International Journal of Economics, Management and Social Science
Vol 9 No 1 March 2026
E-ISSN: 2614-3828 | P-ISSN: 2614-3887
Open Access: https://journal.salewangang.net/ijemss/index

The Effect of Agricultural Supply Chain Digitalization on Food Commodity Marketing Efficiency in the Era of the Industrial Revolution 4.0

Sahrul Salam[1]*, Rizki Abdillah Tanjung[2], Nurlaela[3], Astina[4]
[1234]Universitas Sulawesi Barat, Majene, West Sulawesi, Indonesia
*Correspondence:[1] sahrulsalam@unsulbar.ac.id,[2] rizki.abdillah@unsulbar.ac.id,[3] nurlaelaunsulbar@gmail.com, [4]astina@unsulbar.ac.id

Article Info :
Received:
20/02/2026
Revised:
22/02/2026
Accepted:
25/02/2026

ABSTRACT

The rapid diffusion of digital technologies in agriculture—including precision farming platforms, blockchain-enabled traceability systems, e-commerce marketplaces, and IoT-based logistics—presents transformative opportunities for reforming the inefficient, multi-intermediary supply chains that have historically suppressed farmer incomes and inflated consumer prices across Indonesian food commodity markets. This study investigates the effect of agricultural supply chain digitalization on marketing efficiency for key food commodities in West Sulawesi Province, employing a sequential explanatory mixed-methods design. Quantitative data were collected from 312 farmers, 48 agricultural cooperatives, and 86 agribusiness intermediaries across five districts, analyzed using structural equation modeling and marketing efficiency ratio analysis. Qualitative data from 36 key informant interviews elaborated the mechanisms and barriers of digital adoption. Results demonstrate that supply chain digitalization significantly improves marketing efficiency ($\beta = 0.541$, $p < 0.001$), reduces marketing margins by an average of 18.7 percentage points, and increases farmer price-received-to-retail-price ratios from 0.38 to 0.57. IoT-based logistics coordination and digital marketplace platforms demonstrate the strongest individual effects on efficiency outcomes. Barriers including limited digital infrastructure, low digital literacy, and inadequate financial inclusion constrain adoption particularly among smallholder farmers in remote areas. The study contributes a context-specific model of agricultural supply chain digitalization for developing economy settings and recommends targeted policy interventions to accelerate equitable digital transformation in the Indonesian agricultural sector.

Keywords: agricultural supply chain; digitalization; marketing efficiency; Industry 4.0; food commodities; Indonesia; West Sulawesi; blockchain; precision agriculture

1. INTRODUCTION

Agriculture remains the backbone of Indonesia's rural economy, employing approximately 27.3% of the national workforce and contributing 13.7% of GDP as of 2023 (BPS, 2023). Yet Indonesian agricultural supply chains are characterized by deep-seated structural inefficiencies: long multi-tier intermediary chains, inadequate cold-chain logistics, poor price transparency, and limited market information access for smallholder farmers result in farmer income shares of retail price that routinely fall below 40% for major food commodities (Natawidjaja et al., 2021; Sanjaya &

Kusumastuti, 2022). These inefficiencies constitute a persistent barrier to agricultural productivity growth, rural poverty reduction, and national food security.

The Industrial Revolution 4.0 (IR 4.0), characterized by the convergence of digital, physical, and biological systems through technologies including the Internet of Things (IoT), artificial intelligence (AI), blockchain, big data analytics, and cloud computing, is progressively reshaping global agricultural value chains (Schwab, 2016; Klerkx et al., 2019). Digital agricultural platforms can reduce transaction costs, enhance price transparency, enable direct farmer-to-consumer connections, improve logistics coordination, and generate real-time market intelligence that empowers smallholder decision-making (Kamilaris et al., 2019; Verdouw et al., 2021).

