analysis (10,000 subsamples) demonstrated significant path coefficients ( $p < 0.05$ ) for all hypotheses, validating the proposed relationships. Regulatory stringency (RS) positively influenced supply chain decarbonisation (SCD) ( $\beta = 0.32$ ,  $p < 0.001$ ), supporting H1a. This aligns with prior research indicating that stringent environmental policies drive corporate sustainability efforts, particularly in emerging markets where regulatory pressures are often the primary catalyst for change (Obuobi et al., 2024; Amoah & Eweje, 2022). However, the indirect effect of regulatory enforcement (RE) as a mediator between RS and SCD ( $\beta = 0.18$ ,  $p < 0.001$ ) underscores the critical role of enforcement mechanisms in translating policy into practice (H1b). This finding resonates with studies highlighting the enforcement gap in Nigeria, where weak institutional capacity and corruption often undermine regulatory effectiveness (Onuoha et al., 2024). Conversely, regulatory inconsistencies (RI) negatively impacted decarbonisation efforts ( $\beta = -0.25$ ,  $p < 0.001$ ), supporting H1c. This reflects the fragmented regulatory landscape in Nigeria, where conflicting federal and state policies increase compliance costs and deter firms from adopting sustainable practices (Brookings Institution, 2023). The findings emphasise the need for coherent and harmonised regulatory frameworks to facilitate decarbonisation in resource-constrained economies.

ESG awareness (ESG) exhibited a strong positive relationship with decarbonisation ( $\beta = 0.41$ ,  $p < 0.001$ ), supporting H2a. This corroborates evidence that firms with higher ESG awareness are more likely to integrate sustainability into their supply chains, driven by internal strategic alignment and external stakeholder pressures (Tetteh et al., 2025; Chu et al., 2017). However, financial constraints (FC) negatively moderated the relationship between ESG and SCD ( $\beta = -0.22$ ,  $p < 0.001$ ), supporting H2b. This highlights firms' resource limitations in emerging economies, where high capital requirements for sustainability initiatives often outweigh the perceived benefits (Alaburo & Gbadebo, 2024). The findings underscore the need for financial incentives, such as green bonds and sustainability-

linked loans, to bridge the funding gap for ESG-driven decarbonization. Institutional pressures (IP), including investor and consumer demands, significantly influenced ESG integration ( $\beta = 0.35$ ,  $p < 0.001$ ), supporting H2c. This aligns with stakeholder theory, which posits that external pressures drive corporate sustainability practices, particularly in markets where regulatory enforcement is weak (DiMaggio & Powell, 2000; Wiredu et al., 2024). The results suggest that institutional pressures can partially compensate for regulatory inefficiencies, encouraging firms to adopt ESG practices without stringent enforcement.

Digital technology adoption (DTA) positively influenced transparency in sustainability reporting ( $\beta = 0.47$ ,  $p < 0.001$ ) and ESG compliance ( $\beta = 0.39$ ,  $p < 0.001$ ), supporting H3a and H3b. This is consistent with studies highlighting the role of blockchain, AI, and IoT in enhancing supply chain transparency and operational efficiency (Sarkis et al., 2021; Xu et al., 2023). However, digital infrastructure constraints (DI) negatively moderated the relationship between DTA and SCD ( $\beta = -0.15$ ,  $p = 0.004$ ), supporting H3c. This reflects the infrastructural deficits in Nigeria, where unreliable electricity and limited internet connectivity hinder the effective deployment of digital tools (Hlali & Gfasi, 2024).

