Multi-Level Model of Digital Transformation and ESG Integration for Decarbonizing Supply Chains in Emerging Economies

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Abstract

The decarbonization of supply chains has become a strategic imperative in global efforts to combat climate change; yet, empirical evidence on how this transition unfolds in emerging economies remains scarce. This study addresses this gap by developing and testing a multi-level model that examines the interplay between institutional voids, regulatory pressures, digital transformation, and ESG integration in driving supply chain decarbonization within Nigeria's carbon-intensive sectors. Drawing on survey data from 306 supply chain professionals across manufacturing, construction, energy, and logistics industries, the study employs structural equation modeling to test hypothesized relationships. Findings reveal that regulatory stringency alone is insufficient in weak institutional environments; regulatory enforcement, rather than the formal existence of regulations, is the true catalyst for sustainable transitions ($\beta = 0.412$, $p < 0.001$). ESG-driven strategies exhibit strong mediating effects (indirect effect = 0.289, $p < 0.01$) but are significantly constrained by institutional voids, including infrastructural deficits, financial constraints, and policy instability. Notably, digital innovations—particularly blockchain, AI, and IoT—emerge as critical enablers of carbon transparency and traceability, achieving a predictive accuracy of 89.4% in the integrated framework. The study contributes a replicable, empirically validated framework that bridges institutional theory, complexity theory, and structuration theory,

offering actionable insights for policymakers, sustainability officers, and technology innovators seeking to align economic development with climate resilience in rapidly industrializing regions.

Keywords: Institutional Voids, Regulatory Enforcement, Digital Transformation, ESG Integration, Supply Chain Decarbonization, Emerging Economies, Nigeria

1. Introduction

1.1 Background

The escalating climate crisis has elevated supply chain decarbonization from a voluntary corporate initiative to a strategic imperative for organizations worldwide. Global supply chains account for approximately 80% of global greenhouse gas emissions, making their transformation central to achieving the Paris Agreement's goals of limiting global warming to well below 2°C above pre-industrial levels. The urgency of this transition is amplified by mounting stakeholder pressures—from investors demanding ESG compliance, consumers seeking sustainable products, and regulators imposing increasingly stringent environmental standards.

Despite the global consensus on the importance of supply chain decarbonization, the trajectory of this transition remains poorly understood, particularly in emerging economies . Nigeria, as Africa's largest economy and the continent's most populous nation, presents a critical case study. The country's carbon-intensive sectors—including manufacturing, construction, energy, and logistics—contribute significantly to economic output while generating substantial emissions. Yet, the institutional environment within which these sectors operate is characterized by what scholars have termed "institutional voids": weaknesses in regulatory enforcement, infrastructural deficits, financial constraints, and policy instability that collectively undermine sustainable business practices .

Contemporary scholarship on supply chain decarbonization has predominantly focused on developed economies, where stable regulatory frameworks, robust infrastructure, and mature digital ecosystems facilitate sustainability transitions . However, these conditions rarely apply in emerging economies, where firms must navigate complex, often contradictory, institutional pressures while simultaneously pursuing economic growth. This contextual disconnect represents a significant gap in both academic understanding and practical knowledge, as the strategies that succeed in developed markets may prove ineffective or even counterproductive in emerging economy contexts.

The emergence of digital technologies—including blockchain for traceability, artificial intelligence for optimization, and the Internet of Things for real-time monitoring—offers new

possibilities for overcoming institutional constraints . These innovations promise to enhance carbon transparency, enable more efficient resource allocation, and provide verifiable evidence of sustainability performance. However, their adoption in emerging economies faces unique barriers: unreliable internet connectivity, limited technical expertise, financial informality, and cultural resistance to technological change. Understanding how firms navigate these challenges while simultaneously responding to regulatory pressures and pursuing ESG integration is essential for designing effective decarbonization strategies.

1.2 Problem Statement

Despite growing recognition of the importance of supply chain decarbonization, existing research suffers from several critical limitations that constrain both theoretical understanding and practical application. First, the literature has predominantly focused on firm-level factors—such as organizational capabilities, managerial commitment, and resource availability—while paying insufficient attention to the institutional context that shapes and constrains firm behavior . This narrow focus is particularly problematic for emerging economies, where institutional voids fundamentally alter the calculus of sustainability investment .

Second, while regulatory frameworks are widely recognized as drivers of corporate sustainability, the distinction between regulatory stringency (the formal existence of regulations) and regulatory enforcement (their practical implementation) is often blurred . Studies from Ghana and Nigeria suggest that while firms generally respond to environmental regulations, disparities in enforcement efficiency, corruption, and informal networks hinder consistent adoption . This enforcement gap means that assumptions derived from developed economy contexts—where regulations are typically enforced—may not hold in emerging economies.

Third, the role of digital transformation in enabling sustainability transitions has been predominantly examined through a technological lens, emphasizing the capabilities of specific tools while neglecting the institutional conditions necessary for their effective deployment. As recent research has shown, digital innovations are not automatic enablers of sustainability; their effectiveness hinges on stable regulatory and infrastructural conditions that are often absent in emerging economies . Without understanding these contextual dependencies, firms and policymakers risk investing in technologies that fail to deliver expected benefits.

Fourth, the interaction between ESG integration, regulatory pressures, and digital transformation remains undertheorized. While each of these elements has been examined individually, their joint effects on supply chain decarbonization have received limited empirical attention. This is a significant omission, as these factors are likely to interact in complex, non-linear ways that are not captured by single-factor analyses.

Finally, the absence of validated predictive frameworks tailored to emerging economy contexts represents a critical gap. Existing models derived from developed economies may not generalize,

and their application in emerging economies could produce misleading predictions and suboptimal decisions.

Thus, the central problem addressed by this study is: **How do institutional voids and regulatory pressures interact with digital transformation and ESG integration to shape supply chain decarbonization outcomes in emerging economies, and how can this relationship be modeled to support evidence-based decision-making?**

1.3 Objectives of the Study

General Objective

The overall aim of this research is to develop and empirically validate a multi-level model that explains the complex relationships between institutional voids, regulatory pressures, digital transformation, ESG integration, and supply chain decarbonization in emerging economies.

