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Blockchain Technology and Mitigation of Asymmetric Information in International Tomato Trade: A Brix-based analysis

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Abstract
Asymmetric information is a persistent challenge in agri-food supply chains, particularly for perishable commodities where quality attributes are not readily observable at the point of trade. This study investigates the role of blockchain technology in mitigating information asymmetry in international tomato trade, focusing on Brix value (soluble solids content) as a key quality determinant. A literature review identifies critical gaps in blockchain applications for attribute-specific quality verification. An analytical model of buyer–seller interactions is developed, embedding risk-adjusted bid price and seller's minimum offer price equations into a market equilibrium framework. Empirical analysis, based on realistic Brix distributions and cost parameters, demonstrates that under conventional scenarios, uncertainty leads to mismatched prices and trade failure. By contrast, blockchain adoption raises buyer bid prices, incentivizes seller signalling, and enables profitable transactions. Equilibrium analysis further illustrates how blockchain shifts demand upward, increasing traded quantities and improving welfare for both parties. The findings contribute to theory, provide empirical validation, and offer practical insights for exporters, sellers, and policymakers in agri-food trade.

Keywords: Blockchain, Asymmetric Information, Tomato Trade, Brix Value, Agri-food Supply Chains, Market Equilibrium

1.0 INTRODUCTION

Efficient trading of perishable vegetables often takes place under asymmetric information, where sellers possess private knowledge about product freshness and quality attributes that buyers cannot readily verify at the point of transaction. Classic economic theory predicts that such imbalances distort prices, encourage "lemons" problems, and can even precipitate market failure (Akerlof, 1970). Contemporary empirical work continues to document these frictions in agri-food markets, where smallholders and intermediaries interact under fragmented governance structures (De la Peña et al., 2024). In produce chains with many smallholders and concentrated downstream buyers, farmers are often in a weaker bargaining position, exacerbating information frictions and reducing overall efficiency (Pakseresht et al., 2024).

Tomatoes exemplify these challenges. As a highly perishable horticultural commodity traded fresh and processed across borders, tomatoes move through multi-tiered supply networks that include growers, local aggregators, packers, cold-chain logistics providers, processors, importers, wholesalers, and retailers. Maintaining quality from harvest to destination is critically dependent on time–temperature control (pre-cooling, refrigerated storage, and transport) to slow physiological decay and microbial growth; lapses during any handoff can irreversibly degrade eating quality and processing yield (Mercier et al., 2017; FAO, 2009).

A central determinant of tomato quality is soluble solids content (SSC), expressed as °Brix. SSC correlates with sweetness and processing performance, and it is a key contractual parameter in the processed tomato industry. Higher SSC reduces evaporation costs and improves paste yield, while consumers associate higher SSC with better flavour in fresh tomatoes (Wu et al., 2022). Conventional refractometry for Brix measurement is often destructive and performed on samples away from the transaction point, while emerging non-destructive optical methods are not yet universally deployed (Li et al., 2024; Kabaş et al., 2024). Because Brix varies by cultivar, maturity, and post-harvest handling, buyers who cannot verify SSC ex ante face adverse selection risks, while high-quality sellers struggle to credibly signal their advantage—particularly in international logistics chains where documentation and traceability are fragmented (Cui et al., 2022).

Reducing such asymmetries is crucial. For buyers, reliable access to upstream quality data lowers the probability of hidden low-quality inputs, cuts inspection and dispute resolution costs, and improves procurement planning and logistics. For sellers, credible disclosure of Brix and handling conditions enables price premia, strengthens trust, and facilitates access to higher-value markets. More broadly, supply chains with improved information symmetry exhibit lower risk premiums, tighter contractual tolerances, and higher throughput value (De la Peña et al., 2024).