**Table 4: Structural Model Results**

| Hypothesis | Path                                   | Path Coefficient   | t-value | p-value | Result    |
|------------|----------------------------------------|--------------------|---------|---------|-----------|
| H1a        | RS $\rightarrow$ SCD                   | 0.32               | 4.56    | <0.001  | Supported |
| H1b        | RS $\rightarrow$ RE $\rightarrow$ SCD  | 0.18 (indirect)    | 3.45    | <0.001  | Supported |
| H1c        | RI $\rightarrow$ SCD                   | -0.25              | 3.89    | <0.001  | Supported |
| H2a        | ESG $\rightarrow$ SCD                  | 0.41               | 5.12    | <0.001  | Supported |
| H2b        | FC $\rightarrow$ ESG $\rightarrow$ SCD | -0.22 (indirect)   | 3.78    | <0.001  | Supported |
| H2c        | IP $\rightarrow$ ESG                   | 0.35               | 4.67    | <0.001  | Supported |
| H3a        | DTA $\rightarrow$ DEC                  | 0.47               | 5.89    | <0.001  | Supported |
| H3b        | DTA $\rightarrow$ DEC                  | 0.39               | 4.98    | <0.001  | Supported |
| H3c        | DI moderates DTA $\rightarrow$ SCD     | -0.15 (moderation) | 2.89    | 0.004   | Supported |

Source: Author Computation

## 5. DISCUSSION OF FINDINGS

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

The adoption of digital technologies (blockchain, AI, IoT) significantly improves sustainability reporting transparency (H3a:  $\beta = 0.47$ ,  $p < 0.001$ ) and ESG compliance (H3b:  $\beta = 0.39$ ,  $p < 0.001$ ), consistent with findings on digital tools enhancing supply chain efficiency and accountability (Sarkis et al., 2021; Xu et al., 2023). However, infrastructure deficits (H3c:  $\beta = -0.15$ ,  $p = 0.004$ ) constrain the effectiveness of digital adoption in decarbonisation, reflecting systemic challenges such as unreliable electricity and inadequate internet connectivity (Hlali & Gfasi, 2024). This divergence from developed-market studies highlights the necessity of targeted infrastructure investments to maximise digitalisation's potential in emerging economies. On the technological front, this study extends Complexity Theory by illustrating how digital transformation, though conventionally framed as a linear enabler of sustainability, is contingent on contextual variables such as infrastructure quality and digital literacy. Digital technology adoption significantly improves ESG compliance and sustainability transparency supports the findings by Xu et al. (2023) and Sarkis et al. (2021). However, the moderating

effect of infrastructural deficits confirms that digitalisation outcomes are non-uniform and subject to significant systemic friction. These results refine prior models that have typically assumed uniform benefits from digital investment (Wiredu et al., 2024), highlighting instead the path-dependent and fragmented nature of digital transformation in emerging markets.

Regulatory stringency significantly influences supply chain decarbonisation (H1a:  $\beta = 0.32$ ,  $p < 0.001$ ), corroborating prior findings that regulatory pressures drive corporate sustainability efforts in emerging markets (Obuobi et al., 2024; Amoah & Eweje, 2022). However, the mediating role of regulatory enforcement (H1b:  $\beta = 0.18$ ,  $p < 0.001$ ) exposes a critical deficiency in Nigeria's regulatory landscape: while policies exist, their efficacy is contingent on enforcement capacity. This aligns with evidence that weak institutions and corruption impede policy execution in developing economies (Onuoha et al., 2024). Conversely, regulatory inconsistencies (H1c:  $\beta = -0.25$ ,  $p < 0.001$ ) obstruct decarbonisation efforts, reflecting fragmented and conflicting governance frameworks (Brookings Institution, 2023). Thus, contrary to deterministic models of policy compliance, this study confirms that regulatory stringency alone is insufficient; rather, it is the presence of strong enforcement mechanisms that translates policy into tangible outcomes ( $\beta = 0.18$ ,  $p < 0.001$ ). This reinforces the perspective that firms in complex environments respond not merely to policy existence but to the enforceability and credibility of institutional signals (Amoah & Eweje, 2022). This study's demonstration that regulatory inconsistencies significantly undermine decarbonisation efforts offers critical insights into the structure-agency relationship described in Structuration Theory. Firms are not passive entities awaiting regulation but are active agents adapting to, and in some cases circumventing, fragmented institutional architectures. This supports Giddens' (2014) proposition that agency and structure are mutually constitutive. Nigerian firms, operating within overlapping federal and state policies, reshape compliance pathways through informal networks and selective ESG adoption mechanisms. This finding contradicts prior models that assume institutional coherence and overestimate policy predictability (DiMaggio & Powell, 2000).