Specific Objectives

1. To identify and quantify the key predictors of supply chain decarbonization performance in emerging economies, including regulatory enforcement, institutional voids, digital technology adoption, and ESG integration practices.
2. To design a hybrid structural equation model that captures the direct, mediated, and moderated relationships among institutional, regulatory, technological, and organizational factors in driving decarbonization.
3. To validate the proposed framework using empirical data from Nigeria's carbon-intensive sectors and demonstrate its predictive accuracy and practical utility for stakeholders.

1.4 Research Questions

1. What combination of institutional, regulatory, technological, and organizational variables most accurately predicts supply chain decarbonization performance in emerging economies?
2. How does the proposed multi-level framework compare to traditional single-factor approaches in terms of predictive accuracy and explanatory power?
3. What are the primary implementation barriers to digital transformation and ESG integration in the context of supply chain decarbonization, and how can these barriers be systematically addressed?

1.5 Significance of the Study

For Practitioners and Administrators

This study provides evidence-based guidance for supply chain managers, sustainability officers, and corporate leaders navigating the complexities of decarbonization in emerging economies. By

identifying which factors most strongly predict decarbonization success and highlighting the mediating role of ESG integration, the framework offers actionable insights for resource allocation, technology investment, and strategic planning. The predictive model enables organizations to benchmark their performance, identify areas for improvement, and make data-driven decisions.

For Policymakers

The findings illuminate the critical role of regulatory enforcement—rather than merely regulatory stringency—in driving sustainable transitions. This has significant implications for policy design, suggesting that investments in enforcement capacity, institutional coordination, and compliance monitoring are at least as important as the formal enactment of regulations. The study also provides evidence on the infrastructure and support needed to enable digital transformation for sustainability, informing policy priorities and program design.

For Academic Literature

This research makes several theoretical contributions. First, it extends institutional theory by operationalizing and empirically testing the concept of institutional voids in the specific context of supply chain decarbonization. Second, it bridges complexity theory and structuration theory to explain how firms navigate non-linear, dynamic institutional environments . Third, it advances the literature on ESG integration by examining its mediating role between regulatory pressures and decarbonization outcomes. Finally, it contributes to the growing body of research on digital sustainability by identifying the conditions under which digital technologies enable (or fail to enable) sustainability transitions.

For Future Researchers

The validated framework and measurement instruments developed in this study provide a foundation for future research in other emerging economy contexts. The operationalization of key constructs—institutional voids, regulatory enforcement, digital transformation, and ESG integration—enables replication and extension. The study also identifies specific avenues for further investigation, including cross-country comparisons, industry-specific analyses, and dynamic modeling of institutional change.

1.6 Scope and Limitations

Scope

This study focuses on Nigeria's carbon-intensive sectors, including manufacturing, construction, energy, and logistics. The geographic scope is limited to Nigeria to ensure contextual specificity and data quality, while the sectors selected represent the highest-emitting industries and the greatest potential for decarbonization. The time frame for data collection spans 2023–2025, capturing recent developments in regulatory frameworks, technology adoption, and sustainability

practices. The study examines firms of varying sizes, including both large multinational subsidiaries and domestic enterprises, to capture the diversity of organizational responses.

Limitations

1. The cross-sectional design limits causal inferences; relationships identified are associative rather than causal.
2. Data on certain variables, particularly digital technology adoption, rely on self-reporting, which may introduce social desirability bias.
3. The focus on Nigeria limits generalizability to other emerging economies, though the theoretical framework is designed for adaptation.
4. The study does not capture long-term dynamics of institutional change or the evolution of technology adoption patterns.
5. Resource constraints prevented the collection of objective emissions data, relying instead on managerial assessments and proxy measures.

2. Literature Review

2.1 Conceptual Review

Institutional Voids

Institutional voids refer to the absence of market-supporting institutions that enable the efficient functioning of markets and the effective implementation of regulations . These voids manifest in multiple dimensions: regulatory voids (weak enforcement, policy instability, overlapping mandates), infrastructural voids (inadequate connectivity, unreliable power supply), financial voids (limited access to capital, financial informality), and cognitive voids (lack of technical expertise, limited awareness of best practices) . In emerging economies, institutional voids create significant barriers to sustainable business practices by increasing transaction costs, reducing predictability, and undermining the effectiveness of formal regulations . As highlighted in recent research, these voids are not merely external constraints but are embedded in the institutional fabric of the economy, systematically shaping firm behavior and strategic choices .

Regulatory Pressures

Regulatory pressures encompass both the formal existence of environmental regulations (regulatory stringency) and the practical implementation and enforcement of these regulations (regulatory enforcement) . In emerging economies, a significant gap often exists between these

two dimensions: while comprehensive environmental frameworks may exist on paper, enforcement is frequently compromised by corruption, inadequate funding, limited technical capacity, and political interference . This enforcement gap fundamentally alters how firms respond to regulations, as the risk of non-compliance is often low, and the benefits of compliance may not materialize. Research from Ghana and Nigeria indicates that disparities in enforcement efficiency, corruption, and informal networks hinder consistent regulatory compliance . Thus, understanding regulatory pressures requires attention to both the formal and practical dimensions of regulation.

Digital Transformation

Digital transformation for sustainability refers to the adoption and integration of digital technologies—including blockchain, artificial intelligence (AI), the Internet of Things (IoT), and data analytics—to support environmental sustainability objectives . In the context of supply chain decarbonization, these technologies enable carbon transparency through enhanced tracking and traceability, improved efficiency through data-driven optimization, and verifiable reporting through immutable records . However, as research has shown, the effectiveness of digital technologies hinges on institutional conditions: stable regulatory frameworks, reliable infrastructure, and adequate technical support systems . Without these enabling conditions, digital transformation may fail to deliver expected sustainability benefits, or worse, may create new risks and vulnerabilities. The concept of "digital sustainability" emerges at the intersection of digital transformation and sustainability goals, requiring simultaneous attention to technological, institutional, and organizational factors.

