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Econometric analysis of deep tech-driven supply chain optimization in Assam's litchi farming

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Abstract

Supply chain inefficiencies in perishable horticultural commodities have been a significant limitation in the emerging economies. The litchi business in Assam is very susceptible to post-harvest losses, logistical fragmentation and price volatility. The combination of deep technologies such as artificial intelligence (AI), Internet of Things (IoT), blockchain and predictive analytics can improve the resiliency and efficiency of the supply chain. This paper is an econometric analysis of deep technology-based supply chain optimization in three litchi-producing districts in Assam, namely, Sonitpur, Jorhat, and Tinsukia, with a focus on the results of comparative performances. A panel dataset based on district-level observations was modeled with the help of fixed-effects and multivariate regression and the effect of technology adoption on the main supply chain indicators such as transportation efficiency, post-harvest loss rates, price realization and market integration were estimated. To determine inter-district differences and statistically significant determinants of efficiency gains, a comparative analysis was performed. The results show that there is a significant positive relationship between the deep technology adoption and supply chain performance. The level of deep integration of technology has a great effect on the optimization of supply chain in the litchi sector of Assam but it is not equally applied in all districts. To scale adoption, it is critical to strengthen digital infrastructure, encourage capacity-building efforts and enhance public-partnerships. The research offers empirical findings to define policy formulation and specific interventions to enhance the effectiveness and sustainability of Agri-supply chains in resource-limited areas.

Keywords: Deep technology, supply chain optimization, econometric analysis, litchi industry, Assam, AI, IoT, blockchain

1. Introduction

Agriculture remains one of the pillars of economic organization of India with extensive contribution to generating jobs, livelihoods, and food security of the nation. In this general industry, the horticulture has become a high value subsector owing to its income diversification capability, export income and nutritional security. India is among the top producers of fruits and vegetables in the world and the horticulture sector has always recorded higher growth rates and value addition than the traditional food grain production (Government of India, 2022; FAO, 2021) ^[7, 6]. Litchi is a unique horticultural commodity taking into consideration that it has great market demand, nutritional worth and export capacity. Nonetheless, it is extremely perishable, which requires an effective and adaptable supply chain system to maintain quality and deliver it to markets in time (Singh *et al.*, 2023) ^[9].

Litchi production and marketing are especially vulnerable to both time and environmental factors. The fruit has a narrow harvesting period and very prone to physiological decay, microbial and loss of moisture. As a result, any small inefficiencies in post-harvest processing, storage and transportation may cause significant quantitative and qualitative losses. Research has shown that losses of perishable horticultural commodities in India, post-harvest, are between 15 and 30 percent, which is mainly caused by the lack of a proper cold chain infrastructure, improper handling procedures, and logistical bottlenecks (FAO, 2021; World Bank, 2020) ^[6, 8]. Such losses do not only decrease the income of farmers but also lead to price fluctuations and inefficiencies in the market.

Assam is a state in the northeastern part of India that has become an important producer of litchi

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due to its conducive agro-climatic factors such as the right temperatures, fertile alluvial soils and sufficient rainfall. Sonitpur, Jorhat and Tinsukia are among the districts that are known to grow litchi and contribute significantly to the local agriculture sector. Although this is possible, the litchi supply chain in Assam is underdeveloped and disjointed. The lack of an integrated cold storage system, poor transportation infrastructure, ineffective access to real-time market information, and poor institutional coordination still hinder efficiency and competitiveness (Government of Assam, 2023). Such structural limitations can lead to distress sales and poor price realization to farmers and value chain wastage.

The development of deep technologies in recent years has brought about new opportunities to deal with long-standing inefficiencies in agricultural supply chains. The use of Artificial Intelligence (AI), Internet of Things (IoT), blockchain technology, and predictive analytics are becoming more mainstream in order to make operations more efficient, transparent, and decision-making. The use of AI can optimize logistics, predict demand, and enhance route planning, thus minimizing the delays and costs of transportation (Tripathi and Mishra, 2022) ^[5]. The sensors of IoT allow monitoring the temperature, humidity, and conditions in the storage in real time, which is essential to preserve the quality of perishable products (Rejeb *et al.*, 2020) ^[4]. Blockchain technology enables the sharing of data between stakeholders in a secure and transparent manner, making it more traceable and less information asymmetric (Kshetri, 2018) ^[2]. Moreover, predictive analytics systems may help to predict market trends and price changes, allowing farmers and traders to make informed choices (Wolfert *et al.*, 2017) ^[3].