The Indonesian government has recognized the transformative potential of agricultural digitalization through multiple policy initiatives, including the Digital Agriculture 4.0 roadmap, the SIMOHTAN agricultural information system, and the Kartu Tani digital farmer identity program (Kementan RI, 2022). However, implementation remains uneven across regions, and the empirical evidence base for the effects of specific digital interventions on marketing efficiency outcomes in Indonesian agricultural supply chains remains fragmented and geographically concentrated in Java.

West Sulawesi Province presents a theoretically productive context for this investigation. As one of Indonesia's younger provinces (established 2004), West Sulawesi combines significant agricultural potential—including major production of cocoa, shallots, corn, and rice—with substantial infrastructure deficits and comparatively low digital adoption rates. The province thus represents conditions typical of many agricultural frontiers in Eastern Indonesia where digitalization potential is highest but adoption barriers are most formidable (Wahyuni & Ginting, 2023).

This study addresses the following research questions: (1) What is the current state of supply chain digitalization adoption among agricultural actors in West Sulawesi? (2) To what extent does supply chain digitalization affect marketing efficiency for major food commodities? (3) Which specific digital technology components exert the strongest effects on efficiency outcomes? (4) What structural, institutional, and behavioral barriers constrain digital adoption among smallholder farmers? The answers to these questions contribute both to the academic literature on digital agricultural transformation and to practical policy design for accelerating equitable digitalization in Indonesian agriculture.

Table 1. Study Area Profile and Key Food Commodities Investigated by District

District	Area (km²)	Farmer Households	Main Commodities	Sample (n)
Polewali Mandar	2,022.30	58,420	Rice, corn, shallots	74
Majene	947.84	21,340	Cocoa, rice, vegetables	58
Mamuju	4,954.58	44,180	Cocoa, palm oil, corn	68
Mamuju Tengah	3,014.40	31,250	Cocoa, rice, cassava	62

Mamuju Utara	3,043.75	27,680	Palm oil, corn, cocoa	50
Total	**13,982.87**	**182,870**	**5 commodity groups**	**312**

Source: BPS West Sulawesi Province (2023) and field survey data, 2024.

2. LITERATURE REVIEW

2.1 Agricultural Supply Chain Structure and Marketing Inefficiency

Agricultural supply chains in developing countries typically involve multiple layers of intermediaries between farm gate and final consumer: collectors (pengepul), sub-district traders, district traders, wholesalers, processors, and retailers. Each intermediary layer captures a margin, collectively resulting in large price spreads between farm gate and retail prices (Natawidjaja et al., 2021). In Indonesian rice markets, for example, studies have documented farm gate-to-retail price ratios as low as 0.35–0.42, implying that farmers receive less than half the final consumer price (Suryana et al., 2020).

Marketing efficiency, in the agricultural economics literature, is conventionally assessed through two complementary metrics: operational efficiency (the ratio of marketing costs to marketing margins) and pricing efficiency (the degree to which price signals are transmitted accurately and rapidly along the supply chain) (Shepherd, 1997; Tomek & Kaiser, 2014). High marketing margins, low farmer price shares, and sluggish spatial price integration are all indicators of marketing inefficiency, with multiple documented causes including market power concentration among intermediaries, inadequate price information, high transaction costs, and poor logistics infrastructure.

2.2 Digital Technologies in Agricultural Supply Chains: A Taxonomy

IR 4.0 technologies are being applied across the full spectrum of agricultural supply chain functions. Verdouw et al. (2021) propose a taxonomy of agricultural digitalization organized around four functional domains: production intelligence (precision agriculture, crop monitoring, yield prediction); logistics coordination (IoT-based tracking, cold chain management, route optimization); market connectivity (e-commerce platforms, price information systems, contract farming apps); and supply chain governance (blockchain traceability, smart contracts, digital certification).

Blockchain technology has attracted particular attention for its potential to create tamper-proof, transparent records of transactions and product movements across supply chains, enabling traceability from farm to fork while simultaneously creating auditable records for certification, quality assurance, and financial transactions (Ge et al., 2017; Tripoli & Schmidhuber, 2018). Pilot implementations in rice, cocoa, and coffee supply chains in Southeast Asia have demonstrated improvements in quality verification, reduction in fraud, and enhanced premium price access for certified smallholders (Kowalczyk & Rotter, 2016; Saberi et al., 2019).

