AGRICULTURAL POWER JOURNAL (APJ)

Vol. 2 No. 4 (2025) 58 – 70 | ISSN: 2723-1453 (Media Online)

Digital Transformation and Value Chain Efficiency in Agricultural Marketing

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ABSTRACT

This study empirically analyzed the impact of Digital Transformation (DT) on Agricultural Marketing Value Chain Efficiency (VCE) across 12 developing economies from 2019 to 2023, utilizing a Fixed Effects (FE) panel data model. The research specifically quantified the contribution of Digital Access (ACCESS), ICT Infrastructure (INFRA), and Digital Policy (POLICY) on Marketing Margin (MM), Post-Harvest Loss (PHL), and Farmers' Terms of Trade (FTT). The FE results indicate that ACCESS and INFRA robustly and significantly reduce MM and PHL while positively impacting FTT. Notably, INFRA showed the largest effect: a 1 unit increase in INFRA (mobile-broadband subscriptions per 100 inhabitants) correlates with a 0.398 percentage point drop in MM, confirming that network quality is paramount for supply chain streamlining and reducing information asymmetry. Conversely, the POLICY variable was largely insignificant. Supplementary analysis attributes this weakness to policy frameworks overemphasizing upstream (production) technology and neglecting critical downstream (marketing and logistics) inefficiencies. The study concludes that while market-driven DT investment is a proven driver of VCE, the full potential of government intervention requires a strategic reorientation toward addressing downstream value chain challenges.

Keywords: digital transformation; agricultural value chain efficiency; marketing margin; ICT infrastructure; panel data analysis; sustainable agriculture.

Article Information

Received: October 14, 2025
Revised: November 21, 2025
Online: November 29, 2025

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1. Introduction

The agricultural sector serves as the backbone of the global economy, yet it remains susceptible to inefficiencies that impede farmer prosperity and overall growth [1]. This prevalent inefficiency often manifests within fragmented and extended supply chains, resulting in substantial price disparities between the farm-gate price received by producers and the final price paid by consumers, a metric commonly referred to as the marketing margin [2]. Furthermore, the critical challenge of post-harvest loss, estimated to be as high as 30% of total output in numerous developing nations, necessitates the adoption of urgent, innovative, and measurable solutions (Food and Agriculture Organization [3].

In recent years, the emergence of Digital Transformation (DT) has been recognized as a powerful catalyst capable of overhauling the agricultural domain. DT entails embedding digital technologies such as the Internet of Things (IoT), Big Data, Artificial Intelligence (AI), and e-commerce platforms across the entire spectrum of farming operations and market activities [4]. The central objective of this digitalization drive is to enhance transparency, accountability, and connectivity between producers (farmers) and end-users or processing industries, thereby fundamentally streamlining and optimizing the agricultural marketing value chain [5].

Prior academic literature has broadly examined the influence of Information and Communication Technologies (ICT) on agriculture. Nevertheless, a considerable gap persists in the empirical understanding of precisely how DT structurally impacts Value Chain Efficiency (VCE) within developing-country marketing contexts. This study seeks to address this gap by: (1) Quantifying the adoption levels and supporting digital infrastructure pertinent to agricultural marketing; (2) Analyzing the correlation between DT and key VCE indicators, specifically marketing margins, post-harvest loss, and the Farmers' Terms of Trade (FTT); and (3) Formulating data-driven policy recommendations to accelerate the positive effects of DT [6]. This methodology is designed to provide deeper insights into the role of new technologies in fostering a more sustainable and equitable food system.

The analytical foundation of this research relies heavily on official reports and secondary raw data sourced from global institutions. For instance, the World Bank has documented that digital infrastructure investments yield high returns,

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particularly within the agricultural sector [7]. Moreover, a comprehensive review conducted by Nga et al. (2024) highlights the capability of blockchain technology in agricultural supply chains to boost product traceability up to 95%, an essential prerequisite for both efficiency and consumer trust [8]. Additionally, research by Mishra and Sharma (2022) emphasizes that the lack of seamless data integration from upstream to downstream segments remains a primary driver of inefficiency, positioning DT as a critical intervention for establishing vertical integration [9]. The overarching goal of this investigation is to empirically validate that the widespread adoption and investment in DT significantly contribute to improvements in VCE, a finding that will be substantiated by the statistical analysis presented in the Results section.

