Agricultural Digitalization and Supply Chain Agility: Examining Post-Pandemic Agri-SMEs in Developing Economies

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Abstract

The COVID-19 pandemic exposed severe vulnerabilities in agri-food supply chains across developing economies, yet the role of digitalization in enhancing supply chain agility among small and medium agribusiness enterprises (agri-SMEs) remains insufficiently theorized and empirically validated. This study addresses this gap by developing and testing a predictive framework linking agricultural digitalization dimensions—digital logistics infrastructure, mobile-enabled market access, and data-driven decision analytics—to supply chain agility outcomes in post-pandemic agri-SMEs. Using a mixed-methods design combining survey data from 412 agri-SMEs across Kenya, Nigeria, and Uganda with fuzzy-set qualitative comparative analysis (fsQCA) and structural equation modeling (SEM), the study identifies digital logistics infrastructure and trust-enabled collaboration as the strongest predictors of agility, with the validated model achieving 89.4% classification accuracy in distinguishing high-agility from low-agility firms. Findings reveal that mobile-based market access platforms mediate 34.2% of the digitalization–agility relationship, while rural connectivity gaps remain the most significant moderating barrier. The

study concludes that digitalization enhances agility not through technology adoption alone but through complementary investments in logistics infrastructure and inter-firm trust. Practical implications include a replicable agility assessment framework and prioritized intervention metrics for SME administrators and policymakers.

Keywords: agricultural digitalization, supply chain agility, agri-SMEs, post-pandemic recovery, developing economies

1. Introduction

1.1 Background

The COVID-19 pandemic precipitated unprecedented disruptions across agri-food value chains in developing economies, with containment measures restricting personal movement, transport options, and market access in ways that fundamentally altered production and trade patterns . Smallholder farmers and small-scale market actors in Kenya and Uganda experienced massive negative income effects, with market actors particularly hard hit due to their dependence on free movement . These disruptions exposed the fragility of traditionally configured agri-food supply chains and catalyzed interest in digitalization as a pathway to enhanced resilience and agility .

Agricultural digitalization encompasses the deployment of digital technologies—including mobile platforms, IoT sensors, data analytics, and blockchain-enabled traceability—across agricultural production and distribution processes. In developing economies, digitalization has largely taken mobile-based forms, with applications ranging from market price information and e-commerce platforms to digital financing and extension services . Evidence from Nigeria suggests that farmers using e-commerce platforms experienced a 40% reduction in transaction costs and a 30% average revenue increase through direct buyer access . However, despite these documented benefits, adoption among small and medium agribusiness enterprises (agri-SMEs) in Sub-Saharan Africa remains fragmented and far below potential .

Supply chain agility—defined as a firm‘s capacity to rapidly sense and respond to market disruptions while maintaining operational continuity—has emerged as a critical organizational capability in post-pandemic agri-food systems. Prior research has identified digital logistics infrastructure, e-governance, trust and collaboration, and social sustainability as critical success factors for digital transformation in agri-food supply chains . Yet the specific mechanisms through which different dimensions of digitalization translate into agility outcomes for resource-constrained agri-SMEs remain poorly specified and insufficiently validated.

1.2 Problem Statement

Despite growing recognition that digitalization may enhance supply chain resilience, three critical gaps persist in the literature. First, existing studies on agri-food digitalization predominantly focus on large-scale farms or global agribusiness firms, with scant empirical attention to the distinctive constraints and capabilities of agri-SMEs in developing economies . The digitalization process in Sub-Saharan Africa tends to be mobile-based, yet the application of IoT, big data, artificial intelligence, and business analytics remains very rare . Second, while digitalization is frequently promoted as transformational for smallholders, the evidence base linking specific digitalization dimensions to measurable agility outcomes is weak and often anecdotal; Aker et al. and Abate et al. note that despite high expectations, digital innovations often fail to move beyond small pilot projects to widespread adoption . Third, no validated predictive framework exists that specifically models the digitalization–agility relationship for agri-SMEs as organizational units, incorporating both enabling factors and contextual barriers characteristic of developing-economy contexts.

The consequence of these gaps is that policymakers and SME administrators lack empirically grounded guidance on which digitalization investments yield the greatest agility returns under resource constraints. This study addresses this unsolved issue by developing and validating a predictive framework that quantifies the contribution of distinct digitalization dimensions to supply chain agility in post-pandemic agri-SMEs.

1.3 Objectives of the Study

General objective: To develop and validate a predictive framework linking agricultural digitalization dimensions to supply chain agility outcomes among post-pandemic agri-SMEs in developing economies.

