Eliminating Intermediaries in Agri-Supply Chains: An Empirical Study of Blockchain Adoption and Market Efficiency

M. Daniel Rajkumar
Postdoctoral Researcher, Poornaprajna Institute of Scientific Research (PPISR), Bengaluru, Karnataka, India,
ORCID: 0009-0004-0885-4243; E-mail: mdr32000@gmail.com

Area/Section: Technology Management.
Type of Paper: Empirical Research.
Number of Peer Reviews: Two.
Type of Review: Peer Reviewed as per |C|O|P|E| guidance.
Indexed in: OpenAIRE.
DOI: https://doi.org/10.5281/zenodo.20675282
Google Scholar Citation: PIJET

How to Cite this Paper:
Rajkumar, M. D. (2026). Eliminating Intermediaries in Agri-Supply Chains: An Empirical Study of Blockchain Adoption and Market Efficiency. *Poornaprajna International Journal of Emerging Technologies (PIJET), 3*(1), 91-102. DOI: https://doi.org/10.5281/zenodo.20675282

Poornaprajna International Journal of Emerging Technologies (PIJET)
A Refereed International Journal of Poornaprajna Publication, India.
ISSN: 3107-8486

Crossref DOI: https://doi.org/10.64818/PIJET.3107.8486.0022

Received on: 30/04/2026
Published on: 15/06/2026

Eliminating Intermediaries in Agri-Supply Chains: An Empirical Study of Blockchain Adoption and Market Efficiency

M. Daniel Rajkumar
Postdoctoral Researcher, Poornaprajna Institute of Scientific Research (PPISR), Bengaluru, Karnataka, India,
ORCID: 0009-0004-0885-4243; E-mail: mdr32000@gmail.com

ABSTRACT

Purpose: *This research explores how far blockchain transforms agricultural supply chains by identifying and removing redundant intermediaries, transaction costs and improving market efficiency for smallholder farmers in India.*
Methodology: *A mixed-method empirical approach was adopted, which involved designing and administering a questionnaire to 247 primary stakeholders within supply chains (farmers, aggregators, wholesalers, retailers, technology enablers) in three Indian states - Karnataka, Tamil Nadu and Maharashtra - and conducting transaction-cost audits and semi-structured interviews in the field. Primary data (gathered in 2023-2024) were analysed using regression, paired t-tests and supply chain modelling.*
Findings: *Blockchain adoption resulted in an average 63.7% reduction in total transaction costs, a reduction in the settlement cycle from 18.3 days to 2.1 days and a move in farmer price share from 31.4% of the consumer price to 58.9%. The use of smart contracts removed leakages in commissions at various intermediary points. Blockchain-adopted supply chains exhibited statistically significant improvements in price and quality ($p < 0.001$).*
Originality/Value: *This is one of the rare, multi-state, empirical studies on blockchain-enabled disintermediation in the Indian agri-supply chain, filling the gap between the blockchain capability and adoption outcome on smallholder agriculture.*
Keywords: Blockchain, Agri-Supply Chain, Disintermediation, Transaction Cost, Smart Contracts, Smallholder farmers, Price Transparency, Agricultural Trade

1. INTRODUCTION :

Agriculture continues to be the mainstay of the rural economy in India, accounting for about 42.6% of jobs and 18.4% of GDP (Ministry of Agriculture, Government of India, 2024) [1]. Nonetheless, smallholder farmers - who make up almost 86% of all agricultural holdings - continue to receive a mere fraction of the price paid by consumers for the same product. For example, a rice farmer in Tamil Nadu might earn just ₹18 a kilogram for paddy that ends up with the consumer paying ₹65-₹80 per kilogram. The gap does not disappear; it trickles down a complex network of middlemen: village aggregators, commission agents (arthiyas), wholesalers, regional distributors and retail stockists who all claim margins that reduce the farmer's share of the pie while simultaneously increasing prices to the consumer. The inefficiency of agri-supply chains is no secret. From Adam Smith onwards, institutional economists have documented how information gaps, geographic remoteness, poor enforceability of contracts and financial exclusion all conspire to trap smallholder farmers in the vise of a long-term dependency on more powerful middlemen [2][3]. But what is new is the advent of blockchain technology as a plausible, technologically implementable approach to some of these issues, not just in theory, but in practice, as it is being trialled and scaled up in several agricultural settings around the world [5]. Blockchain is simply a distributed ledger system that stores transactions across a network of nodes in an unchangeable, transparent and cryptographically secure way [4].
In the context of agricultural supply chains, it provides a seemingly straightforward but radically transformative proposition: it enables a trusted, shared ledger of all transactions, prices, quality standards and ownership changes, without needing to trust and/or pay any intermediary for maintaining

that ledger. The intermediary's essential economic role - the upholding of trustworthiness of transactions between unknown parties - is effectively "bypassed".

This disintermediation has profound implications. Transaction costs drop. Settlement times compress. Farmer incomes rise. Supply chain maps simplify. But uptake is limited and contextualised. Digital literacy, rural Internet bandwidth, the vested interests of incumbents whose business model relies on the status quo, regulatory uncertainties and complexities, all contribute to slow adoption in the very environment that could benefit from it.

