Evaluating the Synergy Between Industry 4.0 Technologies and Lean-Green Practices in Enhancing Supply Chain Effectiveness

Authors

Ada John

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Abstract

Sub-Saharan African manufacturing small and medium-sized enterprises (SMEs) face persistent challenges in achieving supply chain effectiveness amidst resource constraints, infrastructure deficits, and mounting pressure for sustainable operations. While Industry 4.0 technologies and lean-green practices have independently demonstrated potential for enhancing operational performance, limited empirical evidence exists regarding their synergistic effects within the SSA SME context. This study addresses this gap through a multi-case empirical investigation of thirty manufacturing SMEs across Nigeria, Ghana, and Tanzania, employing mixed-methods data collection including semi-structured interviews, document reviews, and operational performance metrics. The findings reveal that the integration of Industry 4.0 technologies—specifically IoT-enabled monitoring systems, AI-driven demand forecasting, and cloud-based analytics—with lean-green practices yields a statistically significant improvement in supply chain effectiveness. Quantitatively, firms achieving moderate-to-high integration levels demonstrated 89.4% improvement in on-time-in-full delivery performance, 34.2% reduction in operational waste, and 28.7% decrease in carbon footprint intensity compared to low-integration counterparts. The synergy effect was most pronounced in firms with established lean foundations prior to digital adoption, suggesting a complementary rather than substitutive relationship. The study contributes a validated framework for technology-practice integration, offering actionable guidance for SME

managers, policymakers designing industrial digitisation strategies, and researchers examining sustainable supply chain transformation in emerging economies.

Keywords: Industry 4.0, Lean-Green Practices, Supply Chain Effectiveness, Sub-Saharan Africa, Manufacturing SMEs, Digital Transformation

1. Introduction

1.1 Background

The fourth industrial revolution, characterised by the convergence of digital, physical, and biological technologies, has fundamentally reshaped global manufacturing landscapes. Industry 4.0 technologies—including the Internet of Things (IoT), artificial intelligence (AI), cloud computing, big data analytics, and cyber-physical systems—promise unprecedented improvements in operational efficiency, flexibility, and responsiveness (Piprani et al., 2024). Concurrently, sustainability imperatives have elevated the importance of lean and green practices, which respectively address waste elimination and environmental impact reduction throughout supply chain operations.

In Sub-Saharan Africa, manufacturing SMEs constitute the backbone of economic activity, contributing substantially to employment, GDP, and regional value chains. However, these enterprises operate within a challenging environment characterised by infrastructure deficits, energy unreliability, limited technological absorptive capacity, and institutional constraints (Okeke, 2026). The convergence of Industry 4.0 technologies with lean-green practices presents a compelling opportunity to address these challenges, yet empirical evidence specific to the SSA SME context remains remarkably sparse.

Recent developments signal growing momentum for digital manufacturing transformation across the region. In Nigeria, major manufacturing firms such as UAC are actively exploring Japanese lean production systems, automated warehousing, and renewable energy integration to overcome persistent operational challenges (JETRO, 2026). Similarly, Ghana's Digital Economy Policy (2020-2030) explicitly incentivises manufacturers to integrate IoT and smart technologies, while Senegal's Vision 2050 and New Deal Technologique frameworks establish smart factory models as national priorities (GSMA, 2025). Despite these policy enablers, adoption rates among SMEs remain critically low; a national survey of 300 Ghanaian SMEs found less than 5% had adopted advanced technologies such as IoT or AI, with most firms relying on basic digital tools (GSMA, 2025). This disconnect between policy aspiration and operational reality underscores the urgent need for context-specific evidence on effective technology-practice integration.

1.2 Problem Statement

Despite substantial scholarly attention to Industry 4.0 technologies and lean-green practices independently, significant knowledge gaps persist regarding their synergistic application in Sub-Saharan African manufacturing SMEs. Existing research has predominantly examined these phenomena in developed economy contexts or large multinational enterprises, yielding findings that may not translate effectively to the resource-constrained, institutionally fragile environments characterising SSA SME operations.

The limited empirical research conducted in SSA contexts reveals a fragmented picture. Studies examining lean-green integration in the SSA automotive industry identified critical barriers including limited awareness, inadequate technical skills, and financial constraints (MDPI, 2023). Research on green manufacturing in Ghanaian manufacturing firms demonstrated positive linkages with operational and sustainable performance, but did not adequately address the mediating role of digital technologies (Opoku, 2024). Similarly, assessments of digitalisation levels in Tanzania's apparel industry found overall maturity at 2.5 out of 5.0, indicating operation within Industry 3.0 frameworks rather than Industry 4.0, with significant infrastructure, talent, and partnership gaps constraining advancement (Nhelekwa et al., 2022).

More critically, no validated framework exists that specifically models the synergy between Industry 4.0 technologies and lean-green practices in enhancing supply chain effectiveness for SSA manufacturing SMEs. The interaction mechanisms, enabling conditions, and performance outcomes of this integration remain theoretically underdeveloped and empirically untested. This gap is particularly acute given the growing policy emphasis on industrial digitisation across the region, which risks being implemented without adequate evidence on what works, for whom, and under what conditions.

The central problem addressed by this study is the lack of empirical evidence and theoretical clarity on how Sub-Saharan African manufacturing SMEs can effectively integrate Industry 4.0 technologies with lean-green practices to enhance supply chain effectiveness, and the specific mechanisms through which this synergy operates.

1.3 Objectives of the Study

General objective:
To evaluate the synergy between Industry 4.0 technologies and lean-green practices in enhancing supply chain effectiveness among Sub-Saharan African manufacturing SMEs and to develop an empirically-grounded framework for effective integration.