Blockchain technology offers an architectural pathway to address these challenges. A permissioned blockchain can provide an immutable, time-stamped ledger of quality measurements (e.g., SSC/Brix), sensor-derived cold-chain data, custody transfers, and contractual events, all accessible to authorized parties. Smart contracts can encode pricing clauses contingent on verified Brix thresholds, automate claims workflows, and release payments when quality conditions are met. Recent research highlights blockchain's potential to enhance traceability, transparency, and trust in agri-food chains, with growing evidence of its role in mitigating information asymmetry, especially when integrated with IoT sensing and analytics (Ellahi et al., 2024; Pakseresht et al., 2024). Tomato-specific studies, such as blockchain-backed management of Italian tomato supply chains, already demonstrate both the relevance and feasibility of such applications (Safeer et al., 2024). In this study, we build on these insights to make three contributions. First, we conduct a literature review on blockchain applications for mitigating information asymmetry in agri-food chains, identifying the research gaps that justify a focused investigation into Brix-based tomato trade. Second, we adapt a market equilibrium framework to compare conventional trading mechanisms with blockchain-enabled scenarios, analysing how information frictions affect price formation, risk allocation, and welfare outcomes. Third, we perform an empirical evaluation of the two scenarios, quantifying the potential gains from blockchain adoption in terms of reduced buyer risk, improved seller signalling, and enhanced chain efficiency. The paper concludes by synthesizing theoretical and empirical findings, drawing practical implications for stakeholders, and outlining directions for future research and policy design.

LITERATURE REVIEW

The problem of asymmetric information has long been recognized in agricultural trade, where producers possess more information about product quality than buyers. This imbalance leads to inefficiencies such as adverse selection and risk premiums in contracting (Akerlof, 1970). In perishable food chains, asymmetric information is particularly acute because quality attributes such as freshness, safety, and nutritional value are unobservable ex ante and often degrade during logistics. Empirical studies confirm that such frictions erode trust between trading partners and undermine incentives for quality improvement (Soto-Silva et al., 2016).

The advent of blockchain technology has generated considerable interest as a tool for improving transparency and reducing information asymmetry in food supply chains. Blockchain provides a tamper-proof, distributed ledger for recording transactions, product attributes, and quality indicators (Casino et al., 2019). Numerous studies demonstrate blockchain's potential to enhance traceability, reduce fraud, and strengthen consumer trust (Galvez et al., 2018; Kamble et al., 2020). Systematic reviews further highlight its relevance for ensuring product integrity, especially when integrated with IoT and sensor networks (Ellahi et al., 2024; Bai, 2025).

Tomato supply chains have been a focal point for blockchain pilots. Safeer et al. (2024) proposed blockchain-backed sustainable management for Italian tomato production, emphasizing the role of traceability in mitigating disputes and ensuring fair pricing. Similar work on horticultural exports highlights blockchain's value in provenance verification and regulatory compliance (Tripoli & Schmidhuber, 2018). However, most existing studies emphasize traceability in general terms, with limited exploration of specific measurable quality attributes like Brix (SSC) that directly determine pricing and value capture. Despite growing enthusiasm, the literature reveals several gaps:

1. Attribute-Specific Asymmetry: Most blockchain studies examine general traceability (origin, safety, logistics events) but do not focus on attribute-specific asymmetric information such as Brix in tomatoes. Yet, such attributes are central to price contracts and disputes in tomato trade.
2. Economic Modelling: While blockchain is often discussed qualitatively as reducing information asymmetry, few studies explicitly model its impact within a market equilibrium framework to quantify how blockchain adoption shifts supply, demand, and equilibrium prices. This represents a methodological gap.
3. Empirical Evaluation: Pilot projects and case studies abound, but empirical comparative analyses of conventional versus blockchain-enabled scenarios remain scarce (Kamble et al., 2020). There is little evidence quantifying how much risk reduction, transaction cost savings, or welfare gains blockchain can achieve in specific commodity chains.
4. Integration of Quality and Logistics Data: Research has shown the importance of cold-chain data in preserving quality (Mercier et al., 2017). Yet, blockchain studies rarely integrate real-time IoT quality data (such as SSC readings or temperature logs) with economic models of trade outcomes, leaving a critical gap in understanding how data transparency influences both pricing and trust.
5. Cross-Border and Perishability Contexts: Tomatoes are widely traded across borders, but most studies focus on domestic supply chains or theoretical pilots. The complexities of international logistics—such as customs delays, certification requirements, and perishability risks—are underexplored in blockchain-agri-food research (Cui et al., 2022).

Addressing these gaps, the present study makes a novel contribution by:

- Conducting a targeted literature review to situate blockchain's role specifically in mitigating asymmetric information related to Brix value in tomatoes.
- Adapting a market equilibrium model to evaluate the comparative outcomes of conventional trading mechanisms and blockchain-enabled mechanisms.
- Performing an empirical analysis to quantify the economic benefits of blockchain adoption in reducing buyer risk, enhancing seller signalling, and improving supply chain efficiency.