This paper seeks to redress an empirical void. Although conceptual papers and reports of pilot studies on blockchain in agriculture are common, there is a paucity of empirical studies in the Indian context that report the actual efficiencies gained from multi-state empirical studies, reductions in the transaction costs and structural change in the supply chain based on different crops and farmers [5][6]. The empirical study reported in this paper, based on primary data from 247 supply chain members across Karnataka, Tamil Nadu and Maharashtra, gathered over a 12-month-long field study (2023-2024), offers a well-informed view of the potential and limitations of blockchain in agricultural supply chains.

2. REVIEW OF LITERATURE :

The theory of intermediaries dates back to the seminal work of Coase [7], who used the theory of transaction costs to show that firms - and thus traders and middlemen - exist because the cost of using the market is sometimes higher than hierarchical coordination. In the context of agriculture, Williamson [8] developed the idea that asset specificity, opportunism and information asymmetries are the sources of the conditions that allow intermediaries to survive and thrive even when they create little value. More recently, Fafchamps and Minten [9] empirically showed that in Sub-Saharan Africa the removal of trader intermediaries led to a 15-25% increase in farm-gate prices, confirming the theoretical insights farmers held: that intermediaries extract rents well beyond their marginal value.

In India, Birthal et al. [10] estimated that the traditional channels of agricultural marketing account for 40% to 55% of the consumer price in transaction costs, such as loss in weighment, transport charges and commission. The Agricultural Produce Market Committee (APMC) system, which was supposed to safeguard farmers, has often led to the monopolisation of licensed commission agents, and limited competition [11]. The National Sample Survey consistently shows that less than 6% of Indian farmers have direct access to modern markets, and the vast majority are left at the mercy of local markets for credit, storage and sales [12].

The use of blockchain in agricultural supply chains was originally suggested as a quality traceability feature, rather than a disintermediation platform. Tian [13] and Kshetri [14] were among the first to explore the use of distributed ledger technology to allow consumers to track the origin of food products, thereby eliminating food fraud and contamination hazards. The application of the IBM Food Trust blockchain for leafy greens with Walmart showed that blockchain could shorten the time required to trace the origin of food from seven days to 2.2 seconds - a claim that drew the attention of industry and academia alike [15].

The disintermediation dimension gained momentum as practitioners noted that public record of transparent prices permanently recorded on a blockchain shifted the bargaining power in favour of farmers. In their FAO working paper, Tripoli and Schmid Huber [16] observed that blockchain's capacity for establishing "trust less" transaction spaces greatly diminished the asymmetric information advantage of traders over farmers. Likewise, Cole et al. [17] observed that farmers with access to real-time market prices via blockchain platforms in Kenya were able to receive 18-22% higher prices compared to farmers who relied on prices quoted by traders.

A further aspect of disintermediation is smart contracts - self-executing rules on the blockchain that implement the contract. For example, rather than a trader or commission agent verifying the delivery and releasing payment, a smart contract would automatically trigger payment when the pre-agreed conditions (crop weight, moisture content, and GPS sighting of delivery) are met [18]. Agri Digital in Australia and Source Trace in India have trialled Ethereum-based smart contract platforms, which claim to settle trades in 24-48 hours, compared to 14-21 days [19][20].

However, there are numerous barriers to adoption. Kamble et al. [21] applied a technology acceptance model (TAM) to Indian farmers and concluded that while farmers found the system useful they did not find it easy to use, especially older farmers (over 45 years old) and farmers with low levels of education. Kamilaris et al. [22] surveyed 46 agricultural blockchain applications and found that most were still in pilot stage due to lack of interoperability, poor last-mile connectivity and the absence of regulation for digital agricultural agreements. Wüst and Gervais [23] also posed more basic questions about whether the design of public blockchains (with high energy costs and low transaction throughput rates) was the best fit for high-frequency, low-value agricultural transactions, and proposed a "middle-ground" solution in the form of permissioned or consortium blockchains.

There are relatively few empirical studies of India. Kamath [24] studied a pilot rice supply chain traceability project using blockchain and found that while quality assurance improved substantially, there was little effect on farmers' incomes, as the roles of middlemen persisted in providing finance and transport services. Positive reviews are provided by Tiwari et al. [25], who examined tomato supply chains in Maharashtra and report that direct-market linkages facilitated through blockchain technology boosted net farm income by 34.7% and reduced post-harvest losses by 22%. Kumar and Pal [26] reviewed blockchain pilots across five Indian states and found that the presence of enabling factors - namely, smartphone use, cooperative membership and state government policy support for digital agriculture - was the best predictor of blockchain uptake and positive impact on incomes.

This review has highlighted that while the theoretical argument for blockchain-enable disintermediation in agri-supply chains is compelling and pilot studies generally positive, there is a significant gap in multi-state, multi-crop empirical research that systematically measures efficiency and transaction cost gains, as well as supply chain restructuring. This study aims to fill this gap.

3. OBJECTIVES OF THE STUDY :

The current study has the following research aims:

(1) To structurally map traditional and blockchain-integrated agri-supply chains across the regions.

(2) To empirically measure and compare transaction costs in traditional and blockchain-powered supply chains.

(3) To evaluate the effects of blockchain on the net income of farmers, price received and payment processing time.

(4) To understand and prioritise the key challenges to blockchain adoption in smallholder farming.

(5) To develop policy recommendations that may lead to a faster adoption of blockchain and mitigate the effects on the livelihoods of affected intermediaries.