Specific objectives:

1. To identify the key digitalization predictors—including digital logistics infrastructure, mobile market access, data analytics capability, and trust-enabled collaboration—of supply chain agility in agri-SMEs.
2. To design a hybrid model integrating structural equation modeling with fuzzy-set qualitative comparative analysis that explains variance in agility outcomes and identifies configurational pathways to high agility.
3. To validate the framework using empirical data from agri-SMEs across three developing economies and assess its predictive accuracy against baseline models.

1.4 Research Questions

1. What combination of digitalization variables most accurately predicts supply chain agility in post-pandemic agri-SMEs?
2. How does the proposed digitalization–agility framework compare to traditional technology-adoption models in terms of explanatory power and classification accuracy?

3. What are the implementation barriers and enabling conditions that condition the effectiveness of digitalization for agility in resource-constrained agri-SME contexts?

1.5 Significance of the Study

For practitioners/administrators: The study provides agri-SME managers with an empirically validated diagnostic framework identifying which digitalization investments—particularly logistics infrastructure and trust-building mechanisms—yield the greatest agility returns. The 89.4% classification accuracy of the model enables practical self-assessment.

For policymakers: Findings inform the design of targeted interventions, suggesting that public investment in rural connectivity and digital logistics infrastructure may generate disproportionately larger agility benefits than direct technology subsidies alone.

For academic literature: The study extends dynamic capabilities theory and organizational agility literature to the under-researched context of developing-economy agri-SMEs, introducing a validated measurement model and demonstrating the mediating role of mobile market access.

For future researchers: The framework provides a replicable methodological template for cross-context validation and longitudinal extension.

1.6 Scope and Limitations

This study focuses on agri-SMEs (firms with 5–100 employees) engaged in production, processing, or distribution of agricultural products in Kenya, Nigeria, and Uganda, surveyed during 2024–2025. The study excludes large agribusiness corporations, purely subsistence farms, and firms in conflict-affected regions. Limitations include reliance on self-reported agility measures, cross-sectional design precluding causal inference, and the exclusion of informal micro-enterprises. The sample, while stratified, may not fully represent the heterogeneity of agri-SMEs across all developing economies.

2. Literature Review

2.1 Conceptual Review

Agricultural Digitalization. Agricultural digitalization refers to the integration of digital technologies—including mobile applications, IoT devices, data analytics platforms, and blockchain systems—into agricultural production, marketing, and supply chain coordination processes . In developing-economy contexts, digitalization manifests predominantly through mobile-based tools: SMS price alerts, e-marketplace platforms, mobile money payment systems, and digital extension services . The FAO documents diverse digitalization models, from whole-

farm digitization platforms to smartphone-accessible mechanization services targeting smallholders .

Supply Chain Agility. Supply chain agility denotes an organization's capability to rapidly detect and respond to market changes, disruptions, and opportunities while maintaining operational efficiency. Agility comprises three dimensions: sensing capability (detecting changes), response capability (adapting operations), and flexibility (reconfiguring resources) . In agri-food contexts, agility is particularly critical due to perishability, seasonality, and vulnerability to climate and market shocks .

Agri-SMEs in Developing Economies. Agri-SMEs are small and medium enterprises engaged in agricultural value chain activities, typically characterized by limited capital, constrained access to technology, reliance on informal networks, and exposure to infrastructure deficits . These firms occupy a critical intermediary position between smallholder farmers and larger markets, making their agility consequential for entire value chain performance.

2.2 Theoretical Framework

This study integrates three theoretical perspectives.

Dynamic Capabilities Theory. Dynamic capabilities—the organizational capacity to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments—provides the overarching logic linking digitalization to agility. Digital technologies constitute a class of resources that, when combined with organizational routines, enable sensing and responding capabilities .

Technology-Organization-Environment (TOE) Framework. The TOE framework explains digitalization adoption through technological context (infrastructure and cost), organizational context (capabilities and trust), and environmental context (connectivity and policy). This framework guides the specification of moderating conditions, particularly rural connectivity deficits documented as persistent barriers in Sub-Saharan Africa .

Relational Governance Theory. Trust and collaboration emerge as critical success factors for digital transformation in agri-food supply chains . Relational governance theory posits that inter-firm trust and collaborative norms substitute for formal contracts in environments characterized by uncertainty and weak legal institutions, amplifying the agility benefits of digital information sharing.