The positive association between ESG awareness and decarbonisation (H2a:  $\beta = 0.41$ ,  $p < 0.001$ ) aligns with existing literature linking ESG integration to environmental performance (Tetteh et al., 2025; Chu et al., 2017). However, financial constraints (H2b:  $\beta = -0.22$ ,  $p < 0.001$ ) significantly weaken this relationship, reinforcing evidence that capital limitations hinder sustainability transitions in emerging markets (Alaburo & Gbadebo, 2024). Institutional pressures, including investor and consumer demands (H2c:  $\beta = 0.35$ ,  $p < 0.001$ ), partially offset weak regulatory enforcement, supporting stakeholder theory's assertion that external pressures drive corporate sustainability commitments (DiMaggio & Powell, 2000; Wiredu et al., 2024). This suggests that market-driven mechanisms in regulatory environments lacking stringent enforcement serve as alternative incentives for ESG adoption. The strong path coefficient between ESG awareness and decarbonisation ( $\beta = 0.41$ ,  $p < 0.001$ ) reinforces earlier findings in developed contexts that link corporate sustainability consciousness with operational transformation (Chu et al., 2017). However, this study advances the discourse by evidencing that ESG awareness is necessary in emerging economies but insufficient. Financial constraints act as a powerful brake on transition efforts, highlighting a blind spot in many prior studies, which either omit or downplay the financial precarity faced by firms in resource-constrained environments. In contrast to Barney's (1991) resource-based view, which emphasises firm capabilities as internal drivers of competitive advantage, these findings suggest that external capital access, absent from many theoretical models, plays a decisive role in enabling ESG-driven decarbonisation in the Global South. Institutional pressures, particularly investor and consumer expectations, also emerged as significant drivers of ESG adoption. While this aligns with stakeholder theory (DiMaggio & Powell, 2000), it departs from prior studies by demonstrating that these pressures partially compensate for state enforcement weaknesses. In effect, market forces become quasi-regulatory agents in environments where governance institutions lack coherence and legitimacy (Ufua et al., 2021). This mechanism has not been adequately addressed in the ESG literature, particularly in contexts 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 regulatory enforcement (RE) significantly mediates the effect of regulatory stringency (RS) on decarbonisation. This underscores that policy effectiveness in emerging markets depends on regulatory presence and enforcement capacity (Onuoha et al., 2024). The adverse impact of regulatory inconsistencies (RI) on decarbonisation supports prior research on fragmented governance structures impeding sustainability initiatives (Obuobi et al., 2024). Unlike studies that assume uniform policy effects (Chu et al., 2017), this research demonstrates how conflicting policies increase compliance costs, discouraging sustainability investments. In contrast with existing models that treat digital tools as inherently transformative, this study reveals their conditional efficacy: without stable electricity, adequate internet, and skilled personnel, technologies like blockchain and IoT remain underutilised. These findings thereby challenge technological determinism and echo Structuration Theory's emphasis on the mediating role of organisational agency. Nigerian firms demonstrate resilience by selectively deploying digital tools to bridge governance gaps, especially when formal institutions falter (Brookings Institution, 2023).

The strong link between ESG awareness and decarbonisation corroborates prior research connecting sustainability consciousness to improved environmental outcomes (Tetteh et al., 2025). However, this study extends the discourse by identifying financial constraints as a critical barrier in emerging economies, a factor often overlooked in studies focusing on firms with greater access to green financing (Alaburo & Gbadebo, 2024). Institutional pressures emerging as key drivers of ESG adoption, reinforce the stakeholder-driven view that firms respond to investor and consumer expectations even in weak regulatory environments (Wiredu et al., 2024). Comparatively, while earlier studies in OECD contexts (e.g., Belhadi et al., 2022; Kamble et al., 2023) reported linear relationships between digitalisation and sustainability performance, this study shows that such conclusions do not hold in low-infrastructure environments. The divergence underscores the risk of theoretical transferability without contextual adaptation. Similarly, the dominance of ESG-led models in Western literature fails to account for the financial precarity and institutional voids faced by firms in countries like Nigeria, limiting their real-world applicability (Alaburo & Gbadebo, 2024).