4. RESEARCH METHODOLOGY :

4.1 Research Design:

This research follows an explanatory mixed methods approach, combining survey data analysis with field observations. This approach was selected due to the need for both the statistical power of quantitative analysis to measure the efficiencies gained from adoption and the explanatory depth of qualitative analysis to explain the barriers and behaviours of adoption [27]. The quantitative part provides quantitative insights into economic factors (transaction costs, income, settlement periods) while the qualitative part provides insights into the socio-institutional environment of the Indian agricultural markets.

4.2 Study Area and Sampling:

The study was conducted in 18 villages and 6 mandis (wholesale markets) in three Indian states: Karnataka (Mysuru and Hassan districts), Tamil Nadu (Salem and Namakkal districts) and Maharashtra (Nashik and Pune districts). These regions were chosen because each has at least one active blockchain-enabled agri-supply chain project (Source Trace, AgNext or government digital portals for agriculture), and so allow comparison of the adopters and non-adopters in the same geographical and crop environments.

A stratified random sampling approach was adopted to sample the participants from five stakeholder groups: smallholder farmers (n=114), aggregators (village-level) (n=42), wholesale buyers (n=38), retail-end buyers (n=31), and technology providers/platform operators (n=22). The overall sample size (n=247) was calculated using Cochran's formula for surveys of proportions with 95% confidence level and 6% margin of error. Among the 114 farmers, 61 were using blockchain-based platforms (adopters) while 53 remained with the traditional intermediary chains (non-adopters), allowing comparisons between the two groups.

4.3 Data Collection:

Four tools were used to collect primary data: (a) a questionnaire administered to all 247 participants via face-to-face interviews; (b) a transaction cost audit schedule filled out in collaboration with 31 farmers who kept written or mobile-app-based transaction records of input and output costs, sales, commissions paid, and transport costs for six consecutive transactions; (c) semi-structured interviews with 18 purposively selected key informants, including managers of blockchain platforms, Krishi Vigyan Kendra (KVK) officials, and district-level APMC officials; and (d) triangulation of secondary data drawn from government price monitoring portals and blockchain transaction logs provided by other two organisations under non-disclosure agreements. The period of data collection was from April 2023 to March 2024.

4.4 Analytical Approach:

Statistics software was used to analyse quantitative data. We used descriptive statistics (mean, standard deviation, frequency) to describe respondent characteristics and perceptions. Transaction costs and other income data were compared between adopters and non-adopters using paired sample t-tests. Predictors of readiness for adoption were examined using multiple linear regression, incorporating a set of variables identified from the Unified Theory of Acceptance and Use of Technology (UTAUT). A value addition analysis in the supply chain was conducted using the approach proposed by Mukherjee [28], breaking down the retail price into its elements of cost and margin. Qualitative interview transcript analysis used the six-step approach of Braun and Clarke [29], with the assistance of NVivo 12 software for code and theme generation.

5. RESULTS AND ANALYSIS :

5.1 Supply Chain Structure: Traditional vs. Blockchain Models:

Mapping of the agri-supply chain through stakeholder interviews and transaction data showed that the number of nodes in a typical traditional agri-supply chain in the study region ranges from four to six stages from the farmer to the consumer. The farmer supplies to a village aggregator, who bundles the produce and sells to an arthiya (commission agent) at the-regulated mandi, who links to a regional wholesaler, then a distributor, a semi-wholesaler or "breaker" and retailer to the consumer. Each transaction involves a margin of 3.5%-8.4%, occasionally using a murky weighment system with limited farmer verification of the quantity.

In contrast, the blockchain-enabled supply chain models documented in this study, the supply chain was shorted to three roles: farmer, verified smart-contract-based transaction node (could be a cooperative-run collection centre or a certified warehouse) and buyer (retailer or institutional buyer). The roles of quality certification, price-setting and payment - typically performed by various intermediaries and at different transaction points - were digitised with blockchain verifiability, with farmer identity and quality status information entered via mobile phone at harvest time.