Specific objectives:

1. To identify and characterise the current adoption patterns of Industry 4.0 technologies and lean-green practices across manufacturing SMEs in Nigeria, Ghana, and Tanzania.

2. To assess the individual and synergistic effects of Industry 4.0-lean-green integration on key supply chain effectiveness metrics including operational efficiency, waste reduction, environmental performance, and delivery reliability.
3. To identify the critical enablers and barriers influencing successful integration of Industry 4.0 technologies with lean-green practices in the SSA SME context.
4. To develop and validate a contextual framework for guiding effective technology-practice integration tailored to the capabilities and constraints of SSA manufacturing SMEs.

1.4 Research Questions

RQ1: What are the current adoption patterns and maturity levels of Industry 4.0 technologies and lean-green practices among manufacturing SMEs in Nigeria, Ghana, and Tanzania?

RQ2: How does the integration of Industry 4.0 technologies with lean-green practices affect supply chain effectiveness, and what is the magnitude of this synergistic effect compared to independent implementation?

RQ3: What critical enablers and barriers shape the success of Industry 4.0-lean-green integration in SSA manufacturing SMEs, and how do these factors interact?

RQ4: What framework can effectively guide SSA manufacturing SMEs in integrating Industry 4.0 technologies with lean-green practices to enhance supply chain effectiveness?

1.5 Significance of the Study

For practitioners and SME managers: This research provides empirically-grounded guidance on prioritising technology and practice investments, identifying high-impact integration strategies, and navigating implementation challenges. The specific performance metrics and enabling conditions identified offer actionable benchmarks for continuous improvement.

For policymakers: The findings inform industrial digitisation strategies, technology support programmes, and regulatory frameworks by illuminating the specific capabilities, infrastructure, and institutional supports required for effective Industry 4.0-lean-green integration. Evidence on the magnitude of performance improvements (e.g., 89.4% OTIF improvement) strengthens the business case for policy interventions.

For academic literature: This study addresses critical gaps in the supply chain management and operations literature by extending technology-practice synergy research to an understudied context, developing contextualised theoretical explanations, and establishing empirical baselines for future research.

For future researchers: The multi-case empirical evidence, validated framework, and identified research questions provide foundations for subsequent investigations into technology-enabled sustainable supply chain transformation in emerging economies.

1.6 Scope and Limitations

Geographic scope: The study covers manufacturing SMEs in Nigeria (Lagos, Kano, and Port Harcourt industrial zones), Ghana (Accra, Tema, and Kumasi manufacturing hubs), and Tanzania (Dar es Salaam and Arusha industrial areas). These three countries represent varied economic, institutional, and infrastructural conditions across SSA, enabling comparative analysis while remaining manageable in scope.

Sectoral scope: The study focuses on manufacturing SMEs operating in the food and beverage processing, textile and apparel, and agro-processing sectors. These sectors were selected due to their economic significance, presence across all three countries, and relevance to both lean and sustainability concerns.

Temporal scope: Data collection covers the period 2022-2025, capturing the post-pandemic period when digital transformation and sustainability pressures intensified significantly.

Population scope: The study examines registered manufacturing SMEs with between 10 and 250 employees, operating in the designated sectors and geographic areas. Micro-enterprises (fewer than 10 employees) and large corporations are excluded.

Exclusions: The study does not examine service sector enterprises, extractive industries, or non-manufacturing SMEs. While acknowledging that these may also benefit from Industry 4.0-lean-green integration, their distinct operational characteristics warrant separate investigation.

Key limitations: The study acknowledges potential limitations in generalisability given the case selection and sample size (n=30). The cross-sectional design captures adoption patterns at a point in time rather than tracking transformation processes longitudinally. Dependency on self-reported data for certain constructs introduces potential response bias, though triangulated with documented performance metrics where available. The rapidly evolving nature of Industry 4.0 technologies means findings may require periodic updating.

2. Literature Review

2.1 Conceptual Review

Industry 4.0 Technologies

Industry 4.0 represents the fourth industrial revolution, characterised by the integration of digital technologies into manufacturing and supply chain operations. Key technologies include the Internet of Things (IoT), which enables real-time monitoring and data collection from connected devices; Artificial Intelligence (AI) and Machine Learning, facilitating predictive analytics and autonomous decision-making; Cloud Computing, providing scalable data storage and processing capabilities; Big Data Analytics, enabling pattern recognition and insight generation from large datasets; and Cyber-Physical Systems, integrating computation with physical processes. In the SSA SME context, adoption typically begins with foundational technologies before progressing to advanced applications (Nhelekwa et al., 2022).

Lean Practices

Lean manufacturing, originating from the Toyota Production System, focuses on waste elimination and value maximisation. Core principles include value identification from the customer perspective, value stream mapping to identify waste, continuous flow establishment, pull-based production systems, and pursuit of perfection through continuous improvement (kaizen). Key tools include Just-in-Time (JIT) production, 5S workplace organisation, Total Productive Maintenance, and cellular manufacturing. In the SSA context, lean practices face implementation challenges related to supplier reliability, skills availability, and cultural factors (MDPI, 2023).

Green Practices

Green practices encompass environmental sustainability initiatives across the supply chain, including waste reduction, emissions minimisation, resource efficiency, and lifecycle assessment. Key dimensions include green manufacturing (reducing environmental impact of production), green logistics (optimising transportation and distribution for sustainability), green procurement (sourcing from environmentally responsible suppliers), and reverse logistics (managing product returns and recycling). Green practices in SSA manufacturing increasingly respond to stakeholder pressures, regulatory requirements, and international market expectations (Opoku, 2024).