It is on this background that this research attempts to fill this gap by undertaking an econometric analysis of deep technology-based optimization of the supply chain in the litchi industry in Assam. The paper will examine how far the use of AI, IoT, blockchain, and other technologies impact the main supply chain indicators of transportation efficiency, post-harvest losses reduction, price realization, and market integration, based on three Litchi producing districts, including Sonitpur, Jorhat, and Tinsukia. The study offers a comparative and evidence-based evaluation of the technological impact by district, using panel data analysis and fixed-effects regression models.

This study is important as it contributes to the academic literature and policy discourse. Not only does it contribute to the knowledge base of supply chains of agricultural technologies in the emerging economies, but it also provides practical information to policymakers, practitioners and stakeholders who want to maximize efficiency, limit losses and maximize the welfare of the farmers. By doing this, the research aligns with more national and global goals of sustainable agricultural development, reducing food waste, and digital innovation to support inclusive rural development (OECD, 2019; World Bank, 2020) ^[10, 8].

2. Literature Review

The adoption of modern technologies in supply chains in agricultural operations has been a topic that has garnered considerable attention over the last few years especially in terms of enhancing efficiency, minimizing post-harvest losses, and market connections. An expanding literature shows the disruptive potential of digital innovations like Artificial Intelligence (AI), the Internet of Things (IoT), blockchain, and predictive analytics in dealing with structural inefficiencies in agri-value chains (Tzounis, A., *et al.*, 2017) ^[14].

One of the major areas of study is the use of Artificial Intelligence (AI) in supply chain and logistics optimization. Artificial intelligence (AI) systems, such as machine learning algorithms and route optimization models, have shown significant potential in transportation time minimization, fuel consumption, and accuracy in delivery. Research has shown that AI-powered logistics planning will be able to optimize routes dynamically according to the real-time traffic, weather patterns, and variable demand, thus delivering perishable goods in time. Such optimization is important in the context of horticultural produce, where a delay may cause rapid spoilage of the produce, and minimize of economic losses (Zhang, Y., *et al.*, 2021) ^[13].

The other significant direction of research is the use of the Internet of Things (IoT) in cold chain management. Both IoT sensors and devices enable real-time monitoring of temperature, humidity, and conditions in the storage devices, as well as the supply chain. Empirical research has demonstrated that continuous monitoring is very effective in minimizing spoilage and preserving quality of products, particularly the highly perishable fruits. Automated alerts and corrective measures are also facilitated by IoT systems and allow avoiding deviations of optimal storage conditions. This means that farmers and distributors will be able to guarantee a higher shelf life and market value of their produce (Kamilaris, A., *et al.*, 2018) ^[12].

There has also been a lot of attention to the role of blockchain technology in the agricultural supply chains. The blockchain is a decentralized and unchangeable system of ledgers that can increase transparency and traceability in every step of the supply chain. Available literature indicates that blockchain has the potential of addressing information asymmetry, fraud, and creating trust among existing stakeholders including farmers, traders, retailers, and consumers. Blockchain allows the end-to-end traceability of agricultural goods, assuring consumers of the source, quality, and treatment of the materials, making it especially essential in markets such as export-based and quality-sensitive ones.

Also, predictive analytics have become an effective demand forecasting and price prediction tool. Predictive models can be used to make sound predictions based on historical evidence, weather trends, market trends, and consumer behaviour to assist stakeholders make informed decisions. Studies have shown that these analytics can decrease market uncertainty, eliminate excess production and stabilize prices. To farmers, it will mean that they are able to plan their harvests more efficiently and have a more stable income whereas to the supply chain actors, it will mean that it is easier to plan their inventory and efficiently plan their distribution (Li, X., Wang, Y., *et al.*, 2020) ^[11].

Although there has been a lot of research on these technological interventions, a clear gap in region and crop-specific research has been observed. Specifically, there is a dearth of scholarly literature regarding the use of these technologies in Assam, the litchi supply chain of which has a favorable agro-climatic environment but is marred by infrastructural and logistical problems. Also, current research is usually generalized and does not focus on localized differences in production, infrastructure and technological adoption, which is imperative in explaining localized differences (Aker, J. C. 2011) ^[1].

Hence, the research attempts to fill this gap by analyzing how deep technologies can enhance the efficiency of the litchi supply chain in Assam, with particular attention to the differences on the district level. In this way, it will have the potential to contribute to the academic literature as well as policy making, providing insights that will be relevant to the regional agricultural contexts (Wolfert, S., *et al.* 2017) ^[3].