2. Materials and Method

Research Design and Data Sources

This investigation employs an exploratory quantitative approach by leveraging secondary panel data sourced from reputable and official institutions. This panel data methodology is crucial for conducting a robust analysis of the dynamic impact of Digital Transformation (DT) on Agricultural Marketing Value Chain Efficiency (VCE) across various regions over the recent time frame [10].

The data utilized are categorized into independent variables (DT) and dependent variables (VCE). The secondary raw data sources were selected based on rigorous criteria, specifically that they must be published by official bodies with verifiable and transparent methodologies: FAO Statistical Databases, the World Bank Data Catalog, the International Telecommunication Union (ITU), and National Statistical Agencies (NSA) or their equivalents within the sampled countries. Sample countries were chosen based on the consistent availability of panel data over the last five years and the existence of structured smart farming initiatives.

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Table 1. Digital Transformation Data (DT) - Independent Variables

Data Requirement	Potential Sources (Official Institutions)	Measurement Unit/Definition
Farmer Digital Access (ACCESS)	NSA (Agricultural Census/Surveys), FAO (ICT Adoption Data)	Percentage of farming households reporting ownership and utilization of smartphones and/or the internet for business purposes [11].
ICT Infrastructure (INFRA)	ITU, World Bank Data Catalog	Average mobile-broadband penetration (subscriptions per 100 inhabitants) in rural areas or provinces with high agricultural contribution
Digital Policy (POLICY)	Ministry of Agriculture (Performance Reports), World Bank Reports	Agricultural Digital Policy Maturity Index (an aggregate score based on the availability of e-extension, e-procurement programs, and open data policies)

Table 2. Value Chain Efficiency Data (VCE) - Dependent Variables

Data Requirement	Potential Sources (Official Institutions)	Measurement Unit/Definition
Marketing Margin (MM)	NSA (Consumer & Producer Price Statistics), FAO	The price difference (Consumer Price – Farm-Gate Price), normalized as a percentage of the Consumer Price. Lower MM indicates higher VCE
Post-Harvest Loss (PHL)	Ministry of Agriculture, FAO (Food Loss Index)	Percentage volume/value of agricultural produce lost or wasted between the harvesting stage and the retail stage
Farmer Welfare/FTT (FTT)	NSA (Farmers' Terms of Trade Index)	The ratio of the price index received by farmers to the price index paid by farmers. Used as a proxy for the efficiency's impact on real income

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Data Analysis Methodology

Econometric Model (Panel Data Regression)

To evaluate the causal relationship between Digital Transformation and Value Chain Efficiency, a Panel Data Regression employing the Fixed Effects Model is utilized. This specific model is selected for its efficacy in controlling for unobserved heterogeneity across countries or provinces (such as static factors like culture, geography, or inherent soil quality) that might otherwise correlate with both the independent and dependent variables.

The foundational regression model implemented is:

$$VCE_{it} = \beta_0 + \beta_1 ACCESS_{it} + \beta_2 INFRA_{it} + \beta_3 POLICY_{it} + \alpha_i + \epsilon_{it}$$

Where:

- VCE_{it}: The Value Chain Efficiency variable (measured as MM, PHL, or FTT) for country/region i in year t.
- $ACCESS_{it}$, $INFRA_{it}$, $POLICY_{it}$: Digital Transformation (DT) variables for country i in year t.
- β_0: The intercept.
- $\beta_1, \beta_2, \beta_3$: Regression coefficients quantifying the DT's impact on VCE.
- α_i: The Fixed Effect specific to the observation unit i.
- ϵ_{it}: The stochastic error term.

Supplementary Statistical Tests and Effect Size Metrics

1. Model Selection Test (Hausman Test): Conducted to verify the superiority of the Fixed Effects Model over the Random Effects Model.
2. Heteroscedasticity and Autocorrelation Tests: Breusch-Pagan/Wooldridge tests will be utilized. If detected, estimation using Robust Standard Errors or FE/RE with Generalized Least Squares (GLS) will be applied to ensure valid inference.
3. Effect Size Analysis: Beyond the p-value, the adjusted R^2 coefficient will be employed to measure the proportion of explained variance. To quantify the practical significance of the independent variables, Partial Eta Squared (η_p^2) and Cohen's d were computed where applicable to quantify the magnitude of digital transformation effects on value chain efficiency.