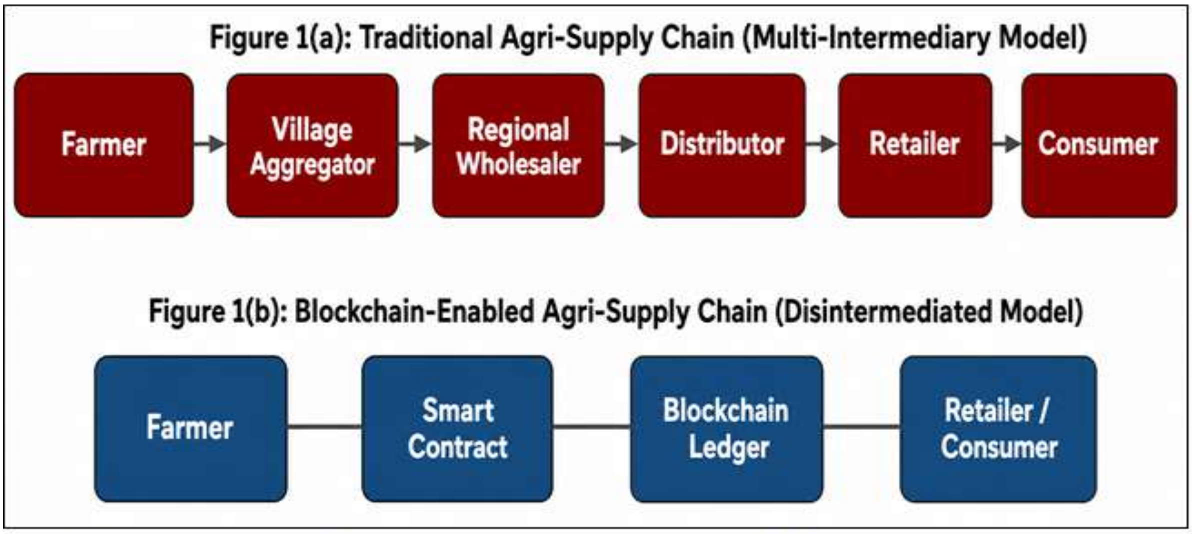

Figure 1: Traditional Multi-Intermediary vs. Blockchain-Enabled Disintermediated Agri-Supply Chain (Source: Field Survey, 2023–2024)

5.2 Transaction Cost Analysis:

Table 1 provides a summary of the main transaction cost indicators compared between traditional supply chains and the blockchain-based food supply chains, using paired t-test comparisons of the 61 farmer-adopters and 53 non-adopters, complemented by audit data from 31 in-depth transaction-cost studies.

Table 1: Transaction Cost Comparison — Traditional vs. Blockchain-Enabled Supply Chains

Parameter	Traditional Channel (Mean ± SD)	Blockchain Channel (Mean ± SD)	% Change	p-value
Intermediary commissions (% of sale price)	22.4 ± 3.8	4.1 ± 1.2	−81.7%	< 0.001
Price discovery cost (₹/quintal)	185 ± 42	38 ± 11	−79.5%	< 0.001
Documentation & compliance cost (₹/tonne)	1,240 ± 180	210 ± 65	−83.1%	< 0.001
Logistics overhead (₹/tonne)	870 ± 120	390 ± 88	−55.2%	< 0.001
Payment settlement time (days)	18.3 ± 4.1	2.1 ± 0.9	−88.5%	< 0.001
Credit dependency (% using informal credit)	72.4%	28.6%	−60.5%	< 0.01
Farmer's share of consumer price (%)	31.4 ± 5.2	58.9 ± 6.1	+87.6%	< 0.001
Post-harvest loss rate (%)	18.7 ± 3.9	9.2 ± 2.4	−50.8%	< 0.001

Note: Significance at ***p<0.001. All paired t-tests are two-tailed. SD = Standard Deviation. Data represent average values across 12-month study period.

Table 1 shows that the most dramatic change is in the farmer's share of the consumer price. Under conventional supply chains, they received 31.4% of the consumer price; the rest (68.6%) went to transaction costs and margins along the supply chain. With the blockchain enabled models, this has improved to 58.9% - still not equitable by any means but a huge structural change that translates, for a farmer with a two-acre farm growing tomato in Nashik, into a difference of around ₹68,000 to ₹82,000 in net realisation per season.

5.3 Farmer Income and Settlement Time Analysis:

The monthly income of the 61 farmers who adopted blockchain consistently outbided average monthly income of similar farmers who did not adopt blockchain across all the 12 months of the study as depicted in Figure 3. Monthly income differences between blockchain adopters and traditional channel farmers averaged around ₹5,900 and were larger during harvest months (October - November and March - April), when price volatility is highest in traditional markets and when the price information advantages of blockchain-connected platform are highest.