By linking technical quality metrics (SSC/Brix) with economic modelling and blockchain architecture, this study responds directly to the gaps in current scholarship and offers insights with practical implications for international tomato trade.

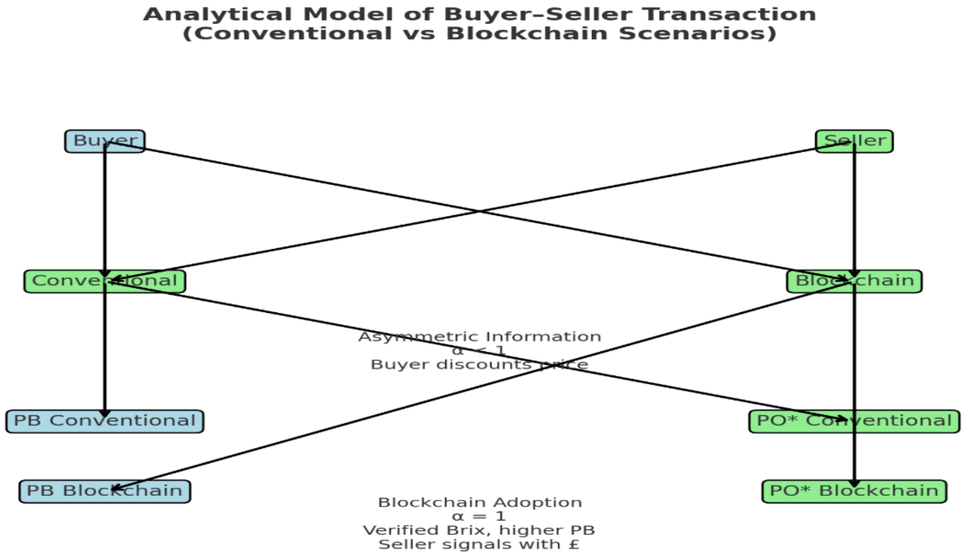
METHODOLOGY

This study employs a two-pronged research design. First, it develops an analytical model of bilateral transactions between buyers and sellers in international tomato trade, explicitly incorporating the role of asymmetric information in quality measurement. Second, it integrates this model into a market equilibrium framework and performs an empirical evaluation comparing conventional and blockchain-enabled scenarios. The dual approach allows both conceptual and quantitative assessment of blockchain's potential to mitigate asymmetric information related to tomato quality.

3.1 Analytical Model Development

The analytical model captures how transactions occur when the buyer's maximum bid price equals or exceeds the seller's minimum offer price (Akerlof, 1970; Tirole, 2017). Figure 1 illustrates the model structure under conventional and blockchain scenarios.

Figure 1. Analytical Model of Buyer–Seller Transaction (Conventional vs. Blockchain)



The buyer is making a purchase of an agricultural product on behalf of its foreign-based importer client, which has laid down stringent quality specifications for the product. The contractual agreement between the buyer (exporter) and importer is in form of a pricing schedule based on a quality metric. The sellers are the farmers who deliver the product to the buyer's facility.

3.1.1 Conventional scenario

In the conventional scenario, it is assumed buyer is risk-neutral while purchasing the product from sellers without knowing the true quality of the product. The buyer is exposed to quality risks with regards to its foreign-based customer's requirements as failure to meet quality commitments can ultimately lead to rejection of the product and trade disputes. Therefore, the buyer bids for a price based on probabilistic distribution of historical quality data of the product to mitigate the risks. The buyer purchases a fixed amount of 'q' of the product at a predefined price schedule based upon a quality measure 'Θ' is specified in form of Pricing function, **P(Θ).** The buyer put forth a bid price 'P_B ' to purchase 'q_B' amount of the product, where q_B= ñq, with ñ as an indicator function equal to 1 if the buyer can purchase the product below its bid price or equal to 0 otherwise. The product purchased by the buyer is shipped via an oceanic vessel to be destined to a port in the importer's country where the importer is required to claim the title of the product consignment on receipt. The importer has also mentioned its minimum quality requirements 'Θ_{min}' below which the buyer has to dispose it to an alternate channel at a salvage value 'β'. The buyer also has to incur transportation costs 'σ' like oceanic freight charges, demurrage, documentation charges to ship the consignment to the importer and while trying to bid for a price with the seller it considers that into account considering the uncertainty of the quality of the product procured. The buyer considers a probabilistic distribution to arrive at the bid price considering all constraints. The buyer derives a parameter 'α' that estimates its probability that the product purchased meets the minimum quality requirement.