ESG Integration

Environmental, Social, and Governance (ESG) integration refers to the systematic incorporation of ESG criteria into business strategy, operations, and decision-making processes . In the context of supply chain decarbonization, ESG integration involves establishing sustainability policies, setting emissions reduction targets, implementing monitoring and reporting systems, and engaging stakeholders on sustainability issues. ESG integration can be understood as a mediating mechanism: regulatory pressures may motivate firms to adopt ESG practices, but it is the effective implementation of these practices that translates into decarbonization outcomes. However, ESG integration in emerging economies faces significant constraints: costs, technical expertise gaps, and infrastructure limitations can undermine even well-intentioned initiatives . Understanding the specific barriers to ESG integration is essential for designing support mechanisms and capacity-building programs.

Supply Chain Decarbonization

Supply chain decarbonization refers to the systematic reduction of greenhouse gas emissions across the entire value chain, from raw material extraction to end-of-life disposal . This includes scope 1 emissions (direct operations), scope 2 emissions (purchased energy), and scope 3

emissions (supply chain, logistics, and product use). Achieving deep decarbonization requires coordinated action across multiple tiers of the supply chain, involving suppliers, logistics providers, and customers. In emerging economies, supply chain decarbonization is complicated by several factors: fragmented supply chains with limited transparency, reliance on carbon-intensive energy sources, limited technical capacity among suppliers, and weak institutional support for sustainability initiatives . Despite these challenges, emerging economies are not passive recipients of sustainability requirements; firms are increasingly adopting adaptive strategies, leveraging digital technologies, and developing innovative approaches to overcome institutional constraints .

2.2 Theoretical Framework

This study is grounded in three complementary theoretical perspectives that together provide a comprehensive lens for understanding supply chain decarbonization in emerging economies: Institutional Theory, Complexity Theory, and Structuration Theory .

Institutional Theory

Institutional theory explains how organizations respond to the regulatory, normative, and cognitive pressures of their institutional environment. In the context of supply chain decarbonization, this theory suggests that firms adopt sustainability practices in response to regulatory mandates, industry norms, and stakeholder expectations. However, institutional theory has been criticized for treating organizations as passive recipients of institutional pressures, overlooking their agency in shaping and navigating institutional environments. As recent scholarship has emphasized, institutional voids—the absence of effective market-supporting institutions—fundamentally alter how organizations respond to institutional pressures . In weak institutional environments, regulatory stringency alone is insufficient; regulatory enforcement, institutional coordination, and the presence of alternative governance mechanisms are essential.

Complexity Theory

Complexity theory offers an explanatory framework for understanding how firms navigate non-linear, dynamic institutional environments . Rather than assuming stable, predictable relationships, complexity theory recognizes that institutional pressures interact in ways that produce emergent, sometimes unexpected, outcomes. In Nigeria, weak governance, financial constraints, and infrastructural gaps lead to unpredictable patterns of technological adoption, necessitating firms to develop adaptive strategies aligned with ESG mandates. Complexity theory is particularly relevant to understanding the adoption of digital technologies: the effectiveness of blockchain, AI, and IoT for sustainability is not deterministic but depends on the configuration of institutional, technological, and organizational factors. This perspective emphasizes the importance of context-sensitive analysis and the recognition that solutions that work in one setting may not transfer directly to another.

Structuration Theory

Structuration theory provides a perspective on how institutional structures and corporate agency interact in adopting sustainability practices . Unlike static institutional theory that views firms merely as responding to regulatory pressures, structuration theory proposes that firms actively influence and are influenced by the regulatory and economic systems within which they operate. In Nigeria, where regulatory inconsistencies and weak enforcement hinder ESG adoption, firms adapt strategically, sometimes bypassing regulatory shortcomings through voluntary sustainability commitments and private governance mechanisms. This perspective highlights the reciprocal relationship between institutional structures and organizational action, recognizing that firms are not passive recipients of regulation but actively participate in shaping sustainability practices transitions.

Integration of Theoretical Perspectives

These three theories are integrated to form the study's multi-level framework. Institutional theory provides the basis for understanding the regulatory and institutional context; complexity theory explains the non-linear, adaptive responses of organizations; and structuration theory captures the dynamic, reciprocal relationship between structure and agency. Together, these perspectives enable a more nuanced understanding of supply chain decarbonization in emerging economies than any single theory could provide.

2.3 Empirical Review

A growing body of empirical research has examined the drivers and barriers of supply chain decarbonization, digital transformation, and ESG integration. This section summarizes key studies and identifies their contributions and limitations.

Okeke (2026) conducted a multilevel analysis of regulation, ESG, and digitalization in driving supply chain decarbonization within Nigeria's carbon-intensive sectors . Using survey data from 306 supply chain professionals, the study found that regulatory stringency alone is insufficient in weak institutional environments; regulatory enforcement is the true catalyst for sustainable transitions. ESG-driven strategies exhibited strong mediating effects but were significantly constrained by firm-level challenges, including costs, technical expertise, and infrastructure limitations. Digital innovations—particularly blockchain, AI, and IoT—emerged as critical enablers of carbon transparency and traceability. This study provides foundational empirical evidence for the present research but does not develop or test a comprehensive predictive framework.

Okeke (2024) examined sustainable practices and supply chain management effectiveness in African SMEs . The study utilized quantitative analysis and structural equation modeling to investigate the relationship between sustainability practices and competitive advantage. Findings indicated that sustainable practices positively influence SME competitiveness, though implementation is constrained by resource limitations and institutional weaknesses. The study

highlights the importance of stakeholder support and the need for capacity-building initiatives. However, it did not specifically examine digital transformation or decarbonization outcomes.

Research on Institutional Voids and Digital Sustainability has shown that the absence of local technical support systems indicates a broader breakdown in coordination within digital innovation ecosystems . Digital tools that are physically present but functionally inoperable due to lack of infrastructure for technology acquisition, including training, maintenance, and support, can be described as "implementation voids." Systematic connectivity depressions denote a structural infrastructure gap that legally marginalizes SMEs from digital ecosystems, limiting access to cloud platforms, real-time monitoring systems, digital compliance infrastructures, and integrated supply chains . The digital divide is not merely a technical problem but a failure of governance, evidenced by disproportionate investment in infrastructure and spatial development priorities.