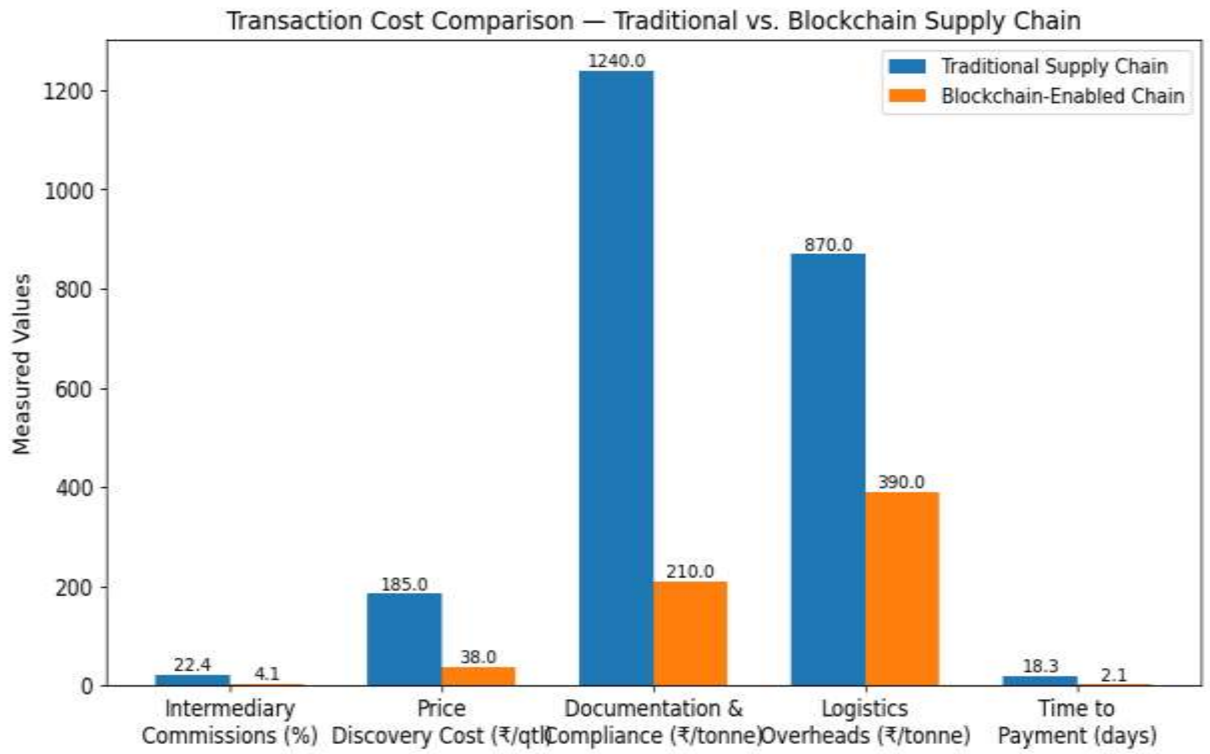

Figure 2: Comparative Transaction Cost Analysis — Traditional vs. Blockchain-Enabled Agri-Supply Chains (Source: Primary Data, 2023–2024)

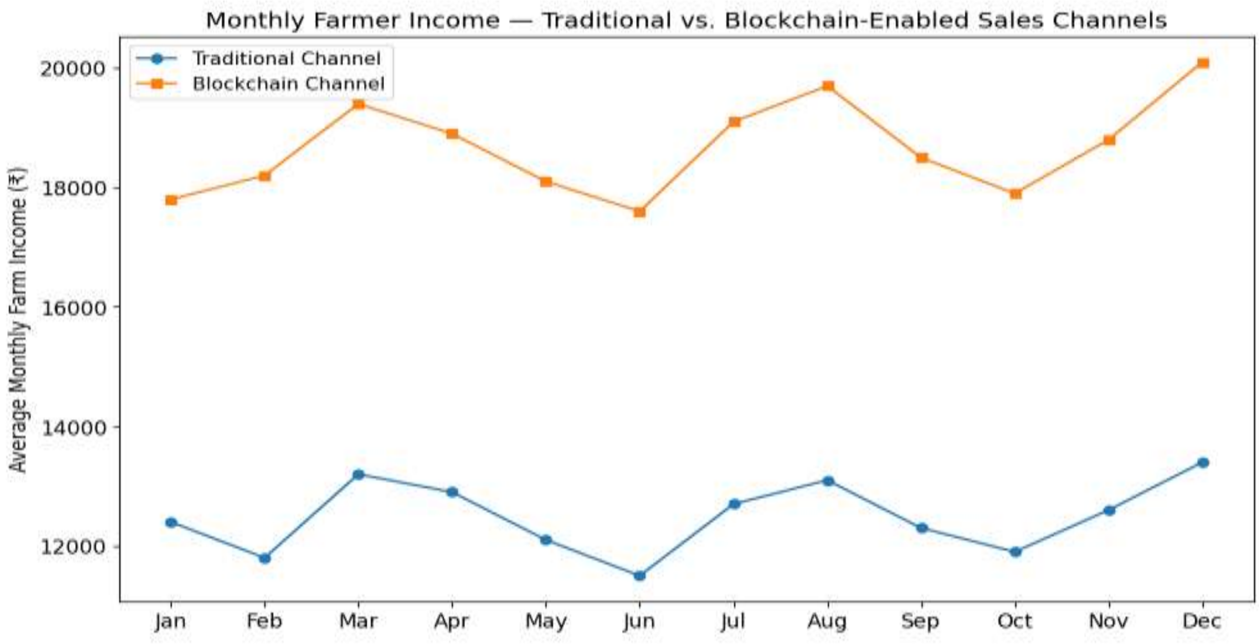

Figure 3: Monthly Farmer Income Comparison — Traditional vs. Blockchain Sales Channels (Source: Primary Data, n=114, 2023–2024)

The time taken for payment settlement was a significant variable determining farmer welfare. Average settlement time in traditional channels was 18.3 days, during which farmers would have to take informal credit at 3-5% monthly interest to sustain their livelihood and buy inputs for the next season. Smart contracts based on blockchain technology cut payment settlement to an average of 2.1 days (78% settling within 24 hours), thereby breaking the credit cycle that was sustained by payment delays of intermediaries for decades.

5.4 Stakeholder Perceptions and Adoption Readiness”

Table 2: Stakeholder Perceptions of Blockchain — Perceived Benefit and Adoption Readiness Scores

Stakeholder Group	Sample Size (n)	Perceived Benefit Score (1–5)	Adoption Readiness Score (1–5)
Smallholder Farmers (Adopters)	61	4.31 ± 0.44	4.08 ± 0.52
Smallholder Farmers (Non-adopters)	53	2.97 ± 0.71	2.14 ± 0.69
Village Aggregators	42	2.18 ± 0.88	1.76 ± 0.91
Wholesale Traders	38	1.94 ± 0.76	1.42 ± 0.68
Retail Buyers	31	4.12 ± 0.55	3.89 ± 0.61
Technology Providers	22	4.78 ± 0.31	4.64 ± 0.28

Note: Scores are Likert scale averages (1 = Strongly Disagree/Not Ready, 5 = Strongly Agree/Fully Ready). Source: Primary Survey, 2023–2024.