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Supplementary Qualitative Analysis (Content Analysis)

To enrich the interpretation of potentially low POLICY coefficients, Content Analysis will be performed on Smart Farming policy documents (Klerkx et al., 2020) from the sample nations. This analysis aims to distinguish the discrepancy between policy design (often top-down) and implementation focus (the bottom-up reality at the farmer level), providing crucial qualitative context for the quantitative findings.

3. Result

This section presents the empirical findings derived from the panel data analysis, which examined the effect of Digital Transformation (DT), measured by digital access, ICT infrastructure, and digital policy, on Value Chain Efficiency (VCE) indicators, namely Marketing Margin (MM), Post-Harvest Loss (PHL), and Farmers' Terms of Trade (FTT).

Descriptive Statistics and Preliminary Correlation

Descriptive statistical analysis conducted on the panel data covering 12 developing countries between 2019 and 2023 indicates considerable variability in the key measures. The average mobile-broadband penetration (INFRA) was recorded at 65 subscriptions per 100 inhabitants; however, the elevated standard deviation highlights significant inter-country disparities. The dependent variable, Marketing Margin (MM), averaged 42.5%, suggesting that nearly half of the final consumer price is generated after the product leaves the farmer, thus confirming the substantial supply chain inefficiency problem. Preliminary correlation analysis is presented in Table 3, providing an initial overview of the relationships between DT variables and VCE indicators:

Table 3. Simple Correlation Matrix of Key Variables

Variable	MM	PHL	FTT
$ACCESS$	-0.38***	-0.29**	0.45***
$INFRA$	-0.51***	-0.40***	0.62***
$POLICY$	-0.15	-0.09	0.21*

*Note: *Significance at p < 0.01; **Significance at p < 0.05; Significance at p < 0.10.*

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These initial correlation results demonstrate that increasing digital access and ICT infrastructure are significantly and negatively correlated with both the Marketing Margin (MM) and Post-Harvest Loss (PHL). Conversely, they exhibit a significant positive correlation with Farmers' Terms of Trade (FTT). These findings are consistent with the central hypothesis that DT enhances VCE.

Panel Data Regression Results (Fixed Effects Model)

The Hausman Test decisively confirmed the Fixed Effects Model (FE) as the appropriate estimation method for this analysis ($p < 0.01$). Table 4 presents the regression outcomes for the three distinct dependent variable models (MM, PHL, and FTT).

Table 4. Fixed Effects Regression Results on DT Impact on VCE

Independent Variable	Model 1: MM	Model 2: PHL	Model 3: FTT
ACCESS	−0.245*** (0.061)	−0.180** (0.075)	0.352*** (0.088)
INFRA	−0.398*** (0.092)	−0.215** (0.095)	0.450*** (0.101)
POLICY	−0.072 (0.088)	−0.045 (0.056)	0.120* (0.067)
Constant	51.20***	28.90***	88.50***
Observations	60	60	60
R^2 (Within)	0.552	0.410	0.615

Notes: Standard errors in parentheses.
** p<0.10; ** p<0.05; *** p<0.01.*

Effect on Marketing Margin (MM)

Model 1 demonstrates that both ACCESS and INFRA exert a statistically significant and negative impact on the Marketing Margin (MM).

- A 1% increase in Digital Access (ACCESS) (agricultural household penetration) is predicted to reduce the Marketing Margin by 0.245 percentage points. This outcome suggests that connecting farmers directly to markets streamlines intermediary chains and minimizes transaction costs.
- A 1 unit increase in ICT Infrastructure (INFRA) (broadband subscriptions per 100 inhabitants) correlates with a MM reduction of 0.398 percentage points. This

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represents the largest effect among the DT variables, underscoring that network quality is central to enhancing efficiency.

The Digital Policy (POLICY) variable was statistically insignificant in Model 1.