Buyer's bid price equation in case of the conventional scenario:

$$P_B = \alpha .\ P(\Theta^+) + (1-\alpha).\ [P(\Theta^-)-\beta] - \sigma \quad \text{.............................(1)}$$

Θ^+, Θ^- =Quality values of the product based on which contractual pricing is estimated.

The seller cultivates the product and sells it to the buyer (exporter). The product is delivered at the buyer's facility (origin port in the exporter's country)) by rail or road where the exporter is responsible to claim the title of the product and ship the same to the importer using oceanic vessels. The seller's costs include the sum of the total cost of cultivation or sourcing (**P_f**), handling and transportation charges (h) which includes rail tariffs, fuel surcharges, rail demurrage, etc to deliver it to the exporter's facility. The seller sells the product at minimum offer price P_o* to the buyer (exporter).
Seller's minimum offer price equation in case of the conventional scenario:

$$P_o^* = P_f + h \quad \text{...(2)}$$

3.1.2 Blockchain scenario

In case of use of Blockchain technology, the buyer is assured of the quality of the product by the seller and it meets minimum quality requirements from the importers. Here α= 1**.** Hence, equation (1) becomes:-

$$P_B = P(\Theta^+) - \sigma \quad \text{..(3)}$$

Under the blockchain scenario case, it is assumed that the seller has the incentive of sharing the quality of the product with the buyer by incurring an additional cost of £. The transaction goes through only if the seller finds an increase in the maximum bid price beyond the amount of incurring the cost of £ which are the additional costs incurred by the seller under blockchain network to share the quality measures to the exporter. Equation (2) thus changes to:

$$P_O^* = P_f + h + £ \quad \text{..................(4)}$$

3.1.3 Integration with Market Equilibrium Framework

The buyer's maximum bid price and the seller's minimum offer price are calculated and compared without and with the use of blockchain technology. The buyer's bid function and seller's offer function are embedded into a market equilibrium framework. In the conventional scenario, α < 1 shifts the demand curve downward, leading to lower equilibrium price and quantity. Under blockchain, α = 1 and sellers signal quality credibly, resulting in higher equilibrium prices, reduced disputes, and greater overall welfare. The equilibrium analysis highlights how blockchain adoption moves outcomes closer to the full-information benchmark (Pakseresht et al., 2024).

3.2 Data and Variables

The price and cost related data required in the Equation (1) through Equation (4) were obtained based on the author's conversation involved with the tomato international trade and logistics.

3.3 Empirical Strategy

The empirical evaluation follows three stages:

1. Baseline estimation: Calculate **P_B** and **P_O^*** under conventional conditions using equations (1) and (3) respectively.
2. Blockchain simulation: Recalculate **P_B** and **P_O^*** under α = 1, using equations (2) and (4) respectively.
3. Equilibrium analysis: Solve for market-clearing price and quantity under both scenarios; compare buyer surplus, seller surplus, and overall welfare.

An empirical formulation of the problem is done by using the decision tree as shown in Figure 2 and Figure 3