3. Materials and Methods

Data Collection

The panel data that the study uses is based on

- Farmer surveys
- Agricultural departments
- Market committees
- Secondary data (government reports).

Table 1: Variables

Dependent Variables:		Independent Variables:	
1	Transportation efficiency	1	AI adoption level
2	Post-harvest loss rate	2	IoT usage
3	Price realization	3	Blockchain integration
4	Market integration index	4	Digital infrastructure index

Econometric Model

To examine the impact of deep technology adoption on supply chain performance, the study employs a panel data regression model using a fixed-effects approach.

The general econometric model is specified as:

$$Y_{it} = \beta_0 + \beta_1 AI_{it} + \beta_2 IoT_{it} + \beta_3 BC_{it} + \beta_4 DI_{it} + \mu_i + \lambda_t + \epsilon_{it}$$

The model controls for unobserved district-level heterogeneity through fixed effects and ensures robustness in estimating the causal relationship between technology adoption and supply chain performance.

Where:

- Y_{it} = Supply chain performance indicator for district i at time t (measured using transportation efficiency, post-harvest loss rate, price realization, and market integration)
- β_0 = Intercept term
- AI_{it} = Level of Artificial Intelligence adoption
- IoT_{it} = Extent of Internet of Things usage in cold chain
- BC_{it} = Degree of Blockchain integration
- DI_{it} = Digital Infrastructure Index
- μ_i = District-specific fixed effect (captures unobserved heterogeneity across districts)
- λ_t = Time-specific effects
- ϵ_{it} = Error term

Expected Signs of Coefficients

- $\beta_1 > 0$: AI improves logistics efficiency
- $\beta_2 < 0$: IoT reduces post-harvest losses
- $\beta_3 > 0$: Blockchain improves price realization
- $\beta_4 > 0$: Digital infrastructure enhances overall efficiency

4. Results and Discussion

District-wise Comparative Analysis

The relative evaluation of Jorhat, Sonitpur, and Tinsukia reveals evident differences in the use of deep technologies and their influence on the effectiveness of the litchi supply chain. These differences are represented by quantitative measures in the following table:

Table 2: District-wise Comparison of Technology Adoption and Supply Chain Performance

Indicators	Jorhat	Sonitpur	Tinsukia
AI Adoption (%)	75%	50%	20%
IoT Usage in Cold Chain (%)	70%	45%	15%
Blockchain Integration (%)	60%	35%	10%
Transportation Efficiency (Index 1–10)	8.5	6.5	4.0
Cold Storage Availability (%)	80%	55%	25%
Post-Harvest Losses (%)	12%	22%	38%
Average Price Realization (₹/kg)	52	42	30
Farmer Income Growth (%)	28%	15%	5%

Interpretation

- Jorhat is the most technologically integrated, with the best logistics efficiency (8.5 index), minimum post-harvest losses (12%), and maximum price realization (₹52/kg).
- Sonitpur shows moderate adoption resulting in partial efficiency and wastage reduction.
- Tinsukia is far behind, and it has a low level of technology utilization, a lot of losses (38 percent) and low growth of farmer income.
- The statistics clearly show that the adoption of technology and supply chain performance is in a direct relationship where Jorhat is the most underdeveloped and Tinsukia is at the forefront.

Regression Findings

The regression analysis was done to determine the effects of the technological variables on the key supply chain outcomes. The results are presented below:

Table 3: Regression Results

Independent Variable	Dependent Variable	Coefficient (β)	t-Value	p-Value	Interpretation
AI Adoption	Transportation Efficiency	+0.68	4.52	0.001	Strong positive impact
IoT Implementation	Post-Harvest Losses	-0.55	-3.98	0.002	Significant reduction in losses
Blockchain Usage	Price Realization	+0.47	3.21	0.004	Improves transparency & pricing
Digital Infrastructure	Overall Efficiency	+0.72	5.10	0.000	Critical enabling factor

Table 4: Model Summary

Statistic	Value
R ² (Coefficient of Determination)	0.74
Adjusted R ²	0.71
F-Statistic	18.65
Significance Level	$p < 0.05$

Regression Results Interpretation

- The results of the regression indicate that all the independent variables, which include AI, IoT, blockchain,
- and digital infrastructure, are statistically significant ($p < 0.05$) in terms of their effect on supply chain performance.
- The most positive impact on transportation efficiency (0.68) is related to AI adoption, where the logistics will be improved, and the delays will be minimized.
- The application of IoT helps considerably in minimizing the post-harvest losses (-0.55), which confirms its application in cold chain monitoring.
- Price realization ($\beta = 0.47$) is increased by blockchain technology, which advances transparency and trust.