Digital marketplace platforms—including government-sponsored applications like TaniHub (Indonesia), and commercial platforms like Grab Kios and Sayur Box—create direct digital channels connecting farmers or aggregators with buyers, bypassing traditional intermediary layers. Evidence from studies in Java and Sumatra suggests that farmers accessing digital marketplace platforms receive price premiums of 15–35% above traditional channel prices, though access requires digital literacy, smartphone ownership, and reliable internet connectivity that remain significant barriers for many smallholders (Wardhana et al., 2022).

2.3 Theoretical Framework: Transaction Cost Economics and Network Theory

This study draws on two complementary theoretical frameworks. Transaction cost economics (TCE), as developed by Coase (1937) and Williamson (1985), provides a framework for understanding how digital technologies reduce the three primary categories of transaction costs in agricultural markets: search and information costs (reduced by price information platforms and digital market intelligence), negotiation and contracting costs (reduced by digital contract platforms and e-payment systems), and monitoring and enforcement costs (reduced by blockchain traceability and IoT-based quality monitoring). TCE predicts that technology-driven reductions in transaction costs will reduce the comparative advantage of intermediaries, enabling disintermediation or intermediary upgrading that shifts more of the consumer price to the farmer.

Network theory, particularly the concept of network externalities (Katz & Shapiro, 1985), adds a dynamic dimension to this analysis. Digital agricultural platforms exhibit strong network externalities: the value of a platform to any individual user increases with the number of other users. This creates adoption dynamics in which early digitalization may deliver limited benefits but benefits grow rapidly once adoption crosses a threshold. For West Sulawesi's fragmented smallholder landscape, this implies that targeted platform seeding in specific communities or commodity clusters may be necessary to catalyze the self-reinforcing adoption dynamics that generate substantial efficiency gains.

3. METHODOLOGY

3.1 Research Design

A sequential explanatory mixed-methods design (Creswell & Plano Clark, 2017) was employed, in which quantitative survey data were collected and analyzed first, with qualitative interview data subsequently collected to elaborate and explain quantitative findings. This sequence was chosen because the primary research questions concern measurable effects of digitalization on marketing efficiency, with qualitative data serving to illuminate the mechanisms and contextual conditions underlying the quantitative patterns.

3.2 Quantitative Data Collection

The quantitative survey was administered to three populations: (1) 312 smallholder farmers across five districts, selected through proportional stratified random sampling with strata defined by district and commodity group; (2) 48 agricultural cooperatives (koperasi tani), selected through complete enumeration of all registered cooperatives in the study area; and (3) 86 agribusiness intermediaries (traders, collectors, and processors) selected through snowball sampling from farmer networks. Survey instruments measured: Supply Chain Digitalization Index (SCDI, 24 items, α = 0.893); Marketing Efficiency Indicators (farm gate/retail price ratios, marketing margins, and marketing costs, collected through price chain surveys); Digital Adoption Barriers Scale (DABS, 18 items, α = 0.871); and organizational and farm characteristics.

3.3 Marketing Efficiency Analysis

Marketing efficiency was measured using three complementary indicators: the Farmer's Share (FS) of retail price, calculated as the ratio of farm gate price to retail price multiplied by 100; the Marketing Margin Ratio (MMR), calculated as total marketing margin divided by retail price; and the Marketing Efficiency Ratio (MER), calculated as the value of goods sold divided by total marketing costs (Shepherd, 1997). Price data were collected through weekly price surveys at farm gate, district market, and retail levels over a 12-month period (January–December 2024) for five representative commodities: rice, corn, shallots, cocoa, and cassava.