Research on Regulatory Frameworks and Supply Chain Decarbonization has examined how environmental regulations shape corporate sustainability 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. However, overlapping regulatory mandates, weak institutional coordination, and policy uncertainty create a complex compliance landscape. Conflicting federal and state regulations result in inefficiencies, selective enforcement, and increased transaction costs, deterring firms from investing in sustainable supply chain practices. Enforcement remains compromised by corruption, inadequate funding, and limited technical capacity within regulatory agencies.

Research on Digital Barriers in African SMEs identified cultural resistance to change (39%) and fear of digital monitoring and penalties (39%) as key social barriers . Structural technological barriers included inadequate internet connectivity (47%), the digital divide (47%), incompatible legacy systems (26%), and the absence of technical support ecosystems (24%) . From an economic perspective, the absence of quantifiable financial gains (37%) and financial informality (37%) were significant deterrents to digital sustainability investment. Regulatory obstacles included bureaucratic bottlenecks (34%), policy instability (29%), and insufficient institutional support (37%) . These findings highlight the interaction among infrastructural, financial, regulatory, and cognitive limitations that generate system-wide obstacles to integrating digital sustainability.

2.4 Research Gap

Despite the contributions of existing research, significant gaps remain in both theoretical understanding and empirical evidence. First, while individual studies have examined regulatory pressures, digital transformation, or ESG integration in isolation, no validated predictive framework exists that simultaneously models the interactions among these factors in the context of supply chain decarbonization in emerging economies. Second, existing studies have not

systematically operationalized or empirically tested the concept of institutional voids as a multi-dimensional construct that mediates the relationship between regulatory pressures and organizational responses. Third, the mediating role of ESG integration between regulatory pressures and decarbonization outcomes has received limited empirical attention, despite strong theoretical arguments for such a mediating effect. Fourth, predictive models developed in developed economy contexts have not been validated in emerging economies, raising concerns about their applicability and accuracy. Fifth, the interaction between institutional voids, regulatory enforcement, and digital transformation has been underexplored, despite theoretical arguments that institutional conditions fundamentally shape the effectiveness of digital technologies.

This study directly addresses these gaps by developing and empirically validating a comprehensive, multi-level model that integrates institutional, regulatory, technological, and organizational factors in explaining supply chain decarbonization. The model operationalizes institutional voids as a multi-dimensional construct, tests the mediating role of ESG integration, and examines the moderating effects of digital transformation. By empirically testing the model using data from Nigeria's carbon-intensive sectors, this study provides evidence-based insights for both theory and practice.

3. Methodology

3.1 Research Design

This study employs a quantitative, cross-sectional design with structural equation modeling (SEM) as the primary analytical technique. The quantitative design is appropriate for testing hypothesized relationships among latent constructs, estimating direct and indirect effects, and assessing model fit. SEM enables the simultaneous estimation of measurement models (relating indicators to latent constructs) and structural models (relating latent constructs to each other), providing a comprehensive framework for theory testing. The cross-sectional design, while limiting causal inferences, is appropriate for establishing associations and testing theoretical propositions in a resource-constrained environment.

This design was chosen for three primary reasons: first, the study aims to develop and validate a predictive framework, requiring statistical modeling of complex relationships; second, the study draws on established theoretical frameworks that specify relationships among latent constructs, making SEM the natural analytical approach; third, the data collection approach (survey of supply chain professionals) is consistent with the design and enables the collection of data on multiple constructs simultaneously.

3.2 Study Area and Population

The study was conducted in Nigeria, focusing on the country's carbon-intensive sectors: manufacturing, construction, energy, and logistics. Nigeria was selected as the study setting for several reasons: as Africa's largest economy and most populous country, it represents a critical case in the Global South; its carbon-intensive sectors contribute significantly to emissions and present substantial decarbonization opportunities; its institutional environment exemplifies the institutional voids that characterize many emerging economies; and recent policy developments provide a relevant regulatory context.

The target population comprises supply chain professionals, sustainability officers, and senior managers working in organizations within these sectors. These individuals possess the knowledge and decision-making authority relevant to supply chain decarbonization, digital technology adoption, and ESG integration. The unit of analysis is the organization, with one key informant per organization providing data on organizational practices and performance.

3.3 Sample Size and Sampling Technique

Sample Size: The study employed a sample of 306 respondents. This sample size was determined using standard power analysis for SEM, which recommends a minimum sample size of 200 for models of moderate complexity, with 300+ preferred for robust estimation. The sample of 306 provides adequate statistical power to detect moderate effects and enables the use of maximum likelihood estimation with standard errors robust to non-normality.

Sampling Technique: A stratified random sampling approach was employed, with stratification by sector (manufacturing, construction, energy, logistics) to ensure representation of all key carbon-intensive industries. Within each sector, organizations were randomly selected from industry directories, trade association membership lists, and regulatory databases.

Stratification: The sample was stratified as follows: manufacturing (30%), construction (25%), energy (25%), and logistics (20%). These proportions reflect the relative sizes of these sectors in Nigeria's economy and their respective contributions to emissions. Organizations were sampled proportionally to sector size, with a random selection of firms within each sector.

Justification: Stratification ensures representation of all key sectors and enables sector-specific analyses as a secondary focus. Random selection within strata supports the generalizability of findings. The sample size provides adequate statistical power for the planned analyses, including SEM with multiple latent constructs.

3.4 Data Collection Methods

Data Sources: Primary data were collected through a structured questionnaire administered to key informants (supply chain professionals, sustainability officers, senior managers) in sampled organizations. Secondary data were collected from corporate sustainability reports, regulatory databases, and industry publications to supplement and validate primary data.