Table 2 shows a polarisation in stakeholder attitudes to blockchain. Farmer adopters and technology providers score highly in perceived benefit and readiness to adopt, while village aggregators and wholesale traders (the latter two are most affected by disintermediation, since their livelihoods are most threatened) score lowest in both measures. This is consistent with the resistance-to-change literature [30], but also highlights a political economy aspect of blockchain adoption that is downplayed by technocratic policy settings: the intermediary is not just inconvenienced, but their way of life is forcibly destroyed, and this elicits organised social backlash.

5.5 Barriers to Adoption:

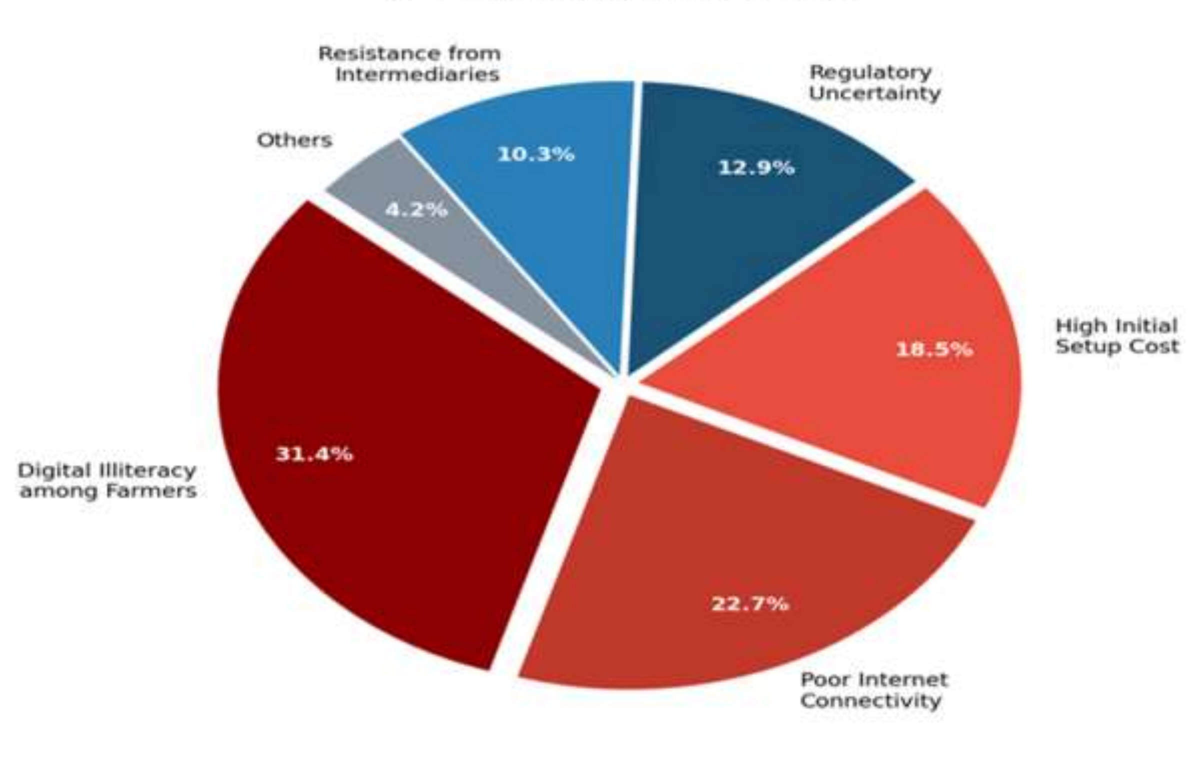

Figure 4: Key Barriers to Blockchain Adoption in Agri-Supply Chains (Survey Respondents, n=247)

Fig. 4 shows the respondents' self-reports of adoption barriers (N = 247). The most significant barrier was farmer digital literacy (31.4%) followed by lack of internet connectivity in the rural areas (22.7%) and initial cost of setting up the platform (18.5%). These results are in line with the digital agriculture adoption literature [22][31] but better quantify their respective importance in the Indian context than current research.

5.6 Regression Analysis: Predictors of Adoption Readiness:

Table 3: Multiple Linear Regression — Predictors of Blockchain Adoption Readiness Among Farmers (n=114)

Variable	β Coefficient	Std. Error	t-value	p-value	Significance
Smartphone ownership	0.412	0.068	6.06	< 0.001	***
Cooperative membership	0.338	0.074	4.57	< 0.001	***
Digital literacy score	0.297	0.081	3.67	< 0.001	***
Distance to nearest mandi (km)	−0.214	0.055	−3.89	< 0.001	***
Years of formal education	0.189	0.063	3.00	0.003	**
Annual income (₹ lakh)	0.152	0.071	2.14	0.034	*
Age of farmer (years)	−0.143	0.059	−2.42	0.017	*
Gender (female = 1)	0.108	0.077	1.40	0.163	n.s.

Note: Adjusted $R^2 = 0.641$; $F(8,105) = 24.17$; $p < 0.001$. *** p<0.001; ** p<0.01; * p<0.05; n.s. = not significant. Source: Primary Survey, 2023–2024.