3.4 Quantitative Analysis

Structural equation modeling (SEM) using AMOS 26 was employed to test the hypothesized relationships between supply chain digitalization components, marketing efficiency, and moderating variables. The measurement model was validated through confirmatory factor analysis (CFA). Path analysis examined direct, indirect, and total effects of digitalization on efficiency outcomes. Mediation analysis tested whether transaction cost reduction mediated the digitalization-efficiency relationship. Group comparisons by commodity type, farm size, and digital adoption level employed one-way ANOVA and independent samples t-tests.

3.5 Qualitative Data Collection and Analysis

Semi-structured interviews were conducted with 36 key informants: 18 farmers (6 high-adopters, 6 medium-adopters, 6 non-adopters), 8 cooperative managers, 6 agricultural extension workers, and 4 local government agricultural officials. Interviews were conducted in Bahasa Indonesia and local languages with research assistant interpretation where needed, audio-recorded with consent, and transcribed verbatim. Thematic analysis (Braun & Clarke, 2006) using NVivo 12 generated themes related to digitalization experiences, adoption barriers, and perceived efficiency outcomes.

Table 2. Descriptive Statistics for Key Study Variables (Farmer Sample, N = 312)

Variable	Mean	SD	Min	Max	Interpretation
Supply Chain Digitalization Index (1–5)	2.71	0.84	1.00	4.90	Low-moderate adoption

Digital Marketplace Use (1–5)	2.34	0.91	1.00	5.00	Low adoption
IoT Logistics Coordination (1–5)	2.18	0.88	1.00	4.80	Low adoption
Blockchain Traceability (1–5)	1.87	0.79	1.00	4.60	Very low adoption
Price Information Access (1–5)	3.12	0.94	1.00	5.00	Moderate
Farmer's Share (% of retail price)	42.3%	8.7%	22.1%	68.4%	Below benchmark (50%)
Marketing Margin Ratio (%)	57.7%	8.7%	31.6%	77.9%	High margin
Marketing Efficiency Ratio	3.84	1.12	1.41	7.38	Moderate efficiency
Digital Adoption Barriers (1–5)	3.68	0.71	1.40	5.00	Moderate-high barriers

Source: Field survey data, 2024. SD = Standard Deviation.

4. RESULTS

4.1 Current State of Supply Chain Digitalization in West Sulawesi Agriculture

The mean Supply Chain Digitalization Index score of 2.71 (SD = 0.84) on a five-point scale indicates low-to-moderate overall digitalization penetration in West Sulawesi agricultural supply chains. Significant variation was observed across technology components: price information access (M = 3.12) was the most widely adopted digital function, reflecting the diffusion of WhatsApp-based price dissemination networks among farmer groups. Digital marketplace platform use (M = 2.34) and IoT logistics coordination (M = 2.18) showed moderate-low adoption, while blockchain traceability applications demonstrated the lowest penetration (M = 1.87), consistent with their recent introduction and greater technical complexity.

Significant district-level variation in digitalization was observed ($F(4,307) = 14.82$, $p < 0.001$). Polewali Mandar district exhibited the highest SCDI score (M = 3.18), reflecting its greater infrastructure development and larger cooperative sector. Mamuju Utara demonstrated the lowest digitalization (M = 2.21), consistent with its more remote location and limited telecommunications infrastructure. Commodity-level variation was also significant: cocoa supply chains exhibited the highest digitalization (M = 3.04), driven by international certification requirements and buyer-led traceability investments; cassava supply chains exhibited the lowest (M = 2.19).

4.2 Effect of Digitalization on Marketing Efficiency

SEM analysis confirmed a strong, statistically significant direct effect of supply chain digitalization on marketing efficiency ($\beta = 0.541$, $p < 0.001$). The model explains 52.7% of variance in marketing efficiency outcomes ($R^2 = 0.527$) and demonstrates good fit (CFI = 0.952, RMSEA = 0.054, SRMR = 0.061). Transaction cost reduction fully mediated 38.4% of the total digitalization-efficiency effect (indirect effect $\beta = 0.208$, $p < 0.001$), with the remaining 61.6% constituting direct efficiency improvements through logistics optimization and market access enhancement.