Types of Data Extracted: The survey instrument captured data on the following constructs: regulatory stringency (perceptions of the stringency of environmental regulations); regulatory enforcement (perceptions of enforcement effectiveness and consistency); institutional voids (infrastructural deficits, financial constraints, policy instability, technical capacity gaps); digital transformation (adoption of blockchain, AI, IoT, and other digital tools for sustainability); ESG integration (comprehensiveness and effectiveness of ESG practices); and supply chain decarbonization (emissions reduction progress and sustainability outcomes).

Time Periods: Data collection occurred between January 2024 and June 2025, capturing recent experiences and practices. Respondents were asked to reflect on the preceding 12 months to minimize recall bias while enabling the assessment of current practices.

Simulated Data: No simulated data were used for the primary analysis. However, for validation purposes, a small set of hypothetical scenarios was generated to test the predictive accuracy of the model under different conditions.

3.5 Research Instruments

Software: The following software and libraries were used: SPSS (version 28) for descriptive statistics and preliminary analyses; AMOS (version 28) for SEM; and R (version 4.2) for supplementary analyses and visualizations.

Preprocessing Steps: Data cleaning involved checking for outliers, missing data, and normality. Missing data were handled using multiple imputation with 20 imputations, as recommended for SEM. Outliers were identified using Mahalanobis distance and retained or removed based on diagnostic criteria. Non-normality was addressed using robust standard errors and bootstrapping for significance testing.

3.6 Validity and Reliability

Content Validity: The survey instrument was developed based on extensive literature review and pilot testing. Items were adapted from validated scales where available and refined through expert review. An expert panel of five academics and practitioners assessed the relevance and representativeness of items, ensuring that all constructs were adequately covered.

Construct Validity: Confirmatory factor analysis (CFA) was conducted to assess the measurement model. Factor loadings, composite reliability, and average variance extracted (AVE) were examined. All constructs demonstrated acceptable construct validity, with factor loadings exceeding 0.60, composite reliability exceeding 0.70, and AVE exceeding 0.50.

Predictive Validity: The predictive validity of the model was assessed through in-sample prediction accuracy and cross-validation. Model predictions were compared to actual decarbonization outcomes, achieving an overall accuracy of 89.4%. The model demonstrated robust predictive performance across sectors and organizational types.

Inter-rater Reliability: For organizations where multiple respondents were available (20% of sample), inter-rater reliability was assessed using intraclass correlation coefficients. Acceptable inter-rater reliability (ICC > 0.70) was observed, supporting the use of single-key informant data.

Internal Consistency: Cronbach's alpha was computed for each multi-item scale. All scales demonstrated acceptable internal consistency ($\alpha > 0.70$), supporting the use of composite measures.

3.7 Data Analysis Techniques

Structural Equation Modeling (SEM): SEM was employed as the primary analytical technique, using AMOS with maximum likelihood estimation. The analysis proceeded in two stages: first, the measurement model was assessed using CFA; second, the structural model was estimated to test hypothesized relationships. Model fit was assessed using multiple fit indices: Comparative Fit Index (CFI > 0.90), Tucker-Lewis Index (TLI > 0.90), Root Mean Square Error of Approximation (RMSEA < 0.08), and Standardized Root Mean Square Residual (SRMR < 0.08).

Mediation Analysis: Mediation was assessed using the bootstrap method with 5,000 resamples and 95% bias-corrected confidence intervals. The indirect effect of regulatory pressures on decarbonization through ESG integration was estimated and tested for statistical significance.

Performance Metrics: Model performance was evaluated using the following metrics: R-squared (variance explained), root mean square error (RMSE), mean absolute error (MAE), and predictive accuracy (percentage of cases correctly classified). These metrics provide a comprehensive assessment of model fit and predictive performance.

Cross-validation: K-fold cross-validation was employed (k=10) to assess the generalizability of the model and prevent overfitting. The model was estimated on 90% of the data and validated on the remaining 10%, with the process repeated 10 times.

3.8 Ethical Considerations

The study was conducted in accordance with ethical guidelines for social science research. All data were collected using de-identified, anonymous surveys. No personal identifying information (PHI) was collected or accessed. Participants were informed of the study's purpose, the voluntary nature of participation, and their right to withdraw at any time. Informed consent was obtained from all participants. The study was exempted from full institutional review board review due to the use of de-identified data and the minimal risk to participants. Data were stored securely and accessible only to the research team.

4. Results

4.1 Data Presentation

The final sample consisted of 306 respondents, representing organizations across four carbon-intensive sectors: manufacturing (n=92, 30.1%), construction (n=76, 24.8%), energy (n=77, 25.2%), and logistics (n=61, 19.9%). The sample included organizations of varying sizes: large enterprises (n=143, 46.7%), medium enterprises (n=98, 32.0%), and small enterprises (n=65, 21.2%). Respondents included supply chain managers (42.5%), sustainability officers (28.4%), and senior managers (29.1%).

Table 1. Descriptive Statistics for Key Constructs

Construct	Mean	SD	Skewness	Kurtosis	Cronbach's α
Regulatory Stringency	3.82	0.94	-0.23	-0.15	0.81
Regulatory Enforcement	3.41	1.02	-0.08	-0.42	0.84
Institutional Voids	3.67	0.89	0.31	-0.28	0.86
Digital Transformation	3.53	0.97	0.12	-0.51	0.83
ESG Integration	3.78	0.92	0.19	-0.36	0.88
Supply Chain Decarbonization	3.49	0.95	-0.02	-0.47	0.85

Note: All constructs measured on 5-point Likert scales. N=306.

Table 1 presents descriptive statistics for the key constructs. Mean scores ranged from 3.41 (regulatory enforcement) to 3.82 (regulatory stringency), indicating moderate levels of regulatory pressures, institutional voids, digital transformation, ESG integration, and decarbonization performance. Skewness and kurtosis values were within acceptable ranges (-1 to +1), supporting the assumption of normality. Cronbach's alpha values exceeded the 0.80 threshold, indicating excellent internal consistency.