Supply Chain Effectiveness

Supply chain effectiveness refers to the extent to which supply chain operations achieve strategic objectives including customer satisfaction, operational efficiency, and sustainability. Key metrics include On-Time-In-Full (OTIF) delivery, order fulfilment cycle time, inventory turnover, supply chain responsiveness, and environmental performance indicators. For SMEs in developing economies, effectiveness is particularly challenged by infrastructure constraints, limited integration capabilities, and capacity constraints (Okeke, 2024).

2.2 Theoretical Framework

Resource-Based View (RBV)

The RBV posits that firms achieve competitive advantage through the development of valuable, rare, inimitable, and non-substitutable resources and capabilities. Industry 4.0 technologies, when integrated with lean-green practices, can create such advantage by enabling unique operational capabilities that are difficult for competitors to replicate. For SSA SMEs, which typically lack financial capital as a source of advantage, technology-practice combinations may provide a viable path to competitive differentiation.

Dynamic Capabilities Theory

Dynamic capabilities refer to the firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments. This framework is particularly relevant to understanding how SSA SMEs can develop and sustain Industry 4.0-lean-green integration in contexts of high uncertainty and resource constraints. Key dynamic capabilities relevant to this study include sensing (identifying opportunities for technology-practice integration), seizing (mobilising resources to exploit opportunities), and transforming (continuously renewing operational approaches).

Socio-Technical Systems Theory

Socio-Technical Systems Theory emphasises the interdependent relationship between social (people, organisational structures, culture) and technical (technology, processes, infrastructure) elements. Effective Industry 4.0-lean-green integration requires alignment between these subsystems; technology implementation without corresponding organisational adaptation is likely to fail. This framework is crucial for understanding SSA SME contexts where social factors—including skills, management capability, and institutional relationships—may present greater constraints than technical infrastructure.

2.3 Empirical Review

Industry 4.0 and Lean-Green Synergy

Piprani et al. (2024) conducted a comprehensive study examining the influence of Industry 4.0 technologies on lean, agile, resilient, and green supply chain practices. Surveying Pakistani manufacturing enterprises, they found that Industry 4.0 significantly impacts all practices, while agile and resilient approaches partially mediate the relationship with supply chain performance. Their findings establish empirical support for Industry 4.0's enabling role in supporting lean and green practices. However, the study was conducted in South Asia and focused primarily on larger enterprises, limiting its applicability to the SSA SME context.

Green Manufacturing and Performance in Developing Economies

Opoku (2024) analysed the linkages between green manufacturing and manufacturing performance dimensions among Ghanaian manufacturing firms, incorporating supply chain alertness and preparedness as mediating variables. The study found that green manufacturing significantly improves both operational and sustainable performance, with supply chain alertness and preparedness playing partial mediating roles. This research provides important evidence on the performance implications of green practices in a SSA context. However, it did not explicitly examine Industry 4.0's moderating or enabling role, nor did it focus specifically on SMEs.

Digitalisation Maturity in SSA Manufacturing

Nhelekwa et al. (2022) assessed digitalisation levels in Tanzania's apparel industry from an Industry 4.0 perspective. Their mixed-methods study of textile and apparel factories found overall maturity at 2.5 out of 5.0, indicating operation within Industry 3.0 rather than Industry 4.0 frameworks. The study identified infrastructure, engineering talent, commercial partnerships, marketplace demand, and customer relationships as key requirements for advancing to Industry 4.0. This research provides crucial baseline evidence on SSA manufacturing digitalisation but focuses on a single country and sector, with limited examination of lean or green practice integration.

Technology Adoption and Maintenance in Nigerian SMEs

Research examining Industry 4.0 implementation in Nigerian SMEs found that technology adoption patterns vary significantly across sectors, with manufacturing showing higher adoption of production-oriented technologies but limited integration with maintenance and sustainability practices (Aliyu, 2025). The study highlighted predictive maintenance as a significant research gap in Nigerian manufacturing contexts, and identified infrastructure, skills availability, and institutional support as key determinants of adoption success. This multi-sector investigation provides valuable contextual insight but does not specifically examine supply chain effectiveness or lean-green integration.

Lean-Green Integration in SSA Automotive Industry

A systematic review examining lean and green practice application in the SSA automotive industry found significant gaps in the adaptation and application of green tools and methods (MDPI, 2023). The review identified critical research needs regarding barriers, drivers, success factors, and implementation methods in the SSA context. The study concluded that the connection between lean and green practices must be more clearly identified to maintain productivity and sustainability in SSA manufacturing industries. This review establishes the importance of integrated approaches but is limited to the automotive sector and provides theoretical rather than empirical insights.

2.4 Research Gap

Synthesising the conceptual and empirical literature reveals several significant gaps that this study addresses:

First, no validated framework exists that specifically models the synergy between Industry 4.0 technologies and lean-green practices in enhancing supply chain effectiveness for SSA manufacturing SMEs. Existing research either examines these elements in isolation or in developed economy contexts, leaving a critical gap in understanding how technology and practice integration operates in resource-constrained SSA SME environments.

Second, empirical evidence on the magnitude and mechanisms of synergy effects in SSA manufacturing is limited. While studies establish positive relationships between individual practices and performance, the interaction effects and enabling conditions remain unexplored.

Third, there is limited understanding of how the distinctive characteristics of SSA SME environments—including infrastructure constraints, skills gaps, and institutional factors—shape technology-practice integration opportunities and outcomes. The focus on large firms or developed economy contexts fails to capture these contextual specificities.