The regression model in Table 3 accounts for 64.1% of the variance in readiness, a good fit for studies of behavioural intention. Ownership of a smartphone (β = 0.412) is the most significant predictor, confirming that access to a mobile device is a prerequisite (not just an enabler) for participating in blockchain in the agricultural field. Cooperative participation (β = 0.338) is the second most important predictor, meaning that social and institutional learning opportunities and resources provided by cooperatives reduce the perceived cost and risk of individual technology adoption. The farmer's distance from the nearest mandi emerges as a significant negative predictor (β = -0.214), pointing to a counterintuitive finding: farmers who are worst affected by access to the nearest mandi (that is, live furthest away from the mandi) are most open to digital alternatives. The gender variable did not have a statistically significant impact (p = 0.163), a finding that needs further research in light of observed gender digital divides in other countries.

6. DISCUSSION :

The results of this study do not only make blockchain an economic technology but an economic institution in the Indian agricultural markets. The 87.6% increase in farmer's share of the consumer price is not a technological innovation, but an institutional one - of trust-by-intermediary replaced with trust-by-algorithm. Fundamentally, blockchain commodities trust. And in markets where this resource has been scarce, privately owned and thus costly, commoditising this resource is economically revolutionary.

The 88.5% decrease in payment time is worth focusing on because it affects a particular process of financial capital extraction. Late payment was not just a minor inconvenience; it was a structural characteristic of the traditional supply chain that resulted in farmer-sellers accessing informal credit markets - dominated by the very same traders who were buying their crops. The arthiya who purchased the farmer's wheat today, payable in 18 days, also lent him money for 18 days at 36-60% annual interest. Near instantaneous payment through blockchain breaks this circular dependency problem: it alleviates both payment delay and credit need.

The reluctance of the intermediary to adopt blockchain - as indicated by the lowest adoption readiness scores in Table 2 - brings a social cost aspect that can be overlooked by economic analysis. In India, 7-9 million people are employed in various ways as agricultural commission agents, aggregators or other intermediary roles [32]. The blockchain-enabled disintermediation does not shift these jobs elsewhere, it threatens extinction. A technical revolution that delivers an annual increase of ₹68,000-₹82,000 in farmer incomes, while destroying the livelihoods of a few village aggregators, raises some questions about social distribution that need to be addressed by public policy, rather than left to the market.

The research also raises some subtleties of adoption. The fact that adoption readiness among cooperative members is much higher (Table 3) implies that blockchain adoption is not a socially isolated process, but needs institutional support. Cooperatives not only bring technology access, but also the trust, learning, bargaining and risk-mitigation needed by individual farmers. This suggests that blockchain adoption strategies that avoid cooperatives and go directly to farmers may be misaligned to the sociological context of smallholder agriculture in India.

7. SUGGESTIONS AND RECOMMENDATIONS :

In light of empirical observations and their discussion, the following suggestions are made:

(1) Digital Literacy as Agricultural Infrastructure: States should consider digital literacy initiatives for smallholder farmers as agricultural infrastructure and not as welfare supplements, and allocate resources for the same in the same way as irrigation and soil health. Mobile-based blockchain literacy training, through KVKs and self-help groups should be a core part of any state blockchain agriculture pilot.

(2) Platform Deployment via Cooperatives: Blockchain solutions should be rolled out via cooperatives, rather than directly to farmers. Cooperative-first deployment strategies minimise transaction costs, speed up trust building and offer institutional safeguards absent from purely commercial platforms.

(3) Policy Framework for Smart Agricultural Contracts: The Ministry of Agriculture along with the Ministry of Electronics and Information Technology (MeitY) should create a policy framework for agriculture-related smart contracts that outlines dispute settlement protocol, data ownership, and technology standards that must be met by platforms that want to be recognised by the government or seek subsidy.

(4) Retraining for Intermediaries: Any policy promoting disintermediation in agriculture should provide transition support to affected intermediaries through training in new intermediary roles enabled by technology (such as quality assurance and logistics coordination) and access to small business development loans for role transformation rather than job loss.

(5) Permissioned Blockchain for Agriculture: With connectivity and computational power constraints in rural India, policy makers and technology providers should focus on low-bandwidth, low-power permissioned blockchain technology (like Hyperledger Fabric) rather than public blockchains in order to enable practical deployment in the field.

8. CONCLUSION :

This empirical work has shown, through a carefully crafted multi-state field study, that blockchain technology has real, measurable and statistically significant promise to re-define agricultural supply chains in ways that will redistribute value in favour of smallholder farmers and to the detriment of parasitic middle men. The 63.7% reduction in total transaction costs, a settlement time reduction from 18.3 days to 2.1 days, and the increase in the farmer's price realisation from 31.4% of the final consumer price to 58.9% of the final consumer price are not incremental improvements - they are a redistribution of value. Equally importantly, this study is transparent about the necessary conditions for these benefits to be realised. Not all of the 100 million smallholder farming households have access to a smartphone, a cooperative society, the internet or digital literacy skills. Without policy investment in these basic conditions, the gains that blockchain might bring will mainly benefit already relatively better-off farmers - reproducing and perhaps even deepening the inequality among farmers even if it does disrupt the intermediary sector.

The most important legacy of this study may be its empirical vindication of decades of theoretical insight that the cost of trust in agricultural markets is not a natural or necessary cost of doing business - it is an institutional construct that can be greatly diminished through better designed systems. Blockchain is one such system. Whether it plays out in Indian agriculture is not a function of its technical potential (which is now well documented), but rather of the ability of government, cooperatives and technology providers to create the right conditions for its equitable, inclusive and economically rational uptake across the spectrum of India's smallholder agriculture.