Table 2. Correlations Among Constructs

Construct	1	2	3	4	5	6
1. Reg. Stringency	1.000					
2. Reg. Enforcement	0.582**	1.000				
3. Inst. Voids	-0.314**	-0.487**	1.000			
4. Digital Transform.	0.285**	0.412**	-0.356**	1.000		
5. ESG Integration	0.325**	0.478**	-0.424**	0.512**	1.000	
6. Decarbonization	0.318**	0.523**	-0.467**	0.482**	0.589**	1.000

*Note: *$p < 0.01$, two-tailed. N=306.*

Table 2 presents Pearson correlations among the key constructs. Regulatory enforcement showed the strongest correlation with decarbonization ($r = 0.523$, $p < 0.01$), followed by ESG integration ($r = 0.589$, $p < 0.01$). Institutional voids were negatively correlated with all other constructs, consistent with theoretical expectations. Digital transformation showed moderate positive correlations with ESG integration ($r = 0.512$) and decarbonization ($r = 0.482$). These correlations provide initial support for the hypothesized relationships.

4.2 Analysis of Results

Measurement Model Assessment: CFA was conducted to assess the measurement model. The model demonstrated acceptable fit: CFI = 0.942, TLI = 0.935, RMSEA = 0.058 (90% CI: 0.051-0.065), SRMR = 0.047. All factor loadings exceeded 0.60 and were statistically significant ($p < 0.001$). Composite reliability exceeded 0.80 for all constructs, and AVE exceeded 0.50 for all constructs, supporting convergent validity. Discriminant validity was supported as the square root of AVE exceeded inter-construct correlations for all pairs.

Structural Model Assessment: The structural model demonstrated good fit: CFI = 0.936, TLI = 0.928, RMSEA = 0.062 (90% CI: 0.055-0.069), SRMR = 0.052. The model explained 61.2% of

the variance in supply chain decarbonization ($R^2 = 0.612$), indicating substantial explanatory power.

Figure 1. Structural Model Results

*Note: Standardized path coefficients. **p < 0.01, ***p < 0.001. $R^2 = 0.612$.*

Direct Effects: Regulatory enforcement demonstrated the strongest direct effect on decarbonization ($\beta = 0.412$, $p < 0.001$), significantly larger than regulatory stringency ($\beta = 0.189$, $p < 0.01$). This finding confirms that enforcement is more important than the formal existence of regulations in driving sustainable transitions. Institutional voids had a significant negative direct effect on decarbonization ($\beta = -0.267$, $p < 0.001$), indicating that institutional weaknesses systematically undermine decarbonization efforts. Digital transformation positively predicted decarbonization ($\beta = 0.253$, $p < 0.001$), supporting the role of digital technologies as enablers.

Mediation Analysis: ESG integration significantly mediated the relationship between regulatory pressures and decarbonization. The indirect effect of regulatory enforcement on decarbonization through ESG integration was 0.289 (95% CI: 0.184-0.394, $p < 0.01$), representing a substantial portion of the total effect. The indirect effect of regulatory stringency through ESG integration was smaller ($\beta = 0.142$, 95% CI: 0.087-0.197, $p < 0.05$). These findings highlight ESG integration as a key mechanism through which regulatory pressures translate into decarbonization outcomes.

Moderation Analysis: Digital transformation significantly moderated the relationship between regulatory enforcement and decarbonization ($\beta = 0.184$, $p < 0.01$), with the positive effect of enforcement being stronger for firms with higher levels of digital transformation. This finding suggests that digital capabilities amplify the effectiveness of regulatory enforcement, consistent with complexity theory predictions that institutional and technological factors interact synergistically.

Model Performance: The integrated model demonstrated robust predictive accuracy, achieving an overall accuracy of 89.4% in classifying firms by decarbonization performance level. The model's sensitivity (89.1%) and specificity (89.7%) were balanced, indicating good discrimination between high and low decarbonization performers. The model explained 61.2% of the variance in decarbonization, substantially outperforming single-factor models (which explained between 15% and 28% of variance).

Feature Importance: The most important predictors of decarbonization, in order of standardized coefficient magnitude, were: regulatory enforcement ($\beta = 0.412$), ESG integration ($\beta = 0.321$), institutional voids ($\beta = -0.267$), digital transformation ($\beta = 0.253$), and regulatory stringency ($\beta = 0.189$). This ranking highlights the primacy of enforcement over formal regulations and the importance of organizational (ESG) and technological (digital) factors.

5. Discussion

5.1 Interpretation

Finding 1: Regulatory Enforcement Drives Decarbonization

The finding that regulatory enforcement ($\beta = 0.412$, $p < 0.001$) is a significantly stronger predictor of decarbonization than regulatory stringency ($\beta = 0.189$, $p < 0.01$) addresses the first research question and confirms the core proposition of the study. This finding aligns with recent research suggesting that in weak institutional environments, regulatory stringency alone is insufficient; regulatory enforcement is the true catalyst for sustainable transitions . This result extends institutional theory by empirically demonstrating the distinction between the formal existence of regulations and their practical implementation. In contexts where enforcement is weak, firms face low compliance risk, undermining the regulatory signal and reducing incentives for decarbonization investment.

This finding also resonates with structuration theory's emphasis on the reciprocal relationship between structure and agency . In weak enforcement environments, firms are not passive recipients of regulations but actively navigate and sometimes circumvent them. The finding suggests that strengthening enforcement capacity is at least as important as enacting new regulations—a critical insight for policymakers in emerging economies.

Finding 2: Institutional Voids Undermine Decarbonization

The negative effect of institutional voids on decarbonization ($\beta = -0.267$, $p < 0.001$) confirms the theoretical expectation that institutional weaknesses systematically undermine sustainability transitions. This finding extends the literature on institutional voids by demonstrating their direct negative impact on decarbonization outcomes. The multi-dimensional operationalization of institutional voids—capturing infrastructural deficits, financial constraints, policy instability, and technical capacity gaps—enables a nuanced understanding of how different institutional weaknesses affect decarbonization.

The finding supports complexity theory's emphasis on the contextual nature of organizational responses . In institutional environments characterized by voids, firms develop adaptive strategies that may not align with formal regulatory mandates. The implication is that addressing institutional voids—through infrastructure investment, capacity building, and policy coordination—may be more important than simply increasing regulatory stringency.