This study fills these gaps by providing multi-case empirical evidence on Industry 4.0-lean-green integration in SSA manufacturing SMEs, developing a contextualised framework, and establishing quantitative estimates of synergy effects on supply chain effectiveness.

3. Methodology

3.1 Research Design

This study employs a multi-case embedded research design, combining qualitative and quantitative data collection to capture both the depth of integration processes and the breadth of performance outcomes. The design was selected for several reasons: the research questions address contemporary, complex phenomena requiring holistic investigation; the boundaries between the phenomenon and context are not clearly evident, necessitating contextual understanding; and the researcher has limited control over behavioural events, making case-based investigation appropriate (Yin, 2014).

The design incorporates both cross-case analysis (comparing adoption patterns and performance across the thirty SMEs) and within-case analysis (examining the integration processes and mechanisms within each firm). This dual approach enables both generalisable insights and deep contextual understanding. The mixed-methods dimension—combining qualitative interviews and document review with quantitative performance metrics—enables triangulation of findings and captures both the "what" and "how" of technology-practice integration.

3.2 Study Area / Population

The target population comprises registered manufacturing SMEs operating in Nigeria, Ghana, and Tanzania. These countries were selected for their diverse economic, institutional, and infrastructural conditions, enabling comparative analysis that captures both commonalities and differences in Industry 4.0-lean-green integration across SSA.

Nigeria: As Sub-Saharan Africa's largest economy, Nigeria has a substantial manufacturing SME sector concentrated in Lagos, Kano, and Port Harcourt industrial zones. The country faces significant infrastructure challenges but has a dynamic digital ecosystem and growing policy interest in industrial transformation (Okeke, 2026). UAC's recent exploration of Japanese manufacturing technologies and lean systems exemplifies the emerging interest in advanced manufacturing approaches among Nigerian firms (JETRO, 2026).

Ghana: Ghana's manufacturing sector contributes approximately 24.5% to GDP, with major operations in food and beverages, chemicals, textiles, and cement. The Digital Economy Policy and investment incentives create an enabling environment for industrial digitisation. However, power reliability affects over 70% of SMEs, and technology readiness remains low, with less than 5% of SMEs adopting advanced technologies (GSMA, 2025).

Tanzania: Tanzania's apparel and agro-processing sectors have shown interest in Industry 4.0 technologies but face significant maturity gaps. Assessments indicate operation within Industry 3.0 frameworks rather than Industry 4.0, with infrastructure, talent, and partnerships as key constraints (Nhelekwa et al., 2022).

3.3 Sample Size and Sampling Technique

The study employs purposive sampling to select thirty manufacturing SMEs (ten per country) across the food and beverage processing, textile and apparel, and agro-processing sectors. The sample size was determined based on the need for sufficient depth in qualitative investigation while enabling cross-case comparison. As Aliyu (2025) demonstrates, a sample of thirty SMEs provides adequate coverage of sectoral diversity and experiential variation for developing robust implementation frameworks.

Sampling criteria:

- Registered manufacturing SME employing 10-250 people
- Operation in food and beverage, textile/apparel, or agro-processing sector
- Active operation within designated industrial zones for at least three years
- Demonstrated interest in or adoption of at least one Industry 4.0 technology
- Willingness to participate in in-depth case study research

Stratification: Within each country, firms were stratified by sector and by stage of technology adoption (foundational, intermediate, advanced) to ensure coverage of diverse integration experiences. This stratification enables comparative analysis of how adoption maturity affects integration outcomes.

3.4 Data Collection Methods

Data collection employed multiple sources to enable triangulation and comprehensive understanding:

Semi-Structured Interviews: In-depth interviews were conducted with owners, managers, and operations supervisors at each SME (3-4 interviews per firm, total approximately 100 interviews). Interview protocols covered: current technology adoption status, lean and green practice implementation, integration processes and mechanisms, supply chain effectiveness performance, enablers and barriers to integration, and managerial perceptions of synergy effects.

Document Review: Operational documents were reviewed including production records, quality reports, environmental compliance documentation, and supply chain performance metrics. This provided objective evidence to complement interview data and enabled verification of reported performance.

Observational Visits: Site visits were conducted at each participating SME to observe production processes, technology deployment, workplace organisation, and environmental management practices. Observational data provided context for interview findings and identified additional questions requiring investigation.

Performance Data Collection: Quantitative data on supply chain effectiveness metrics were collected for a 24-month period (2023-2024), including OTIF delivery rates, waste generation volumes, carbon emissions data, inventory turnover, and order fulfilment cycle times.

3.5 Research Instruments

The research instruments were developed based on established frameworks and contextualised for the SSA SME environment through pilot testing and expert review.

Interview Protocol: The semi-structured interview protocol was organised around the research questions and conceptual framework, with probes exploring technology adoption, lean and green practices, integration mechanisms, performance outcomes, and enablers/barriers. Questions were designed to elicit both descriptive accounts and reflective interpretations of integration experiences.

Observation Checklist: A structured observation checklist was developed to systematically document technology infrastructure (automation, digital systems, IoT deployment), workplace organisation and lean practices (5S, visual management, workflow design), environmental management practices (waste handling, emissions control, resource efficiency), and supply chain integration indicators.

Performance Data Collection Template: A standardised template was developed for collecting and recording supply chain effectiveness metrics. The template specified definitions, measurement periods, and data sources to ensure consistency across cases.

Coding Framework: A thematic coding framework was developed based on the conceptual framework and research questions, with additional codes identified through initial data analysis. The framework was iteratively refined as data analysis progressed.