Commodity-stratified analysis revealed differential effects: digitalization effects on marketing efficiency were strongest for shallots ($\beta = 0.623$) and cocoa ($\beta = 0.598$), reflecting these commodities' higher price volatility, quality differentiation potential, and existing buyer-led digitalization investments. Effects were comparatively weaker for rice (β = 0.412) and cassava (β = 0.387), commodities subject to government price stabilization policies that constrain the efficiency gains achievable through market mechanism improvements.

4.3 Effects on Farmer's Share and Marketing Margins

Comparing high-digitalization (SCDI ≥ 3.5) and low-digitalization (SCDI < 2.5) farmer groups revealed substantial marketing efficiency differences. High-digitalization farmers achieved an average Farmer's Share of 57.2% of retail price, compared to 38.5% for low-digitalization farmers—a gap of 18.7 percentage points representing a substantial income transfer from intermediaries to producers. Marketing Margin Ratios were correspondingly lower in high-digitalization supply chains (42.8% vs. 61.5%). These differences were statistically significant across all commodities (all $p < 0.001$) and robust to controls for farm size, cooperative membership, and district.

Table 3. Marketing Efficiency Indicators by Digitalization Level and Commodity

Commodity	FS Low (%)	FS High (%)	ΔFS (pp)	MMR Low (%)	MMR High (%)	MER Low	MER High
Rice	39.4	54.8	+15.4**	60.6	45.2	3.21	4.87
Corn	36.8	55.4	+18.6**	63.2	44.6	2.98	4.94
Shallots	35.2	61.4	+26.2**	64.8	38.6	2.74	5.62
Cocoa	41.7	62.3	+20.6**	58.3	37.7	3.47	5.81
Cassava	39.4	52.1	+12.7**	60.6	47.9	3.12	4.38
Average	**38.5**	**57.2**	**+18.7****	**61.5**	**42.8**	**3.10**	**5.12**

Note: FS = Farmer's Share; MMR = Marketing Margin Ratio; MER = Marketing Efficiency Ratio; pp = percentage points; Low = SCDI < 2.5 (n=112); High = SCDI ≥ 3.5 (n=89). ** $p < 0.001$ (independent samples t-test).

Source: Price chain survey and digitalization index data, 2024.

4.4 SEM Path Coefficients and Technology Component Effects

Among the four digitalization technology components, IoT-based logistics coordination demonstrated the strongest effect on marketing efficiency (β = 0.487, $p < 0.001$), followed by digital marketplace platforms (β = 0.421, $p < 0.001$), price information systems (β = 0.318, $p < 0.001$), and blockchain traceability (β = 0.274, p = .002). The relatively smaller effect of blockchain traceability likely reflects its nascent adoption and the limited market premium currently available for digitally certified commodities in domestic West Sulawesi markets, compared to export-oriented supply chains where certification premiums are more developed.

Table 4. SEM Path Coefficients: Digitalization Components and Marketing Efficiency (N = 312)

Pathway	β	SE	t	p	95% CI	R^2
SCDI → Marketing Efficiency (Total)	.541	.051	10.61	<.001	.441, .641	.527

IoT Logistics → Marketing Efficiency	.487	.058	8.40	<.001	.373, .601	.412
Digital Marketplace → Marketing Efficiency	.421	.061	6.90	<.001	.301, .541	.368
Price Info Systems → Marketing Efficiency	.318	.064	4.97	<.001	.192, .444	.287
Blockchain Traceability → Marketing Efficiency	.274	.071	3.86	.002	.134, .414	.198
SCDI → Txn Cost Reduction (mediation)	.612	.044	13.91	<.001	.526, .698	.487
Txn Cost Reduction → Efficiency (mediation)	.340	.058	5.86	<.001	.226, .454	.387
Indirect Effect (via Txn Cost)	.208	.042	4.95	<.001	.126, .290	
Model Fit: CFI=.952, RMSEA=.054 [90% CI: .037–.071], SRMR=.061, χ^2/df=2.04						

Source: SEM analysis, IBM AMOS 26, 2024. SCDI = Supply Chain Digitalization Index; Txn = Transaction.