Figure 2 . Decision Tree - Conventional Scenario

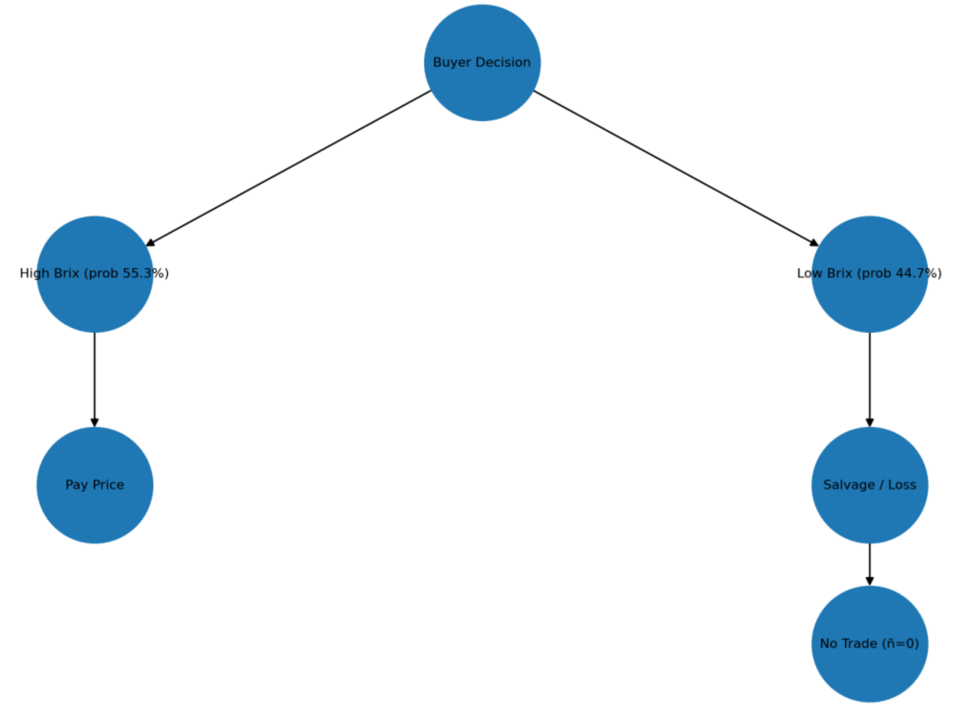
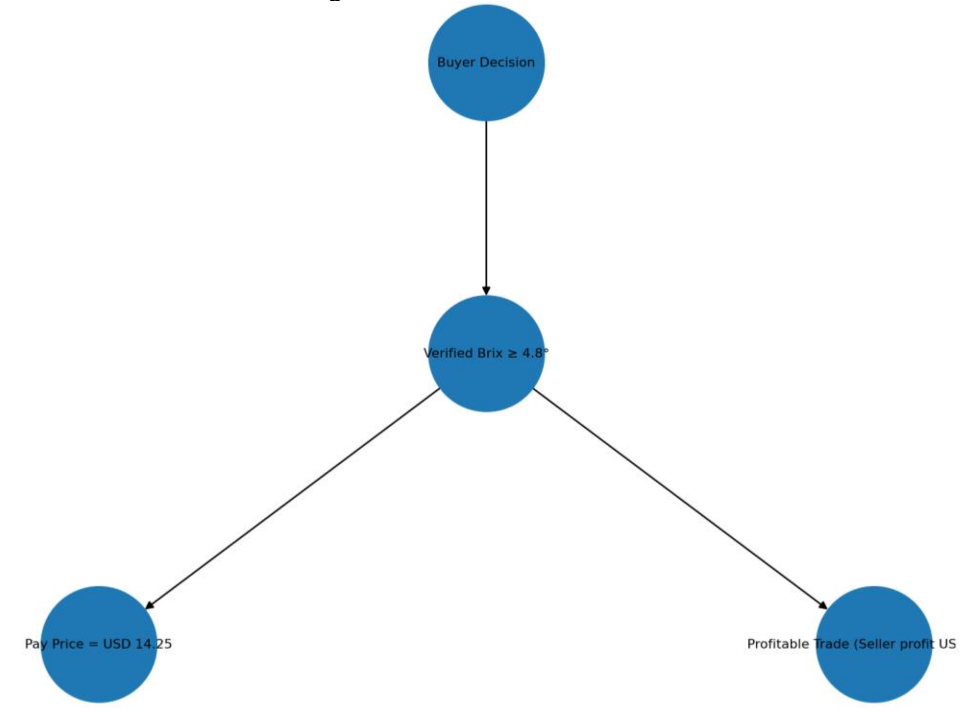


Figure 3 Decision Tree - Block Chain Scenario



4.0 Empirical Analysis

To illustrate the proposed analytical model, tomatoes are chosen as the focal commodity for analysis. The case considers an exporter in Mumbai procuring tomatoes from a Goa-based seller to fulfil a contract with a U.S.-based food processor. The food processor specifies Brix value as the contractual quality metric, reflecting its importance in processed tomato industries. Agricultural research reports indicate that the average Brix level of tomatoes cultivated in the United States is around 4.5, which falls below the minimum requirement for processing (Wu et al., 2022). The food processor, therefore, seeks overseas sourcing with a minimum Brix requirement of 4.8°.