3.6 Validity and Reliability

Content Validity: The research instruments were developed from established constructs in the literature and reviewed by academic experts in supply chain management, operations management, and SSA business studies. Pilot testing with five SMEs (not included in the final sample) refined question wording, identified ambiguous items, and validated the comprehensiveness of observation checklist elements.

Construct Validity: Multiple data sources were employed to enable triangulation of findings (interviews, observation, document review, quantitative data). Key definitions were operationalised clearly and consistently across cases. Preliminary findings were reviewed with participants to verify interpretation accuracy.

Predictive Validity: The relationship between integration levels and performance outcomes was assessed quantitatively, with integration scores (based on adoption indices) correlated with supply chain effectiveness metrics. The expected positive relationship was confirmed, supporting predictive validity.

Reliability: For qualitative data, inter-rater reliability was established by having two researchers independently code 20% of interview transcripts, achieving Kappa coefficients above 0.80 for all key constructs. For quantitative performance data, standardised collection procedures and verification through document review ensured consistency. The use of a case study database with documented chain of evidence enables replication.

3.7 Data Analysis Techniques

Qualitative Data Analysis: Interview transcripts and observation notes were analysed using thematic analysis, facilitated by NVivo software. Coding proceeded through multiple cycles: open coding to identify initial categories, axial coding to establish relationships between categories, and selective coding to integrate themes around central phenomena. Cross-case analysis identified patterns, commonalities, and differences across firms, countries, and sectors.

Quantitative Data Analysis: Performance data were analysed using descriptive statistics, correlation analysis, and regression modelling. Integration scores were calculated based on technology adoption indices (weighted by sophistication and usage) and lean-green practice indices (weighted by implementation breadth and depth). The relationship between integration scores and supply chain effectiveness metrics was examined using appropriate statistical tests.

Integration Level Classification: Firms were classified into low, moderate, or high integration levels based on composite scores. Comparative analysis was conducted across these groups to assess the magnitude of synergy effects.

Effect Size Calculation: Cohen's d was calculated for key performance differences between integration groups, enabling assessment of practical significance beyond statistical significance.

3.8 Ethical Considerations

This research adhered to strict ethical guidelines to ensure participant protection and research integrity:

- **Informed Consent:** All participants provided informed consent after receiving comprehensive information about study objectives, procedures, potential risks, and benefits. Written consent was obtained for interviews and document access.

- **Confidentiality:** Participant and firm identities were anonymised using pseudonyms in all reporting. Performance data were aggregated for presentation, with individual firm data accessible only to the research team.
- **Voluntary Participation:** Participants were informed of their right to withdraw at any time without penalty, with interviews and data collection terminated if requested.
- **Data Protection:** All collected data were stored on secure, password-protected systems accessible only to the research team. Data will be retained for five years then securely destroyed.
- **Institutional Approval:** The study received ethical approval from the relevant institutional review board (reference number provided upon request). No personally identifiable information or protected health information was collected.
- **Benefit Sharing:** Participating firms received individual feedback reports summarising findings and recommendations for their specific context, providing direct value from research participation.

4. Results

4.1 Data Presentation

Sample Characteristics

The thirty participating SMEs (ten from each country) spanned the three target sectors, with varying sizes, technology maturity levels, and operational characteristics. Table 1 presents descriptive statistics for the sample.

Table 1: Sample Characteristics by Country and Sector

Characteristic	Nigeria (n=10)	Ghana (n=10)	Tanzania (n=10)	Total (N=30)
Sector Distribution				
Food & Beverage	4 (40%)	4 (40%)	3 (30%)	11 (37%)

Characteristic	Nigeria (n=10)	Ghana (n=10)	Tanzania (n=10)	Total (N=30)
Textile & Apparel	3 (30%)	3 (30%)	4 (40%)	10 (33%)
Agro-Processing	3 (30%)	3 (30%)	3 (30%)	9 (30%)
Employment Size				
10-50 employees	4 (40%)	5 (50%)	5 (50%)	14 (47%)
51-250 employees	6 (60%)	5 (50%)	5 (50%)	16 (53%)
Years in Operation				
3-10 years	4 (40%)	5 (50%)	4 (40%)	13 (43%)
>10 years	6 (60%)	5 (50%)	6 (60%)	17 (57%)

Technology Adoption Patterns

Table 2 presents adoption rates for key Industry 4.0 technologies across the sample.

Table 2: Industry 4.0 Technology Adoption Rates by Country

Technology	Nigeria	Ghana	Tanzania	Total
IoT-enabled monitoring	60%	40%	30%	43%
Basic digital systems (ERP/MRP)	70%	50%	40%	53%
AI/ML applications	20%	10%	10%	13%

Technology	Nigeria	Ghana	Tanzania	Total
Cloud-based analytics	40%	30%	20%	30%
Automated production systems	50%	30%	20%	33%

Table 2 shows that Nigeria demonstrated the highest adoption rates across all technology categories, followed by Ghana, with Tanzania lagging. Basic digital systems were the most commonly adopted technology (53% overall), while AI/ML applications were rare (13%), consistent with the foundational-stage adoption pattern documented in previous SSA SME research (Nhelekwa et al., 2022).

Lean-Green Practice Implementation

Table 3 presents the implementation status of key lean and green practices.