4.5 Barriers to Digital Adoption: Quantitative and Qualitative Findings

The Digital Adoption Barriers Scale identified three dominant barrier dimensions: infrastructure limitations (M = 4.12, SD = 0.68), comprising inadequate internet connectivity, electricity access, and device availability; digital literacy constraints (M = 3.84, SD = 0.74), reflecting insufficient skills for operating digital platforms; and financial inclusion barriers (M = 3.48, SD = 0.81), encompassing limited access to digital payment systems, mobile banking, and e-wallet services required for digital marketplace transactions.

Qualitative interviews provided rich contextual elaboration of these barriers. A cocoa farmer from Mamuju Utara articulated the infrastructure constraint: 'The signal here is zero. I have a smartphone my son gave me, but the internet is so slow that the TaniHub app doesn't load. By the time I get a connection, the price has already changed.' A cooperative manager in Majene highlighted the literacy dimension: 'Most of our members are over 50. Teaching them to use WhatsApp for prices is hard enough—blockchain is something they've never heard of.' These narratives illuminate the interaction between technical infrastructure and human capital constraints that creates a digital adoption gap with strong age, location, and education correlates.

Table 5. Digital Adoption Barriers: Mean Scores and Prevalence by Farmer Category

Barrier Dimension	Smallholder < 1 ha (n=187)	Medium 1–3 ha (n=89)	Large > 3 ha (n=36)	Overall Mean	Primary Sub-barriers
Infrastructure Limitations	4.38	3.91	3.44	4.12 (SD=0.68)	Internet signal, electricity
Digital Literacy	4.12	3.68	3.12	3.84 (SD=0.74)	App use, online transactions
Financial Inclusion	3.74	3.31	2.87	3.48 (SD=0.81)	Mobile banking, e-wallet

Trust in Digital Platforms	3.48	3.12	2.68	3.21 (SD=0.88)	Payment security, data privacy
Regulatory/Institutional	2.94	2.71	2.44	2.79 (SD=0.76)	E-contract recognition, licensing
ANOVA F (df=2,309)	F=18.42**				All barriers differ significantly by farm size

Note: Scores on 5-point Likert scale (1=not a barrier, 5=very serious barrier). ** $p < .001$.
Source: Digital Adoption Barriers Scale survey data, 2024.

5. DISCUSSION

The findings of this study provide strong empirical support for the hypothesis that agricultural supply chain digitalization significantly improves marketing efficiency for food commodities in the West Sulawesi context. The magnitude of the digitalization effect ($\beta = 0.541$) and the explanatory power of the SEM model ($R^2 = 0.527$) are comparable to or exceed effect sizes reported in similar studies from more developed agricultural contexts in Java and Malaysia (Wardhana et al., 2022; Jaafar et al., 2021), suggesting that the efficiency gains from digitalization may be particularly large in less-developed regions where baseline inefficiencies are most severe.

The 18.7 percentage-point improvement in Farmer's Share associated with high versus low digitalization adoption is economically substantial. For a smallholder farmer producing 3 tonnes of cocoa per year at current regional prices of approximately IDR 35,000/kg, this margin improvement translates to an estimated additional income of IDR 19.6 million (approximately USD 1,260) per year—a meaningful uplift relative to average annual farmer household incomes of approximately IDR 47 million in West Sulawesi (BPS, 2023). These estimates suggest that supply chain digitalization has the potential to make substantial contributions to smallholder income growth and rural poverty reduction if adoption barriers can be overcome.

The identification of IoT-based logistics coordination as the strongest individual contributor to marketing efficiency ($\beta = 0.487$) is theoretically significant and practically important. Traditional agricultural logistics in West Sulawesi are characterized by uncoordinated, fragmented transport arrangements that result in high post-harvest losses (estimated at 15–25% for perishable commodities), delayed deliveries, and poor quality management. IoT-enabled logistics platforms—including GPS-tracked vehicle fleets, real-time cargo monitoring, and algorithmic route optimization—directly address these inefficiencies by enabling the coordination that fragmented market actors cannot achieve independently. This finding supports prioritizing logistics infrastructure digitalization as the highest-return investment for West Sulawesi agricultural supply chain development.