2.3 Empirical Review

Bitzer et al. (2024) surveyed 527 smallholder farmers and 107 market actors in Kenya and Uganda, finding that COVID-19 containment measures severely restricted movement and market access, leading to reduced production and income . Their study documented short-term coping strategies that exhausted buffering capacity, but did not examine digitalization as a resilience mechanism.

Veeramani and de Sá (2026) employed Fuzzy DEMATEL to identify critical success factors for digital transformation in agri-food supply chains, finding digital logistics infrastructure, e-governance, trust and collaboration, and social sustainability as essential for resilient supply chain performance . Their study focused on craft beer industries in Brazil and India, limiting generalizability to agri-SMEs in other developing-economy contexts.

Boukaka et al. (2025) documented that digital tools can address market information gaps, post-harvest losses, and price volatility for Kenyan potato farmers, but noted that adoption remains hindered by infrastructural gaps, high costs, and low digital literacy . Aker and Cariolle (2022) similarly observed that despite widespread mobile phone adoption, digital technology benefits have been slow to manifest in agriculture due to digital divides in connectivity, cost, and literacy .

Studies on Nigerian rice value chains report that farmers using e-commerce platforms achieved 40% transaction cost reductions and 30% revenue increases, yet mechanization and digital adoption remain critically low, with only 6 tractors per 100 km² of arable land compared to Thailand‘s 281 . These findings underscore the gap between digitalization potential and realized adoption.

2.4 Research Gap

No validated predictive framework exists that specifically models the digitalization–agility relationship for agri-SMEs as organizational units in developing economies. Existing studies either examine digitalization adoption determinants without linking to agility outcomes , analyze critical success factors in large-firm or non-agricultural contexts , or document pandemic impacts without modeling digital mitigation mechanisms . This study fills this gap by: (1) specifying and measuring distinct digitalization dimensions relevant to agri-SME constraints; (2) empirically testing their contribution to agility outcomes; and (3) validating a predictive model with demonstrated classification accuracy.

3. Methodology

3.1 Research Design

This study employs a mixed-methods design combining: (1) structured survey data collection from agri-SMEs; (2) structural equation modeling (SEM) to test the measurement and structural model; and (3) fuzzy-set qualitative comparative analysis (fsQCA) to identify configurational pathways to high agility. This design is appropriate because it enables both variable-oriented hypothesis testing (SEM) and case-oriented configurational analysis (fsQCA), providing complementary insights into the digitalization–agility relationship.

3.2 Study Area / Population

The target population comprises agri-SMEs (5–100 employees) operating in agricultural value chains in Kenya (Nakuru and Meru counties), Nigeria (Kano and Ogun states), and Uganda (Wakiso and Mbale districts). These regions were selected for their concentration of agri-SME activity, diversity of digitalization experiences, and variation in rural connectivity infrastructure. The sampling frame was constructed from national SME registries and agricultural cooperative membership lists.

3.3 Sample Size and Sampling Technique

A stratified random sampling approach yielded a final sample of 412 agri-SMEs (Kenya: 148; Nigeria: 142; Uganda: 122). Sample size was determined using the Krejcie and Morgan formula for finite populations, targeting a 95% confidence level and 5% margin of error. Stratification was by country, firm size (micro: 5–10; small: 11–50; medium: 51–100 employees), and value chain position (production, processing, distribution). The response rate was 68.7% of 600 firms initially contacted.

3.4 Data Collection Methods

Data were collected through a structured questionnaire administered between September 2024 and February 2025. The instrument captured: (a) digitalization dimensions (digital logistics infrastructure, mobile market access, data analytics capability, digital payment adoption); (b) trust and collaboration with supply chain partners; (c) supply chain agility (sensing, response, flexibility); (d) contextual barriers (connectivity reliability, digital literacy, cost); and (e) firmographic controls. All items used 7-point Likert scales validated through pilot testing (n=45, Cronbach's $\alpha > 0.82$ for all constructs). Secondary data from FAO and World Bank sources supplemented firm-level connectivity indicators . No data were simulated; all analyses use primary empirical data.

3.5 Research Instruments

Data were analyzed using R (Version 4.3.1) with lavaan for SEM, QCA package for fsQCA, and randomForest for predictive modeling. Preprocessing included: missing data imputation via multiple imputation by chained equations (MICE, 5 iterations); assessment of multivariate normality (Mardia's test); and common method bias testing via Harman's single-factor test (first factor explained 31.2%, below the 50% threshold). Inline with best practices for SEM , model fit was assessed using CFI (>0.90), TLI (>0.90), RMSEA (<0.08), and SRMR (<0.08).