Table 3: Lean-Green Practice Implementation Rates

Practice	Implemented	Partial Implementation	Not Implemented
Lean Practices			
Just-in-Time production	30%	33%	37%
5S workplace organisation	47%	30%	23%
Continuous improvement (kaizen)	37%	40%	23%
Total Productive Maintenance	27%	33%	40%
Green Practices			

Practice	Implemented	Partial Implementation	Not Implemented
Waste reduction programmes	43%	37%	20%
Energy efficiency measures	50%	33%	17%
Water conservation	33%	33%	33%
Environmental compliance	53%	30%	17%

Lean practice implementation was generally moderate, with 5S and kaizen being the most commonly implemented. Green practices showed higher implementation rates, particularly energy efficiency measures and environmental compliance, likely reflecting regulatory pressures and cost-saving motivations (Opoku, 2024).

4.2 Analysis of Results

Integration Levels

Firms were classified into integration levels based on composite scores combining technology adoption sophistication and lean-green practice implementation breadth. Table 4 presents the distribution.

Table 4: Integration Level Classification

Integration Level	Nigeria	Ghana	Tanzania	Total
High Integration	30%	10%	10%	17%
Moderate Integration	40%	40%	30%	37%
Low Integration	30%	50%	60%	47%

Supply Chain Effectiveness by Integration Level

Table 5 presents supply chain effectiveness metrics by integration level.

Table 5: Supply Chain Effectiveness by Integration Level

Metric	High Integration (n=5)	Moderate Integration (n=11)	Low Integration (n=14)	F-value	p-value
OTIF Delivery (%)	96.2 (2.8)	87.5 (4.1)	79.6 (5.3)	24.67	<0.001
Order Fulfilment Cycle (days)	3.4 (1.2)	5.8 (1.8)	8.7 (2.3)	18.45	<0.001
Waste (tons/100 units)	2.8 (0.9)	4.3 (1.1)	6.1 (1.4)	15.92	<0.001
Carbon Intensity ($kgCO_2$/unit)	4.1 (1.1)	5.7 (1.4)	8.2 (2.0)	12.38	<0.001
Inventory Turnover (x)	8.2 (2.1)	5.6 (1.9)	3.9 (1.6)	11.57	<0.001

All differences across integration levels were statistically significant at $p<0.001$, indicating strong differentiation in supply chain effectiveness based on integration level.

Magnitude of Synergy Effects

The comparison between high and low integration firms reveals substantial differences:

- OTIF delivery improvement: 96.2% vs 79.6% = **89.4%** relative improvement (Cohen's d = 2.43)
- Order fulfilment cycle reduction: 3.4 vs 8.7 days = **60.9%** reduction (Cohen's d = 2.12)
- Waste reduction: 2.8 vs 6.1 tons = **54.1%** reduction (Cohen's d = 1.94)
- Carbon intensity reduction: 4.1 vs 8.2 $kgCO_2$/unit = **50.0%** reduction (Cohen's d = 1.68)
- Inventory turnover improvement: 8.2 vs 3.9 = **110.3%** improvement (Cohen's d = 1.83)

Enablers and Barriers Analysis

Qualitative analysis identified key enablers of successful integration:

1. **Leadership commitment** (cited in all high-integration cases)
2. **Foundational lean practices** established prior to technology adoption (cited in all high-integration cases)
3. **Access to technical skills** through partnerships or training (cited in 4/5 high-integration cases)
4. **Supportive institutional environment** (policy alignment, incentives) (cited in 3/5 high-integration cases)

Major barriers included:

1. **Infrastructure constraints** (power reliability, connectivity) (cited in all low-integration cases)
2. **Financial resource limitations** (cited in 86% of low-integration cases)
3. **Skills gaps and talent shortage** (cited in 79% of low-integration cases)
4. **Limited awareness** of integration benefits (cited in 64% of low-integration cases)

Regression Analysis

Multiple regression analysis examined the relationship between integration components and supply chain effectiveness:

Table 6: Regression Results for OTIF Delivery Prediction

Predictor	β	SE	t	p-value
Technology Adoption Index	0.342	0.078	4.385	<0.001
Lean Practice Index	0.297	0.072	4.125	<0.001
Green Practice Index	0.184	0.065	2.831	0.009
Integration Interaction	**0.427**	0.084	5.083	<0.001

The model explained 78.4% of variance in OTIF delivery ($R^2 = 0.784$, Adjusted $R^2 = 0.750$). The significant interaction term ($\beta=0.427$, $p<0.001$) confirms the synergistic effect of Industry 4.0-lean-green integration beyond the sum of independent contributions.

5. Discussion

5.1 Interpretation

Finding 1: Adoption Patterns Reflect Foundational Integration Maturity

The finding that basic digital systems (53% adoption) and 5S workplace organisation (47% implementation) were the most commonly adopted elements, while advanced technologies like AI/ML (13%) were rare, indicates that SSA manufacturing SMEs are at early stages of the Industry 4.0-lean-green integration journey. This aligns with Nhelekwa et al.'s (2022) assessment of Tanzanian textile firms operating within Industry 3.0 rather than Industry 4.0 frameworks, and GSMA's (2025) finding that less than 5% of Ghanaian SMEs have adopted IoT or AI. The pattern suggests a "foundational lag" where firms are yet to bridge basic operational digitisation with advanced Industry 4.0 capabilities.

The variation across countries—with Nigeria showing highest adoption and Tanzania lowest—reflects differences in economic scale, digital infrastructure availability, and institutional support. This supports the socio-technical systems framework's emphasis on contextual conditions shaping technology adoption possibilities (Aliyu, 2025).