Finding 3: ESG Integration Mediates the Regulatory-Decarbonization Relationship

The mediation analysis revealed that ESG integration significantly mediates the relationship between regulatory pressures and decarbonization. This finding addresses the second research question and extends both institutional and structuration theories. The indirect effect of regulatory enforcement through ESG integration ($\beta = 0.289$, 95% CI: 0.184-0.394) is substantial,

indicating that regulatory pressures translate into decarbonization outcomes primarily through the adoption and implementation of ESG practices.

This mediation finding provides empirical support for the theoretical proposition that organizational responses to regulatory pressures are mediated by internal governance mechanisms. Firms that effectively integrate ESG criteria into their strategy, operations, and decision-making are better positioned to translate regulatory mandates into tangible decarbonization outcomes. This suggests that policy efforts should focus not only on enacting regulations but also on supporting firms' ESG capacity building.

Finding 4: Digital Transformation Enhances Regulatory Effectiveness

The moderating effect of digital transformation on the relationship between regulatory enforcement and decarbonization ($\beta = 0.184$, $p < 0.01$) is a significant contribution to the literature. This finding suggests that digital capabilities amplify the effectiveness of regulatory enforcement. Firms with higher levels of digital transformation are better able to monitor compliance, track emissions, and report on sustainability performance, enabling more effective regulatory compliance.

This finding supports complexity theory's emphasis on the interaction among institutional, technological, and organizational factors. Digital transformation is not an automatic enabler of sustainability; its effectiveness depends on the institutional context, including regulatory enforcement. This interaction effect has practical implications: investments in digital technologies are most effective when combined with strong regulatory enforcement.

Finding 5: Integrated Framework Outperforms Single-Factor Models

The finding that the integrated framework explains 61.2% of the variance in decarbonization, substantially outperforming single-factor models (15-28%), addresses the first research question and validates the study's multi-level approach. This demonstrates that supply chain decarbonization in emerging economies is a complex, multi-faceted phenomenon that cannot be adequately explained by single-factor analyses. The integrated framework provides a more comprehensive and accurate understanding of the drivers of decarbonization, enabling evidence-based decision-making.

5.2 Implications

Academic Implications

This study makes several significant contributions to academic literature:

Theoretical Extension: The study extends institutional theory by operationalizing and empirically testing the concept of institutional voids in the specific context of supply chain decarbonization. By demonstrating the distinct effects of regulatory stringency and regulatory enforcement, the study provides a more nuanced understanding of how institutional pressures

shape organizational behavior. The integration of institutional theory, complexity theory, and structuration theory offers a comprehensive theoretical framework for understanding sustainability transitions in emerging economies.

Construct Validation: The study provides validated measurement instruments for key constructs—institutional voids, regulatory enforcement, digital transformation, ESG integration, and supply chain decarbonization—that can be used and refined in future research. The multi-dimensional operationalization of institutional voids captures the complexity of institutional weaknesses and enables more precise analysis.

Mediation and Moderation: The identification of ESG integration as a mediating mechanism and digital transformation as a moderating factor extends understanding of how regulatory pressures translate into decarbonization outcomes. These findings suggest that research should move beyond simple direct effects to examine the complex pathways through which institutional pressures shape organizational behavior.

Contextual Sensitivity: By focusing on Nigeria as an emerging economy context, the study contributes to the growing literature on sustainability in the Global South. The findings challenge the assumption that findings from developed economies can be directly generalized and highlight the importance of context-sensitive research.

Practical Implications

For Practitioners and Administrators:

1. **Prioritize Regulatory Compliance Infrastructure:** Given that regulatory enforcement is more important than regulatory stringency, firms should invest in systems and capabilities to ensure regulatory compliance. This includes tracking regulatory developments, monitoring compliance status, and building internal capacity for ESG reporting.
2. **Strengthen ESG Integration:** The mediating role of ESG integration suggests that firms should systematically embed ESG criteria into strategy, operations, and decision-making. This includes establishing clear sustainability policies, setting emissions reduction targets, implementing monitoring and reporting systems, and engaging stakeholders.
3. **Invest in Digital Transformation:** The moderating role of digital transformation indicates that digital technologies can amplify the effectiveness of regulatory compliance. Firms should invest in blockchain for traceability, AI for optimization, and IoT for monitoring. However, investments should be tailored to organizational context, with attention to infrastructure availability and technical capacity.
4. **Address Institutional Voids:** Firms should develop strategies to navigate institutional weaknesses, including partnering with reliable suppliers, investing in infrastructure, building technical capacity, and engaging with policymakers. While individual firms

cannot eliminate institutional voids, they can adapt their strategies to mitigate their impact.

For Policymakers:

1. **Strengthen Regulatory Enforcement:** The findings suggest that policy efforts should focus on strengthening enforcement capacity, including adequate funding, staffing, and technical expertise for regulatory agencies. Political interference and corruption should be addressed to ensure consistent enforcement.
2. **Reduce Institutional Voids:** Policymakers should invest in infrastructure, financial inclusion, and technical capacity building. These investments create the enabling conditions for sustainable business practices and complement regulatory efforts.
3. **Support Digital Transformation:** Policies should facilitate digital transformation for sustainability, including investment in digital infrastructure, technology transfer programs, and capacity building. Digital technologies can help offset institutional voids and enhance regulatory compliance.
4. **Promote ESG Integration:** Policy should support ESG integration through guidance, capacity building, and recognition programs. ESG integration should be embedded in regulatory frameworks and industry standards.

5.3 Limitations

1. **Cross-Sectional Design:** The cross-sectional design limits causal inferences; relationships identified are associative rather than causal. While the structural model specifies directional relationships, these require longitudinal confirmation.
2. **Self-Reported Data:** Data on key constructs rely on self-reporting, which may introduce social desirability bias. Objective measures of emissions and technology adoption would enhance validity.
3. **Limited Generalizability:** The focus on Nigeria limits generalizability to other emerging economies. While the theoretical framework is designed for adaptation, empirical validation in other contexts is needed.
4. **Resource Constraints:** Resource constraints prevented the collection of objective emissions data, relying instead on managerial assessments and proxy measures. Future research should incorporate objective performance metrics.
5. **Single-Key Informant:** The use of single-key informants per organization introduces potential measurement error. Multi-respondent data would enhance reliability.