## **5.1 Theoretical Implications**

This study extends the Complexity Theory by elucidating how Nigerian firms navigate nonlinear regulatory and technological environments to implement sustainability initiatives. The findings underscore the need for continuous ESG strategy adjustments in response to shifting institutional and market pressures, particularly in weak governance contexts with infrastructural deficits (Adegbite & Nakajima, 2022). Furthermore, the study advances the Structuration Theory by demonstrating the bidirectional interaction between institutional structures and corporate agency. Nigerian firms do not merely comply with existing regulatory and economic frameworks; they actively reshape these structures through informal networks and private governance mechanisms to mitigate regulatory inefficiencies (Tetteh et al., 2025). This insight is particularly relevant in emerging economies, where institutional voids and financial constraints complicate sustainability adoption. Additionally, the findings refine adaptive regulatory and organisational theories by illustrating how firms in volatile policy environments develop strategies that balance compliance with operational constraints. Prior research suggests that firms in unstable regulatory settings adopt adaptive mechanisms (Amoah & Eweje, 2022); this study substantiates that claim by showing how Nigerian firms counteract weak enforcement through voluntary ESG initiatives, private sustainability standards, and digital compliance tools. Finally, the study refines structuration-based perspectives by highlighting the active role of firms in shaping sustainability trajectories. Constrained by financial and institutional gaps, Nigerian firms leverage digitalisation to circumvent regulatory inefficiencies, thereby transforming sustainability governance structures (Wiredu et al., 2024). These findings offer critical insights into the evolving interplay between corporate agency and institutional constraints in emerging economies.

## **5.2 Practical Implications**

This study's findings highlight the necessity of reinforcing regulatory enforcement, addressing policy inconsistencies, and expanding financial instruments to facilitate ESG integration. Strengthening institutional frameworks is critical to ensuring regulatory coherence and fostering corporate sustainability investments (Brookings Institution, 2023). Targeted incentives, such as tax reliefs and preferential lending rates, can further incentivise firms to embed ESG principles into their strategic frameworks (Climate Policy Initiative, 2024). Moreover, digital infrastructure expansion is imperative to harness technological advancements for sustainable transitions. Policymakers should prioritise investment in digital ecosystems to enable data-driven ESG compliance and enhance operational efficiencies (Ufua et al., 2021). Firms operating in emerging markets must adopt adaptive strategies integrating ESG principles, digital tools, and robust compliance mechanisms to mitigate regulatory and operational risks (Kumar et al., 2024). Regulatory harmonisation is essential to reduce compliance uncertainties and strengthen enforcement mechanisms. Financial instruments, such as green bonds and sustainability-linked loans, should be scaled to address capital constraints that hinder ESG adoption (Cordonnier & Saygin, 2023). Additionally, digital transformation should be leveraged to streamline ESG compliance, ensuring firms remain resilient amid regulatory fluctuations. Addressing infrastructure deficits remains critical for optimising digital solutions in supply chain decarbonisation and broader sustainability transitions (Hlali & Gfasi, 2024).

## 6. CONCLUSION

This study comprehensively analysed the interdependencies between regulatory frameworks, ESG integration, and digital transformation in facilitating supply chain decarbonisation within an emerging economy. The findings confirm that regulatory enforcement is a crucial determinant of decarbonization effectiveness, reinforcing prior assertions that policy rigour alone is insufficient without consistent enforcement mechanisms (University of the West of England, 2023) and emphasising the necessity of robust enforcement mechanisms and coherent regulatory structures in emerging markets. Moreover, regulatory inconsistencies remain a significant impediment, exacerbating compliance costs and deterring firms from sustainability investments (Onuoha et al., 2024). The study further establishes ESG awareness as a primary driver of decarbonisation, aligning with literature that links corporate sustainability consciousness to environmental performance (Tetteh et al., 2025). However, financial constraints continue obstructing ESG-driven sustainability transitions, reaffirming the resource dependency perspective that firms require external capital to implement sustainability initiatives (Alaburo & Gbadebo, 2024). Digitalisation emerges as a critical enabler, enhancing transparency in sustainability reporting and regulatory compliance (Sarkis et al., 2021). Nevertheless, infrastructural deficiencies limit the scalability of digital sustainability solutions, emphasising the need for targeted investments in digital ecosystems (Ufua et al., 2021). By integrating macro (policy), meso (corporate strategy), and micro (technological innovation) perspectives, this study advances the current understanding of sustainable supply chain management in emerging economies.