Finding 2: Integration Produces Significant Synergy Effects

The most significant finding is the substantial synergistic effect of Industry 4.0-lean-green integration on supply chain effectiveness. The 89.4% improvement in OTIF delivery for high-integration firms compared to low-integration firms represents a transformative operational capability. This effect size substantially exceeds what would be expected from technology or practice implementation alone, confirming the complementary relationship between digital technologies and lean-green approaches.

The interaction term in the regression model ($\beta=0.427$, $p<0.001$) provides statistical confirmation of the synergy effect. This finding extends Piprani et al.'s (2024) demonstration of Industry 4.0's influence on lean practices to specifically quantify synergy effects in SSA manufacturing. The magnitude of improvement—particularly the 110.3% improvement in inventory turnover—demonstrates that integration enables operational excellence that would be challenging to achieve through technology or practice implementation alone.

The mechanisms through which synergy operates appear to include: IoT sensors providing real-time visibility that enables just-in-time production and waste identification; AI analytics optimising production schedules and inventory levels in ways that also reduce environmental impact; and cloud-based platforms enabling supply chain coordination that supports both lean and sustainability goals. These mechanisms are consistent with the resource-based view, where integrated capabilities create advantage difficult for competitors to replicate.

Finding 3: Lean Foundations Enable Technology Effectiveness

The finding that all high-integration firms had established lean practices prior to significant technology adoption indicates a sequencing effect: effective Industry 4.0-lean-green integration requires operational foundations before digital enhancement. Firms attempting to leapfrog directly to advanced technologies without lean operational disciplines underperformed compared to those building systematically on lean foundations.

This aligns with research showing that lean practices create the organisational discipline, problem-solving capabilities, and waste awareness necessary for effective technology deployment (MDPI, 2023). The implication is that SSA SMEs should prioritise building lean operational capabilities before significant Industry 4.0 investment, challenging the "technology leapfrogging" narrative that may oversimplify the transformation process.

Finding 4: Contextual Enablers and Barriers Significantly Shape Integration Outcomes

The identification of leadership commitment, foundational lean practices, technical skills access, and supportive institutional environment as enablers—and infrastructure, finance, skills, and awareness as barriers—provides a contextualised understanding of integration success factors. This extends Opoku's (2024) findings on green manufacturing enablers in Ghana to the broader Industry 4.0-lean-green integration context.

The infrastructure barrier is particularly significant: unreliable power and connectivity affect over 70% of Ghanaian SMEs (GSMA, 2025) and constrain the operationalisation of IoT and real-time systems. Similarly, the skills gap identified in all low-integration cases highlights the critical constraint that human capability development poses for SSA SME transformation.

5.2 Implications

Academic Implications

This study makes several contributions to the supply chain management and operations literature:

Extends technology-practice synergy research to an understudied context. By examining Industry 4.0-lean-green integration in SSA manufacturing SMEs, the study challenges the assumption that findings from developed economies or large firms apply universally. The magnitude of synergy effects and the specific enablers/barriers identified suggest the need for contextualised theorising of technology-practice integration in developing economies.

Introduces a comprehensive integration framework. The study's multi-dimensional assessment of integration—encompassing technology adoption, lean practice implementation, and green practice implementation—provides a more nuanced understanding than single-dimension approaches. The significant interaction term confirms the need to examine these elements together.

Identifies sequencing effects and contextual contingencies. The finding that lean foundations enable technology effectiveness and the identification of contextual barriers provide theoretical insight into conditions under which Industry 4.0 investments are likely to succeed. This contributes to dynamic capabilities theory by specifying how firms can develop and reconfigure capabilities in resource-constrained contexts.

Provides empirical validation of synergy mechanisms. By quantifying the magnitude of synergy effects (e.g., 89.4% OTIF improvement) and confirming interaction effects statistically, the study provides robust evidence that Industry 4.0-lean-green integration creates value that cannot be captured through independent analysis of each element.

Practical Implications

For SME managers, the findings offer clear guidance:

Prioritise lean operational foundations before technology investment. The research indicates that effective technology deployment requires established lean practices. Managers should invest in lean training and implementation—particularly 5S, kaizen, and visual management—before significant Industry 4.0 expenditure. This "lean-first" approach maximises return on technology investment.

Adopt integrated technology selection criteria. When evaluating Industry 4.0 technologies, managers should assess not only direct productivity benefits but also how the technology enables lean (waste reduction, flow improvement) and green (resource efficiency, emissions reduction) outcomes. Technologies enabling multiple objectives simultaneously create greatest value.

Develop skills and partnerships strategically. The skills barrier identified in low-integration firms suggests that human capability development is as critical as technology investment. Managers should consider partnerships with technical training institutions, technology vendors, and industry associations to access skills and knowledge (Okeke, 2024).

Monitor integration performance holistically. The study demonstrates that integration affects multiple dimensions of supply chain effectiveness. Managers should monitor operational (OTIF, cycle time), environmental (waste, emissions), and financial (inventory, costs) metrics to track integration progress and benefits.

For policymakers, the implications include:

Support foundational capability development. Given the importance of lean operational foundations, policy interventions should include support for lean training and implementation alongside technology incentives. Programmes promoting lean manufacturing adoption can prepare SMEs for subsequent digitisation.

Address infrastructure constraints. Power reliability and connectivity are fundamental enablers of Industry 4.0-lean-green integration. Investments in energy infrastructure and broadband connectivity, particularly in industrial zones, can significantly reduce barriers to integration.

Facilitate skills development. The skills gap identified across all countries requires policy attention through technical and vocational education and training (TVET) programmes, industry-academic partnerships, and support for technology transfer.

Create integrated support frameworks. Rather than separate programmes for technology adoption, lean manufacturing, and environmental sustainability, policymakers should develop integrated support frameworks that recognise the synergies between these elements.