5.4 Future Research Directions

1. **Cross-Country Comparisons:** The framework should be validated in other emerging economies to assess its generalizability and identify country-specific variations. Comparative analysis would reveal how institutional differences shape decarbonization pathways.
2. **Longitudinal Design:** Longitudinal research is needed to examine the evolution of institutional environments, technology adoption patterns, and decarbonization outcomes over time. This would enable causal inference and dynamic modeling.
3. **Objective Performance Metrics:** Future studies should incorporate objective measures of emissions, technology adoption, and ESG performance to complement self-reported data. This would enhance validity and enable more precise measurement.
4. **Sector-Specific Analyses:** While this study included multiple sectors, sector-specific dynamics deserve more detailed investigation. Different sectors face different regulatory pressures, technology options, and decarbonization challenges.
5. **Micro-Level Processes:** Qualitative research is needed to understand the micro-level processes through which firms navigate institutional voids, implement ESG practices, and adopt digital technologies. Such research would reveal the mechanisms underlying the relationships identified in this study.
6. **Intervention Studies:** The framework should be used to design and evaluate interventions for accelerating decarbonization. This includes policy experiments, technology pilots, and capacity-building programs.
7. **Dynamic Modeling:** Future research should develop dynamic models that capture the evolution of institutional environments, technology adoption, and decarbonization over time. This would support scenario analysis and long-term planning.

6. Conclusion

This study developed and empirically validated a comprehensive, multi-level model of supply chain decarbonization in emerging economies. The findings reveal that regulatory enforcement ($\beta = 0.412$, $p < 0.001$) is significantly more important than regulatory stringency ($\beta = 0.189$, $p < 0.01$) in driving decarbonization, highlighting the need to strengthen enforcement capacity. ESG integration mediates the relationship between regulatory pressures and decarbonization (indirect effect = 0.289, $p < 0.01$), indicating that internal governance mechanisms are essential for translating external pressures into tangible outcomes. Institutional voids negatively affect decarbonization ($\beta = -0.267$, $p < 0.001$), underscoring the need to address institutional weaknesses. Digital transformation moderates the enforcement-decarbonization relationship ($\beta = 0.184$, $p < 0.01$), suggesting that digital capabilities amplify regulatory effectiveness. The integrated framework achieves predictive accuracy of 89.4% and explains 61.2% of variance in decarbonization performance, substantially outperforming single-factor models.

The main contribution of this study is the development and validation of a replicable, empirically grounded framework that integrates institutional, regulatory, technological, and organizational factors in explaining supply chain decarbonization in emerging economies. The framework provides a comprehensive understanding of the complex, multi-level dynamics that shape sustainability transitions and offers evidence-based guidance for practitioners and policymakers.

For administrators, the findings suggest prioritizing regulatory compliance infrastructure, strengthening ESG integration, investing in digital transformation, and developing strategies to navigate institutional voids. For policymakers, the findings highlight the importance of strengthening regulatory enforcement, reducing institutional voids, supporting digital transformation, and promoting ESG integration.

As global efforts to combat climate change intensify, supply chain decarbonization in emerging economies will be essential for meeting the Paris Agreement's goals. This study provides a foundation for understanding the challenges and opportunities of this transition, offering actionable insights for aligning economic development with climate resilience in rapidly industrializing regions.

References

1. Okeke, A. (2026). Decarbonizing supply chains in emerging economies: A multilevel analysis of regulation, ESG, and digitalization. *Global Journal of Emerging Market Economies, 18*(2), 151-173.
2. Okeke, A. (2024). Evaluating sustainable practices and supply chain management effectiveness in African small and medium-sized enterprises (SMEs). *Journal of Sustainability Research, 6*(2), e240033.
3. DiMaggio, P. J., & Powell, W. W. (2000). The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. In *Advances in Strategic Management* (Vol. 17, pp. 143-166). Emerald Group Publishing Limited.
4. Pfeffer, J., & Salancik, G. R. (2015). *The external control of organizations: A resource dependence perspective*. Stanford University Press.
5. Scott, W. R. (2013). *Institutions and organizations: Ideas, interests, and identities* (4th ed.). SAGE Publications.
6. Giddens, A. (2014). *The constitution of society: Outline of the theory of structuration*. Polity Press.
7. Kamble, S. S., Gunasekaran, A., & Gawankar, S. A. (2023). Achieving sustainable performance in a data-driven agriculture supply chain: A review for research and applications. *International Journal of Production Economics, 219*, 179-194.
8. Wiredu, G. O., Agyapong, D., & Boateng, R. (2024). Digital transformation and sustainability in emerging economies: A systematic review. *Technological Forecasting and Social Change, 198*, 122-136.
9. Ufua, D. E., Osabuohien, E. S., & Ejemeyovwi, J. O. (2021). Institutional frameworks and sustainable development in Nigeria. *Journal of Institutional Economics, 17*(3), 459-478.
10. Adegbite, E., & Nakajima, C. (2022). Corporate governance and sustainability in Nigeria. *Corporate Governance: An International Review, 30*(2), 178-195.
11. Udeagha, M. C., & Ngepah, N. (2023). Environmental regulation and sustainable development in emerging economies. *Environmental Science and Pollution Research, 30*(15), 43245-43265.

12. Amoah, A., & Eweje, G. (2022). Environmental regulations and corporate sustainability in Ghana. *Journal of Cleaner Production, 330*, 129-142.

13. Onuoha, F. C., Nwosu, O. C., & Ugwu, C. C. (2024). Policy fragmentation and corporate compliance in Nigeria. *African Journal of Business and Economic Research, 19*(1), 89-112.

14. Narula, R. (2020). *Institutional voids and sustainable development in emerging economies*. Oxford University Press.

15. George, G., Haas, M. R., & McGahan, A. M. (2023). Institutional voids and the sustainability of emerging economy firms. *Academy of Management Journal, 66*(2), 489-514.