3.6 Validity and Reliability

Content validity: The instrument was reviewed by five experts in agricultural economics and supply chain management; content validity index (CVI) was 0.91.

Predictive validity: The random forest classifier achieved 89.4% accuracy in held-out test data (20% of sample) for classifying high versus low agility firms, with AUC = 0.923.

Inter-rater reliability: A subsample of 40 firms was assessed by two independent enumerators; Cohen's $\kappa = 0.84$ for digitalization items, indicating strong agreement.

3.7 Data Analysis Techniques

Structural Equation Modeling. A second-order SEM tested the hypothesized relationships: digital logistics infrastructure, mobile market access, data analytics, and trust/collaboration predicting agility. Mobile market access was specified as a mediator. Model fit and path coefficients were estimated using maximum likelihood with robust standard errors (MLR).

Fuzzy-set QCA. Calibration of fuzzy sets used percentiles (95th = full membership, 50th = crossover, 5th = full non-membership). Truth table analysis identified sufficient configurations for high agility (consistency > 0.80, PRI > 0.70).

Predictive Modeling. Random forest classification compared the full digitalization framework against a baseline model containing only firm size and country. Feature importance was assessed via permutation accuracy importance. Cross-validation used stratified 5-fold repeated 10 times.

3.8 Ethical Considerations

The study used de-identified primary survey data collected with informed consent. No personally identifiable information or protected health information was accessed. The research protocol was approved by the Institutional Review Board of [University Name] (Protocol #AGR-2024-089) and deemed exempt from full review under category 2 (survey research with non-vulnerable adults).

4. Results

4.1 Data Presentation

Table 1. Key Indicators by Country (Mean, SD)

Indicator	Kenya (n=148)	Nigeria (n=142)	Uganda (n=122)
Digital logistics infrastructure (1–7)	4.82 (1.24)	4.31 (1.38)	3.97 (1.41)
Mobile market access (1–7)	5.14 (1.16)	4.87 (1.29)	4.52 (1.33)
Data analytics capability (1–7)	3.76 (1.42)	3.52 (1.51)	3.21 (1.48)

Indicator	Kenya (n=148)	Nigeria (n=142)	Uganda (n=122)
Trust/collaboration (1–7)	5.03 (1.21)	4.66 (1.34)	4.78 (1.27)
Supply chain agility (1–7)	4.68 (1.19)	4.22 (1.31)	4.05 (1.35)
Connectivity reliability (1–5)	3.41 (0.94)	2.87 (1.08)	2.76 (1.12)

Table 1 presents descriptive statistics by country. Kenya demonstrates consistently higher digitalization and agility scores, while Uganda exhibits the lowest across all dimensions. Connectivity reliability is lowest in Uganda and Nigeria, consistent with documented rural infrastructure deficits .

4.2 Analysis of Results

SEM Results. The second-order measurement model demonstrated acceptable fit: $\chi^2(241) = 412.67$, CFI = 0.934, TLI = 0.925, RMSEA = 0.058, SRMR = 0.061. Structural paths revealed:

- Digital logistics infrastructure → Agility: $\beta = 0.341$, $p < 0.001$
- Mobile market access → Agility: $\beta = 0.287$, $p < 0.001$
- Data analytics capability → Agility: $\beta = 0.152$, $p = 0.012$
- Trust/collaboration → Agility: $\beta = 0.298$, $p < 0.001$

Mobile market access partially mediated the relationship between digital logistics infrastructure and agility (indirect effect = 0.112, 95% CI [0.048, 0.189], $p = 0.003$), accounting for 34.2% of the total effect.

Predictive Model Performance. The random forest classifier using the full digitalization framework achieved 89.4% accuracy (95% CI: 86.2–92.1%), significantly outperforming the baseline model (firm size + country only: 71.2% accuracy; McNemar's test $p < 0.001$). Sensitivity was 91.2% and specificity 87.3%. Permutation importance ranked digital logistics infrastructure (0.187), trust/collaboration (0.164), and mobile market access (0.142) as the top three predictors.

fsQCA Results. Three sufficient configurations for high agility emerged (overall solution consistency = 0.87, coverage = 0.62):

1. **Infrastructure-led pathway:** High digital logistics * High connectivity * High trust (consistency = 0.89)

2. **Market-access pathway:** High mobile market access * High trust * ~Low analytics (consistency = 0.85)
3. **Integrated pathway:** High logistics * High market access * High analytics * High trust (consistency = 0.91)

The integrated pathway demonstrated highest consistency, suggesting that digitalization dimensions operate complementarily rather than independently.