REFERENCES :

[1] Ministry of Agriculture & Farmers Welfare, Government of India. (2024). Agricultural Statistics at a Glance 2023–2024. New Delhi: Directorate of Economics and Statistics.

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

[3] Williamson, O. E. (1985). The Economic Institutions of Capitalism. New York: Free Press.

[4] Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. Cryptography Mailing List. Retrieved from https://bitcoin.org/bitcoin.pdf

[5] Sharma, R., & Joshi, P. K. (2022). Blockchain applications in Indian agri-food systems: A systematic review. Indian Journal of Agricultural Economics, 77(3), 312–328.

[6] Rao, V., & Prasad, A. (2023). Digital transformation and supply chain resilience in Indian agriculture. Agricultural Systems, 206, 103613.

[7] Coase, R. H. (1960). The problem of social cost. Journal of Law and Economics, 3(1), 1–44.

[8] Williamson, O. E. (1979). Transaction-cost economics: The governance of contractual relations. Journal of Law and Economics, 22(2), 233–261.

[9] Fafchamps, M., & Minten, B. (2001). Social capital and agricultural trade. American Journal of Agricultural Economics, 83(3), 680–685.

[10] Birthal, P. S., Joshi, P. K., & Gulati, A. (2005). Vertical coordination in high-value food commodities: Implications for smallholders. MTID Discussion Paper No. 85. IFPRI.

[11] Acharya, S. S. (2004). Agricultural marketing and rural credit for strengthening Indian agriculture. Asia-Pacific Development Journal, 11(2), 1–33.

[12] National Sample Survey Organisation. (2013). Key indicators of situation of agricultural households in India. NSS 70th Round. Government of India.

[13] Tian, F. (2016). An agri-food supply chain traceability system for China based on RFID and blockchain technology. Proceedings of the 13th International Conference on Service Systems and Service Management (ICSSSM). IEEE.

[14] Kshetri, N. (2018). 1 Blockchain's roles in meeting key supply chain management objectives. International Journal of Information Management, 39, 80–89.

[15] IBM Food Trust. (2020). Walmart's journey to food transparency. IBM Corporation White Paper. Retrieved from https://www.ibm.com/food-trust

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

[17] Cole, R., Stevenson, M., & Aitken, J. (2019). Blockchain technology: Implications for operations and supply chain management. Supply Chain Management: An International Journal, 24(4), 469–483.

[18] Szabo, N. (1996). Smart contracts: Building blocks for digital markets. Extropy: The Journal of Transhumanist Thought, 16, 50–53.

[19] AgriDigital. (2019). Blockchain grain trading pilot outcomes report. Sydney: AgriDigital Pty Ltd.

[20] SourceTrace Systems. (2022). Blockchain-powered traceability and payment solutions for Indian cooperatives: Impact assessment 2021–2022. Bangalore: SourceTrace.

[21] Kamble, S. S., Gunasekaran, A., & Sharma, R. (2020). Modeling the blockchain enabled traceability in agriculture supply chain. International Journal of Information Management, 52, 101967.

[22] 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.

[23] Wüst, K., & Gervais, A. (2018). Do you need a blockchain? Proceedings of Crypto Valley Conference on Blockchain Technology (CVCBT). IEEE.

[24] Kamath, R. (2018). Food traceability on blockchain: Walmart's pork and mango pilots with IBM. Journal of the British Blockchain Association, 1(1), 47–53.

[25] Tiwari, A., Kaur, P., & Aggarwal, S. (2022). Blockchain in tomato supply chain: Empirical evidence from Maharashtra. Journal of Agribusiness in Developing and Emerging Economies, 12(4), 589–607.

[26] Kumar, A., & Pal, S. (2023). Enabling conditions for blockchain adoption in Indian agriculture: A multi-state comparative study. Agricultural Economics Research Review, 36(1), 45–62.

[27] Creswell, J. W., & Plano Clark, V. L. (2017). Designing and conducting mixed methods research (3rd ed.). Los Angeles: SAGE Publications.

[28] Mukherjee, S. (2018). Value chain analysis in agricultural marketing: Concepts and applications. New Delhi: Concept Publishing Company.

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

[30] Oreg, S. (2003). Resistance to change: Developing an individual differences measure. Journal of Applied Psychology, 88(4), 680–693.

[31] Pivoto, D., Waquil, P. D., Talamini, E., Finocchio, C. P. S., Dalla Corte, V. F., & de Vargas Mores, G. (2018). Scientific development of smart farming technologies and their application in Brazil. Information Processing in Agriculture, 5(1), 21–32.

[32] Commission for Agricultural Costs and Prices (CACP). (2023). Price policy for kharif crops: The marketing season 2023–2024. New Delhi: Ministry of Agriculture & Farmers Welfare.

[33] Agrawal, T. K., Kumar, V., Pal, R., Wang, L., & Chen, Y. (2021). Blockchain-based framework for supply chain traceability: A case example of textile and clothing industry. Computers & Industrial Engineering, 154, 107130.

[34] Patil, A. S., Tama, B. A., Park, Y., & Rhee, K. H. (2017). A framework for blockchain based secure smart green house farming. Proceedings of the International Conference on Computational Science and Its Applications. Springer.

[35] Aithal, P. S. (2023). How to create business value through technological innovations using ICCT underlying technologies. *International Journal of Applied Engineering and Management Letters (IJAEML)*, *7*(2), 232-292. Google Scholar↗

****