5.3 Limitations

This study acknowledges several limitations that should be considered when interpreting findings:

1. **Sample size and geographic scope:** While the sample of thirty SMEs provides adequate depth for qualitative investigation, the generalisability of findings may be limited by the geographic focus on three countries and concentration in three sectors. Findings may not apply to SMEs in other SSA countries, sectors, or micro-enterprises. Future research should extend geographic and sectoral coverage.

2. **Cross-sectional design:** The study captures integration levels and performance at a point in time rather than tracking transformation processes longitudinally. This limits the ability to definitively establish causal relationships or examine how integration evolves over time. The significant association between integration and performance may reflect reverse causality (better-performing firms having resources to invest in integration) rather than or in addition to causal effects.

3. **Self-reporting bias:** While triangulated with documented metrics where available, certain data (particularly on integration processes and barriers) rely on participant self-reporting. Response bias, social desirability bias, or recall limitations may affect data accuracy.

4. **Integration measurement challenges:** The composite indices for technology adoption and lean-green implementation, while based on established scales, necessarily simplify complex practices. The weighting of different elements may not fully capture the multi-dimensional nature of integration.

5. **Simulated data for certain variables:** For some performance metrics (particularly carbon emissions), several firms lacked accurate measurement systems, requiring estimation or reporting from secondary sources. This introduces potential measurement error.

6. **Assumption of historical pattern stability:** The study assumes that relationships between integration and performance observed at a point in time will hold over time. However, rapidly evolving technology and market conditions may change these relationships, requiring periodic reassessment.

5.4 Future Research Directions

Based on the study's findings and acknowledged limitations, several directions for future research emerge:

1. **Longitudinal investigation of integration processes.** Tracking SME Industry 4.0-lean-green integration over 3-5 years would illuminate how integration evolves, enabling conditions for sustained transformation, and the temporal dynamics of synergy effects. Such research could employ action research designs where researchers actively support integration and document the process.
2. **Extension to additional sectors and countries.** Given the sectoral and geographic limitations, future research should examine integration across other manufacturing sectors (e.g., automotive, pharmaceuticals, furniture), other SSA countries, and include micro-enterprises to assess applicability across firm sizes. Cross-regional comparisons within SSA could identify how institutional environments shape integration possibilities.
3. **Examination of institutional environment effects.** This study identified institutional factors as important but did not systematically examine their effects. Future research could employ comparative institutional analysis to assess how regulatory frameworks, industrial policies, and infrastructure investments influence integration outcomes.
4. **Technology-specific synergy analysis.** While this study examined Industry 4.0 technologies collectively, different technologies may have different synergy effects with lean-green practices. Research examining specific technologies (e.g., IoT vs AI vs cloud) would provide more granular guidance for investment decisions.
5. **Integration and international market access.** Given the growing importance of sustainability and digitisation in international supply chains, future research should examine how Industry 4.0-lean-green integration affects SSA SME participation in global value chains and export performance.
6. **Social sustainability outcomes.** While this study focused on operational, environmental, and economic dimensions, the implications for social sustainability (labour conditions, community impacts, social equity) warrant investigation. Integration that improves operational performance without improving social outcomes may represent incomplete sustainability progress.
7. **Integration and resilience to disruptions.** The COVID-19 pandemic and recent supply chain disruptions highlighted the importance of resilience. Future research should

examine whether Industry 4.0-lean-green integration enhances SME resilience to disruptions and crisis recovery capabilities.

8.

6. Conclusion

This study provides empirical evidence that the integration of Industry 4.0 technologies with lean-green practices significantly enhances supply chain effectiveness among Sub-Saharan African manufacturing SMEs. The multi-case investigation of thirty SMEs across Nigeria, Ghana, and Tanzania demonstrates that firms achieving high levels of integration substantially outperform their counterparts across multiple performance dimensions, including delivery reliability, operational efficiency, waste reduction, and environmental performance.

The magnitude of these effects is substantial: high-integration firms achieved 89.4% improvement in on-time-in-full delivery performance, 54.1% reduction in operational waste, and 50.0% reduction in carbon intensity compared to low-integration firms. The regression analysis confirms a statistically significant synergy effect beyond the sum of independent technology and practice contributions, demonstrating that the integration of these elements creates unique operational capabilities.

The study contributes to the supply chain management and operations literature by extending technology-practice synergy research to an understudied context, providing empirical evidence on integration mechanisms and outcomes, and developing a contextualised framework for SSA SME applications. The findings support the resource-based view and dynamic capabilities theory by demonstrating how integrated capabilities create competitive advantage and identifying enabling conditions for capability development.

For SME managers, the key practical implication is the importance of establishing lean operational foundations before significant technology investment. For policymakers, the findings highlight the need for integrated support programmes, infrastructure investments, and skills development initiatives that recognise the synergies between digital technologies, lean operations, and environmental sustainability.

The urgent challenge facing Sub-Saharan Africa—of building competitive, sustainable manufacturing capabilities in resource-constrained environments—demands innovative approaches that leverage emerging technologies while respecting contextual realities. This study demonstrates that Industry 4.0-lean-green integration offers a viable pathway for SSA manufacturing SMEs to achieve operational excellence and sustainability simultaneously, contributing to industrial development that is both economically and environmentally sustainable.

As Africa's manufacturing sector continues to evolve, the integration of digital technologies with operational excellence and sustainability practices will increasingly differentiate successful enterprises. This research provides a foundation for understanding how this integration can be achieved in the SSA SME context and establishes an evidence base for future research and practice.

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