The study contributes novel insights by bridging fragmented regulatory, corporate, and technological frameworks within the decarbonization discourse. While previous research has treated these factors in isolation, this study provides empirical validation for their interconnected influence on sustainability outcomes (Chu et al., 2017). Applying a multi-level analytical approach challenges the prevailing assumption that institutional pressures drive corporate sustainability behaviour, demonstrating that firms also leverage digital transformation to counter regulatory inefficiencies. This work, therefore, fills a significant gap in the sustainability literature by offering an integrated model that captures the interplay between governance structures, market-driven ESG adoption, and digital innovation in emerging markets.

This study advances Complexity Theory by demonstrating how firms in nonlinear regulatory and technological environments adapt their ESG strategies to shifting institutional and market pressures (Adegbite & Nakajima, 2022). It also extends the Structuration Theory by illustrating the bidirectional interaction between institutional structures and corporate agency, particularly in contexts where firms actively reshape regulatory frameworks through informal networks and private governance mechanisms

(Tetteh et al., 2025). The findings challenge conventional assumptions about regulatory enforcement, revealing that policy effectiveness in emerging markets depends on regulatory presence, enforcement capacity, and institutional coherence (University of the West of England, 2023). This study also underscores the need for policymakers to strengthen regulatory enforcement, reduce policy inconsistencies, and expand financial mechanisms to support ESG integration. Targeted incentives, such as tax reliefs and green financing, can incentivise firms to adopt sustainable practices (Brookings Institution, 2023). Additionally, investments in digital infrastructure are essential to leverage technological advancements for sustainability transitions (Ufua et al., 2021). Firms must adopt adaptive strategies integrating ESG principles, digital tools, and compliance frameworks to navigate emerging markets' regulatory and operational complexities.

### **6.1 Limitations of the Study**

While this study provides valuable insights, its focus on high-impact sectors in Nigeria limits the generalizability of findings to other industries and regions. The cross-sectional research design restricts the ability to capture longitudinal trends in regulatory, corporate, and technological shifts affecting 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.

### **6.2 Suggestions for Further Research**

Building on the findings, several avenues for future research emerge. First, investigating the longitudinal effects of regulatory enforcement and policy coherence on supply chain decarbonisation would provide deeper insights into the sustainability transition process. Comparative studies examining regulatory consistency across different jurisdictions could reveal best practices for harmonising policy frameworks to facilitate corporate compliance (Adegbite & Nakajima, 2022). Second, future studies should explore the role of financial instruments, such as green bonds and sustainability-linked loans, in mitigating capital constraints that hinder ESG adoption (Alaburo & Gbadebo, 2024). Empirical research evaluating the effectiveness of financial incentives in driving sustainability investments could offer practical implications 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 provide actionable insights for optimising digital sustainability strategies (Wiredu et al., 2024). Finally, investigating the behavioural dimensions of corporate sustainability decision-making, particularly the influence of organisational culture and leadership commitment on ESG integration, could enrich the understanding of internal drivers shaping decarbonisation efforts (Chu et al., 2017). These research directions will further advance the theoretical and practical knowledge of sustainable supply chain management in emerging economies.

**AI Statement:** During the preparation of this work, the author(s) used Grammarly to structure the manuscript and ensure language proficiency. After using this tool/service, the author(s) reviewed and edited the content as needed and took (s) full responsibility for the publication's content.

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