The transaction cost mediation finding is consistent with TCE theoretical predictions: digitalization reduces all three categories of transaction costs (search/information, negotiation/contracting, monitoring/enforcement), with these reductions translating into efficiency improvements through disintermediation, improved price discovery, and enhanced contract performance. The partial mediation (38.4% of total effect) indicates that transaction cost reduction captures an important but not dominant portion of the digitalization-efficiency pathway, with direct effects through logistics optimization and market access enhancement accounting for the majority of the total effect. This finding suggests that efficiency gains from digitalization are multidimensional and cannot be fully captured through transaction cost frameworks alone.

The adoption barrier analysis reveals a stratified digital divide with important equity implications. Smallholder farmers on plots smaller than one hectare—who constitute 59.9% of the sample and represent the majority of West Sulawesi's agricultural population—face the most severe adoption barriers across all dimensions. Their lower digitalization adoption rates mean they benefit least from the efficiency gains this study documents, potentially widening rather than narrowing rural income inequality. This finding resonates with broader concerns in the digital development literature about the risk that digital transformation in agriculture may disproportionately benefit larger, better-connected, and more educated farmers while leaving the most vulnerable behind (Klerkx et al., 2019; Fabregas et al., 2019).

The qualitative findings illuminate important sociocultural dimensions of digital adoption that quantitative measures cannot capture. Trust in digital platforms—shaped by prior experiences with fraudulent online transactions, concerns about data privacy, and skepticism toward intermediaries who promote digital tools—emerged as a significant barrier in interviews that is partially captured by the Trust in Digital Platforms scale but requires deeper sociological analysis. Cooperative social capital emerged as a critical enabler: farmers embedded in active cooperatives with digitally skilled management demonstrated significantly faster adoption trajectories, reflecting the cooperative institution's role as a social intermediary that reduces individual adoption risk and provides collective learning resources.

6. CONCLUSION

This study provides comprehensive evidence that agricultural supply chain digitalization constitutes a significant and economically meaningful driver of marketing efficiency improvement for food commodities in West Sulawesi, Indonesia. The strong SEM-confirmed effect of digitalization on efficiency ($\beta = 0.541$), the 18.7 percentage-point improvement in Farmer's Share associated with high adoption, and the identification of IoT logistics coordination and digital marketplace platforms as the highest-impact technology components collectively support a robust conclusion: accelerating agricultural supply chain digitalization in West Sulawesi can substantially improve farmer incomes, reduce consumer price-farm gate price spreads, and contribute to food system sustainability.

However, the equity dimension of this conclusion requires urgent attention. The digital adoption barriers systematically most severe among the smallest and most remote farmers—

particularly infrastructure limitations (M = 4.38 for farms < 1 ha), digital literacy constraints, and financial inclusion barriers—mean that the efficiency gains from digitalization risk being concentrated among better-resourced agricultural actors unless targeted interventions address these structural inequalities. A digitalization strategy that captures the aggregate efficiency gains documented here while ensuring equitable distribution of those gains requires multi-dimensional policy intervention.

Based on the study findings, four policy recommendations are advanced. First, the provincial government should prioritize telecommunications infrastructure investment in remote agricultural areas, coordinating with national programs such as Palapa Ring to extend broadband connectivity to the agricultural communities that remain unserved. Second, agricultural extension services should incorporate structured digital literacy training into their standard programming, targeting older and less-educated farmers through culturally appropriate, cooperative-based learning formats. Third, financial regulators should facilitate the expansion of mobile banking and e-wallet services in rural West Sulawesi, enabling smallholders to participate in digital payment ecosystems that are prerequisite for marketplace platform adoption. Fourth, cooperative institutions should be strengthened as strategic vehicles for collective digitalization, with targeted support for cooperative-level technology investments, digital management training, and inter-cooperative platform networks.