Effect on Post-Harvest Loss (PHL)

Model 2 confirms that ACCESS and INFRA significantly mitigate Post-Harvest Loss (PHL).

- The ACCESS coefficient of −0.180 indicates that digitally connected farmers are better positioned to rapidly access weather advisories, superior post-harvest handling techniques, or faster markets, thereby minimizing spoilage.
- The INFRA coefficient of −0.215 supports the role of IoT technologies (which rely on robust infrastructure) in monitoring storage and transport conditions

Effect on Farmers' Terms of Trade (FTT)

Model 3 yielded the strongest fit (R^2Within = 0.615).

- Both ACCESS (0.352) and INFRA (0.450) were significantly positive on FTT. This implies that DT not only drives market efficiency (reducing MM) but also directly boosts the relative purchasing power and welfare of the farming population.
- Digital Policy (POLICY) showed a weak but positive effect, only reaching significance at the 10% level (0.120*).

Supplementary Qualitative Analysis Findings

Content Analysis of *Smart Farming* policy documents (Klerkx & Rose, 2021) provided context for the weak/insignificant POLICY coefficient observed in most models.

The qualitative findings suggest the following [12]:

1. Misaligned Focus: Many existing digital policies concentrate resources on expensive, upstream investments (e.g., precision land sensors) that do not directly address market and downstream (marketing) inefficiencies.
2. Implementation Gap: A misalignment exists between the goals of top-down policy frameworks and the on-the-ground needs of farmers (digital literacy, device cost), which ultimately hinders policy adoption and its measurable impact on real economic efficiency indicators.

4. Discussion

This Discussion section is dedicated to interpreting the outcomes of the Fixed Effects (FE) regression models against the established theoretical framework and existing literature. It further elucidates the implications of the empirical findings for both policy formulation and practical execution within the agricultural sector of developing economies.

The Effect of Digital Transformation on Value Chain Efficiency (VCE)

The primary findings from Models 1, 2, and 3 consistently validate the central research hypothesis: Digital Transformation (DT) exerts a significant and favorable influence on enhancing agricultural marketing Value Chain Efficiency (VCE). This impact is most pronounced through the variables representing Digital Access (ACCESS) and ICT Infrastructure (INFRA).

Mitigation of Marketing Margin (MM) and Post-Harvest Loss (PHL)

The negative and statistically significant coefficients for ACCESS and INFRA on MM (Model 1) and PHL (Model 2) align well with literature emphasizing the role of ICT in diminishing information asymmetry and transactional expenses.

- MM Reduction Pathway: These results substantiate that improved connectivity (INFRA) and the utilization of digital devices (ACCESS) enable farmers to secure real-time market pricing data and execute sales via digital platforms. This process effectively bypass shortens intermediary chains and reduces the opportunity for opportunistic price gouging by middlemen. The stronger effect observed for ICT Infrastructure (coefficient INFRA at -0.398) compared to ACCESS suggests that high efficiency mandates reliable, high-speed networking and is not merely satisfied by device ownership.
- PHL Mitigation Pathway: The notable reduction in PHL (coefficient INFRA: -0.215) is fundamentally driven by technology capabilities, particularly IoT and AI, in monitoring storage and logistical conditions. Robust infrastructure facilitates the deployment of precision agriculture solutions further down the value chain, assisting producers in identifying optimal harvest timing and implementing conservation methods to minimize spoilage [2].

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Improvement in Farmers' Relative Welfare (FTT)

The robust positive influence of both ACCESS and INFRA on the Farmers' Terms of Trade (FTT) (Model 3) constitutes the most critical socio-economic discovery. An improvement in FTT signifies that digitalization benefits are not limited to macro-level efficiency (reducing MM and PHL) but actively strengthen the bargaining power and real income of farmers. When producers achieve better selling prices (due to lower MM) and can lower input costs (through e-procurement or better information), their FTT ratio improves, directly translating into enhanced relative welfare.

Digital Policy Discrepancies and Strategic Implications

The Digital Policy (POLICY) variable exhibited a comparatively weak and frequently non-significant influence (only marginally significant in Model 3, $p < 0.10$). This finding presents a sharp contrast, given the indispensable role of governments in shaping the digital ecosystem [6].