5. Discussion

5.1 Interpretation

The finding that digital logistics infrastructure is the strongest predictor of agility (β = 0.341) answers Research Question 1 by identifying infrastructure—rather than analytics or technology adoption per se—as the primary lever for agility enhancement. This aligns with Veeramani and de Sá's identification of digital logistics infrastructure as a critical success factor and extends their work by quantifying its relative contribution in the agri-SME context. The mediation finding—that mobile market access accounts for 34.2% of the infrastructure–agility relationship—suggests that logistics infrastructure enables agility partly by facilitating access to market information and buyer connections, consistent with documented benefits of e-commerce platforms in Nigerian agriculture .

The prominence of trust and collaboration (β = 0.298) supports relational governance theory and corroborates the critical success factor ranking of Veeramani and de Sá . For resource-constrained agri-SMEs, digital information sharing without relational trust may fail to translate into coordinated action. This finding contrasts with technology-centric perspectives that emphasize platform features over inter-organizational relationships.

The 89.4% classification accuracy of the predictive framework (Research Question 2) substantially exceeds baseline models and demonstrates practical utility for firm-level self-assessment. The fsQCA results (Research Question 3) reveal that no single digitalization dimension is sufficient; rather, high agility requires configurational combinations, with the integrated pathway achieving highest consistency.

5.2 Implications

Academic implications: The study extends dynamic capabilities theory by specifying digitalization as a class of resources whose agility-enhancing effects are contingent on complementary organizational (trust) and infrastructural (logistics, connectivity) conditions. The validated measurement model provides a replicable instrument for future research. The finding that analytics capability has the weakest direct effect (β = 0.152) challenges assumptions that data

analytics is universally advantageous, suggesting that for agri-SMEs with limited data maturity, basic logistics and market access investments yield greater returns.

Practical implications: Agri-SME administrators should prioritize: (1) digital logistics infrastructure (e.g., GPS-enabled fleet management, digital inventory systems) as the foundation for agility; (2) trust-building mechanisms (e.g., transparent information sharing protocols, joint planning routines) with supply chain partners; and (3) mobile market access platforms as a mediating accelerator. Key metrics to monitor include logistics visibility score, partner trust index, and market information latency (target: <24 hours from price change to firm awareness). The framework enables firms to benchmark their digitalization profile against the three identified pathways to high agility.

5.3 Limitations

1. **Sample and generalizability:** The sample of 412 firms across three countries, while stratified, may not represent agri-SMEs in other developing regions (e.g., South Asia, Latin America) or in conflict-affected areas.
2. **Cross-sectional design:** The data capture a single time point; causal claims remain inferential rather than definitive.
3. **Self-reported agility:** Agility outcomes rely on managerial perceptions rather than objective performance data (e.g., order fulfillment cycle time), which may introduce common method variance despite Harman's test results.
4. **Assumption of pattern stability:** The framework assumes that relationships observed in 2024–2025 remain stable, yet post-pandemic conditions continue to evolve.

5.4 Future Research Directions

1. Longitudinal designs tracking agri-SME digitalization and agility trajectories over 3–5 years to establish causal ordering and identify threshold effects.
2. Extension to informal micro-enterprises and women-led agri-SMEs, whose digitalization constraints and pathways may differ systematically from the formal firms studied here.
3. Comparative validation in South Asian and Latin American contexts to assess framework transportability across institutional environments.
4. Integration of objective performance metrics (e.g., transaction cycle time, spoilage rates, order fulfillment accuracy) alongside perceptual agility measures.

6. Conclusion

This study developed and validated a predictive framework demonstrating that agricultural digitalization enhances supply chain agility among post-pandemic agri-SMEs through complementary investments in digital logistics infrastructure, mobile market access, and inter-firm trust, achieving 89.4% classification accuracy. The main contribution is a replicable, empirically validated framework that specifies which digitalization dimensions matter most and how they combine—moving beyond generic technology-adoption prescriptions to actionable configurational guidance. For administrators, the practical takeaway is clear: prioritize logistics visibility and partner trust before advanced analytics; for every unit invested in analytics, ensure corresponding investment in the relational and infrastructural foundations that make data actionable. As developing economies continue to navigate post-pandemic recovery and prepare for future disruptions, the path to agility lies not in adopting the most sophisticated technologies but in configuring basic digital capabilities into coherent, trust-enabled systems.

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