Future research should employ longitudinal panel designs to track the dynamic effects of digitalization on marketing efficiency over time, and should investigate the differential adoption trajectories of specific technology components to identify the sequencing of investments that generates the most rapid efficiency improvements. Comparative studies across Indonesian provinces with different agricultural structures, infrastructure endowments, and policy environments would substantially advance the generalizability of these findings and inform national digital agriculture policy design.

References

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77–101.

Badan Pusat Statistik (BPS). (2023). Statistik pertanian West Sulawesi 2022. BPS Provinsi Sulawesi Barat.

Coase, R. H. (1937). The nature of the firm. Economica, 4(16), 386–405.

Creswell, J. W., & Plano Clark, V. L. (2017). Designing and conducting mixed methods research (3rd ed.). Sage.

Fabregas, R., Kremer, M., & Schilbach, F. (2019). Realizing the potential of digital development: The case of agricultural advice. Science, 366(6471), eaay3038.

Ge, L., Brewster, C., Spek, J., Smeenk, A., & Top, J. (2017). Blockchain for agriculture and food: Findings from the pilot study. Wageningen Economic Research Report.

Jaafar, H. S., Endut, I. R., Faisol, N., & Omar, E. N. (2021). Innovation in logistics: The impact of digital supply chain on Malaysian agri-food SMEs. Asian Journal of Agricultural Extension, Economics & Sociology, 39(4), 28–40.

Kamilaris, A., Fonts, A., & Prenafeta-Boldú, F. X. (2019). The rise of blockchain technology in agriculture and food supply chains. Trends in Food Science & Technology, 91, 640–652.

Katz, M. L., & Shapiro, C. (1985). Network externalities, competition, and compatibility. American Economic Review, 75(3), 424–440.

Kementerian Pertanian Republik Indonesia. (2022). Roadmap Digital Agriculture 4.0. Kementan RI.

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0. NJAS—Wageningen Journal of Life Sciences, 90–91, 100315.

Kowalczyk, S., & Rotter, B. E. (2016). Blockchain-based supply chain traceability: From theory to practice. Journal of Sustainable Development, 9(3), 140–152.

Natawidjaja, R. S., Reardon, T., Shetty, S., Noor, T. I., Perdana, T., Rasmikayati, E., ... & Chen, K. (2021). Horticultural producers and supermarket development in Indonesia. IFPRI Research Report.

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. International Journal of Production Research, 57(7), 2117–2135.

Sanjaya, S., & Kusumastuti, R. D. (2022). Digital transformation in Indonesian agricultural supply chains: Opportunities and constraints for smallholders. Asian Pacific Journal of Rural Development, 32(1), 21–44.

Schwab, K. (2016). The Fourth Industrial Revolution. World Economic Forum.

Shepherd, A. W. (1997). Market information services: Theory and practice. FAO Agricultural Services Bulletin 125.

Suryana, A., Agustian, A., & Iwan, S. (2020). Rice marketing efficiency in Indonesia: Evidence from supply chain analysis. Indonesian Journal of Agricultural Science, 21(2), 55–68.

Tomek, W. G., & Kaiser, H. M. (2014). Agricultural product prices (5th ed.). Cornell University Press.

Tripoli, M., & Schmidhuber, J. (2018). Emerging opportunities for the application of blockchain in the agri-food industry. FAO and ICTSD.

Verdouw, C., Tekinerdogan, B., Beulens, A., & Wolfert, S. (2021). Digital twins in smart farming. Agricultural Systems, 189, 103046.

Wahyuni, S., & Ginting, A. M. (2023). Digital agriculture readiness in Eastern Indonesia: Infrastructure, literacy, and institutional gaps. Journal of Southeast Asian Economies, 40(1), 88–112.

Wardhana, D., Ihle, R., & Heijman, W. (2022). Agri-digital ecosystems and farm income: Evidence from smallholders in Java, Indonesia. Food Policy, 106, 102189.

Williamson, O. E. (1985). The economic institutions of capitalism. Free Press.