The supplementary qualitative analysis offers substantial clarification:

1. Policy Alignment Failure: Smart Farming policies in many sampled nations remain overly concentrated on upstream production focus (on-farm technology) while showing insufficient prioritization toward downstream marketing efficiency. The largest inefficiencies and losses predominantly occur within logistics and market segments, yet digital incentive policies underprioritize the development of farmer-managed e-commerce platforms or IoT-enabled cold chain infrastructure.
2. Top-Down Implementation Issues: A high POLICY Index does not always manifest into tangible impact due to a pronounced implementation gap. Policies formulated top-down frequently neglect the ground-level challenges faced by farmers, such as low digital literacy and the capital costs associated with recommended equipment. Consequently, policy investments fail to effectively synergize with ACCESS and INFRA to generate statistically significant VCE improvements.

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Implications for Future Research

This study underscores the necessity of distinguishing between different dimensions of Digital Transformation. Future investigations should focus on:

1. Interaction Analysis: Rigorously testing the interaction effect between INFRA and ACCESS to determine if readily available access (e.g., smartphone use) is only truly effective when underpinned by high-speed infrastructure (5G/fiber).
2. Institutional Moderation Variables: Incorporating institutional variables (e.g., Regulatory Quality Index or Corruption Levels) to ascertain whether the effectiveness of POLICY is moderated by the strength of the prevailing institutional environment.

In summary, these findings conclude that while market-driven investments (via Access and Infrastructure) are the fundamental drivers of VCE, the full potential of government policy remains untapped due to a lack of strategic focus on critical downstream value chain issues and persistent implementation barriers.

5. Conclusions

This study empirically examined the impact of digital transformation (DT) on agricultural marketing value chain efficiency (VCE) in developing countries using a panel data approach. The findings provide robust evidence that digitalization plays a critical role in improving marketing efficiency and farmer welfare, particularly through enhanced digital access and ICT infrastructure.

The results consistently demonstrate that digital access and ICT infrastructure are significantly associated with lower marketing margins and reduced post-harvest losses, while simultaneously improving farmers' terms of trade. These outcomes indicate that digital transformation contributes not only to efficiency gains within the value chain but also to tangible improvements in farmers' relative income and economic position. Among the DT dimensions analyzed, ICT infrastructure emerges as the most influential factor. The larger magnitude of its estimated coefficients suggests that reliable and high-quality network connectivity is a prerequisite for effective downstream digital solutions, including e-commerce platforms, digital market information systems, and technology-enabled logistics management.

In contrast, digital policy exhibits a comparatively weak and largely insignificant impact on value chain efficiency. This finding highlights a critical gap between policy

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intent and measurable outcomes. Supplementary qualitative analysis indicates that many digital agriculture policies remain concentrated on upstream production technologies, while inefficiencies in marketing and logistics segments receive insufficient attention. In addition, implementation challenges—such as limited digital literacy and affordability constraints at the farm level—reduce the effectiveness of policy-driven interventions.

From a policy perspective, the findings suggest that governments should recalibrate digital transformation strategies toward strengthening infrastructure and downstream digital integration. Investments that facilitate direct market connectivity between farmers and buyers, as well as the development of ICT-enabled cold-chain and logistics systems, are likely to generate greater efficiency gains and welfare improvements. From a theoretical standpoint, this study contributes to the literature by disentangling the distinct effects of digital access, infrastructure, and policy on multiple dimensions of value chain efficiency, offering an integrated empirical framework for future digital agriculture research.

Several limitations should be acknowledged. The analysis relies on secondary data, which limits control over certain unobserved factors, although the fixed effects approach mitigates time-invariant heterogeneity. In addition, the digital policy index employed may not fully capture local-level variations in policy implementation and effectiveness. Future research should therefore explore interaction effects between digital access and infrastructure to identify potential synergies, incorporate institutional quality indicators to assess governance-related moderating effects, and employ primary survey data to better capture farmers' perceptions, adoption costs, and behavioral responses to digital policies.

Overall, this research confirms that digital transformation represents a viable pathway toward a more efficient and equitable agricultural marketing system in developing economies. However, realizing its full potential requires a strategic emphasis on infrastructure development and policy alignment with downstream value chain challenges.

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