- Digital infrastructure (0.72) is the most impactful factor, serving as a source of all technological interventions.
- The large R² (0.74) indicates that the model accounts a significant amount of variation in supply chain efficiency.
- The tabular analysis is a strong indicator that districts that are more deeply technology adoptive will have a better supply chain performance, less wastage and more income to the farmers. Jorhat can be considered as an example, Sonitpur demonstrates the progress of
- Transition and Tinsukia emphasizes the necessity to develop the technology and infrastructure.

The results underpin the thesis that to revolutionize perishable agricultural supply chains like litchi in Assam, the adoption of technologies must be integrated with the strong digital infrastructure.

Table 5: Key Comparative Insights across Districts

Factors	Jorhat	Sonitpur	Tinsukia
Technology Integration	High and well-coordinated	Moderate and uneven	Minimal
Infrastructure Availability	Strong digital and cold chain infrastructure	Partially developed	Weak infrastructure
Stakeholder Awareness	High awareness and training	Moderate awareness	Low awareness
Institutional Support	Active government and private participation	Limited support	Weak support systems
Supply Chain Efficiency	Highly efficient	Moderately efficient	Inefficient
Overall Outcome	Model district	Transitional stage	Lagging district

Interpretation and Discussion

The comparison based on the districts reveals that Jorhat is an exemplary district, which was partly caused by high-level integration of digital technologies and close collaboration of the interested parties. Jorhat has been able to capitalize on the full potential of AI, IoT, and blockchain due to the availability of sound digital infrastructure, strong awareness among farmers and supply chain players, and the presence of efficient institutional support infrastructure. This has led to streamlined logistics, less wastage and better economic results. Sonitpur, however, is a picture of an intermediate period when some technology adoption has resulted in moderate development. Although there are certain improvements, the infrastructure gaps and unequal rates of awareness do not allow to realize the technological benefits to the full extent. This implies that a non-systemic adoption yields partial efficiency benefits. On the contrary, Tinsukia demonstrates the constraints of the low technological penetration. Lack of proper infrastructure (especially digital infrastructure and cold chain) and poor awareness among the stakeholders severely limits the implementation and application of modern technologies. Consequently, the district has still experienced inefficiency in terms of high post-harvest losses, ineffective logistics and fluctuations in prices. This highlights the point that in the absence of the support systems, even the sophisticated technologies cannot produce any meaningful results. Comprehensively, the discussion supports the idea that although deep technologies are potent instruments to transform agricultural supply chains, enabling ecosystems are instrumental in this process. Technological adoption should be accompanied

Discussion

The research results clearly show that implementing the deep technologies, i.e. the Artificial Intelligence (AI), Internet of Things (IoT), blockchain and predictive analytics, are instrumental in improving the effectiveness of the agricultural supply chains. The areas where improvements are noticeable include optimization of transportation, minimization of post-harvest losses and improved prices to farmers. Nevertheless, the findings also show that there exists a large difference between districts, which means that the technology adoption is not enough but should be facilitated by the enabling conditions that include infrastructure, awareness, and institutional support. To further explain these variations, the following are the main points of discussion:

by infrastructure development, capacity building and institutional support in order to bring about sustainable and inclusive growth. Therefore, the paper highlights regional imbalances can be addressed using a comprehensive strategy, in which underperforming districts such as Tinsukia should be assisted through specific interventions, and effective models such as Jorhat can be applied and expanded to other similar agro-economic settings.

5. Key Findings

The current research offers significant empirical data that the adoption of deep technologies, including Artificial Intelligence (AI), Internet of Things (IoT), blockchain, and data-driven analytics, can greatly contribute to the effectiveness, transparency, and efficiency of the litchi supply chain. Based on the findings, it is evident that there are logistics optimization, post-harvest losses are reduced, price realization is better and farmers receive higher income in areas where there is greater technological adoption. Nonetheless, another crucial problem pointed out in the study is the imbalanced implementation in districts. Although the level of technological adoption and effective supply chain operations is high in districts such as Jorhat, other areas such as Sonitpur and particularly Tinsukia are still underdeveloped owing to the inadequate infrastructure, low awareness, and poor systems of institutional support. This gap limits the maximum productivity of the digital transformation that is possible in agriculture. To summarize the main findings more, the final observations will be included below:

Table 6: Summary of Key Findings

Aspect	Observation
Technology Impact	Significant improvement in supply chain efficiency through AI, IoT, and blockchain
Best Performing District	Jorhat (high adoption and strong outcomes)
Moderate Performance	Sonitpur (partial adoption and moderate gains)
Lowest Performance	Tinsukia (minimal adoption and persistent inefficiencies)
Major Constraints	Infrastructure gaps, low awareness, weak institutional support
Overall Outcome	Positive impact but uneven distribution of benefits

6. Policy Implications

The empirical results of the research point out that deep technologies have a strong positive effect on supply chain efficiency, but this effect depends on the supportive policy

frameworks and enabling conditions. The following policy implications are suggested in order to have equity and large-scale benefits across districts especially in lagging regions:

Table 7: Policy Recommendations and Expected Outcomes

Policy Area	Key Measures	Target Stakeholders	Expected Outcomes
Infrastructure Development	Expand rural broadband connectivity; establish modern cold storage and pack-house facilities	Government agencies, infrastructure providers	Improved logistics efficiency, reduced post-harvest losses
Capacity Building	Conduct training programs, workshops, and digital literacy campaigns for farmers and supply chain actors	Farmers, FPOs, agri-entrepreneurs	Enhanced adoption of AI, IoT, and digital tools
Public–Private Partnerships (PPP)	Promote collaboration between government, startups, and private firms for technology deployment	Government, private sector, agri-tech companies	Faster diffusion of innovation and cost-effective implementation
Subsidies & Incentives	Provide financial support, subsidies, and tax incentives for adopting IoT devices, AI-based tools, and cold chain technologies	Farmers, cooperatives, SMEs	Increased affordability and higher technology adoption rates
Data Governance Framework	Develop policies for secure data sharing, blockchain regulation, and transparency standards	Policymakers, tech providers, regulatory bodies	Enhanced trust, data security, and accountability in supply chains

Detailed Discussion of Policy Implications

1. Infrastructure Development

The paper highlights the importance of infrastructure, especially, digital connectivity and cold chain systems, in facilitating technological change. Investment in rural broadband networks and temperature-controlled storage facilities should be a priority of policymakers to enable real-time monitoring and effective logistics. The advantages of AI and IoT are not achievable without these underlying infrastructure.

2. Capacity Building

One of the most significant obstacles that were revealed in less-developed districts is the ignorance and technical illiteracy of farmers and other stakeholders. The organized training, digital literacy and extension services should be implemented to provide the user with the knowledge needed to use and enjoy the advanced technology. Capacity building does not only guarantee adoption, but also successful utilization.

3. Public–Private Partnerships (PPP)

The involvement of both the government and the business community can speed up the process of implementing new solutions. With government aid and the skills and technological capabilities of the private sector, resource gaps can be overcome and scalable implementation guaranteed. PPP models have proved especially useful in bringing about cost efficient and locally flexible technologies.

4. Subsidies and Incentives

The initial cost of investment is usually a detriment to farmers and other small stakeholders to adopt advanced technologies. This barrier can be greatly overcome through the provision of subsidies, financial support, and tax incentives. Specific initiatives to stimulate the adoption of IoT devices, AI-driven logistics solutions, and cold chain technologies can lead to extensive adoption.

5. Data Governance Framework

As the use of digital technologies and blockchain systems becomes more and more important, the role of solid data governance becomes pivotal. The policymakers should come up with strict laws to protect the data security, privacy and transparency. A clear structure will improve confidence of the stakeholders and will encourage the ethical and efficient use of data throughout the supply chain.

The policy implications underline that technological progress should be underpinned with the institutional support, investment in infrastructures, and regulations. A multi-stakeholder and coordinated strategy is needed to address regional inequalities, and to make the benefits of deep technologies reach all districts so that we have a more resilient and efficient agricultural supply chain.

7. Conclusion

The research concludes by stating that although deep technology integration can potentially revolutionize the agricultural supply chains, the success of this technology is very sensitive to the favorable ecosystem conditions. Technological tools on their own cannot work without good infrastructure, capacity building and good institutional structures.

Thus, the litchi supply chain needs specific and integrative interventions to be realized to ensure a sustainable and scalable enhancement of the situation, especially in the underdeveloped districts. The development of the rural digital infrastructure, raising the awareness of the stakeholders, and encouraging coordinated institutional support will play a critical role in the balance of regional development. Overall, the paper highlights that the future of agriculture supply chains is in the comprehensive combination of technology with facilitating policy and socio-economic support structures, so that the fruits of innovation percolate up and down the farming ecosystem.

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