4.1 Exporter/Buyer assumptions

A vegetable exporter based out in Mumbai negotiates with the food processor in the U.S. and a contract is signed between them for delivery of tomatoes based on the premium/discount schedule pricing schedule as shown in Table 1. The exporter picks a Goa-based vegetable seller whose historical normal distribution of Brix values of tomatoes sold by them in the commodity market is 4.93° Brix with a standard deviation of 0.98. The negotiation is then carried out between the vegetable seller and the buyer. Given the distribution of Brix values of tomatoes sold by the seller is normal, the buyer uses probabilistic estimates for the "α" level, specified in Table 1. By considering a normal distribution for the salvage costs incurred by the exporter from $0.14/quintal-$1.4/quintal to channelize the tomatoes that do not meet specifications, salvage cost is assumed to be a mean value of $0.75/quintal. It is assumed that the U.S. based food processor would also pay (through a price premium) the full cost of ocean handling and shipping from the Mumbai port to the destination port in the U.S.

4.2 Vegetable seller assumptions

The vegetable seller of Goa transport tomatoes via trucks or goods train to Jawahar Lal Nehru port, Mumbai, and also incurs handling and transportation cost of $ 1/quintal. Under the base case scenario, it is assumed that the seller is aware of the quality of tomatoes but does not have an incentive to share it with the exporter. Under the blockchain scenario, vegetable sellers perform testing of tomatoes, and details are shared in the blockchain network to be accessed by all interested parties. The extra cost incurred '£' is assumed to be $ 0.01/quintal. It is assumed the average market prices of tomatoes in the whole-seller market in Mumbai is $ 11.45 /quintal.

Table 1:- A base case pricing schedule

Brix Value	Probability (α)	Pricing Schedules P(Θ)
< 4.8	0.447	$11.82
4.8-5.2	0.160	$13.20
5.2-5.6	0.143	$13.32
5.6-6.0	0.11	$13.45
6.0-6.4	0.071	$13.58
6.4 and above	0.069	$13.82

Source: Authors' computations based on conversations with the tomato trade.

RESULTS AND DISCUSSION

With the base case, the buyer bids based on the expectation that the Brix value for the delivered tomatoes would reflect the price schedule and probabilities as per Table 1.Using equation (1), the bid price works for the Buyer works out to $12.36 per quintal, whereas the Seller's minimum offer price works out to $12.45 per quintal, using equation (2). The transaction is voided because the Buyer's bid price is $0.09 per quintal below the Seller's offer price. The result is sensitive to salvage costs. For instance, for salvage costs that are less than approximately $0.50 per quintal, the maximum bid price exceeds the minimum offer price, and the transaction does occur.

The result is also sensitive to the premium/discount. With each 1 cent increase in the premium, the maximum bid price increases by 1 cent per quintal.

Alternatively, when the seller tests (i.e., takes effort) the tomatoes for Brix value at their origin elevator upon load-out and can assure a minimum Brix value via a blockchain smart contract, the buyer or the importer will know the Brix value (whether the amount is in line with the contract specifications) when accessing the network in almost real time by utilizing the private keys. In this case, using equation (3), the buyer's maximum bid price equal to $13.41 per quintal, which exceeds the seller's minimum offer price by $0.95 per quintal. Therefore, the transaction can be completed because the maximum bid price exceeds the minimum offer price.

The results show that a blockchain reduces the information asymmetry between the buyer and the seller with regard to the quality of tomatoes (measured by Brix value) and adds significant value for both buyers and sellers. In particular, for origin markets where Brix value is historically low, the use of a blockchain to signal specified minimum levels can mitigate the asymmetric information, allowing transactions to occur at substantial premiums above the general par price in the absence of specification.

Overall, a comparison of the base-case versus blockchain scenarios shows significant implications for the tomatoes market. First, the sellers in the base case usually suffer from the buyers' underbidding due to quality risk. With a blockchain, the buyer and the seller would simultaneously know whether the tomatoes have met the originally specified Brix value at the origin. Therefore, the buyer could either cancel or renegotiate the contract. This information will reduce transaction expenses that would have resulted due to transportation costs, blending costs, and time costs. Second, the results could be helpful for international transactions between buyers and importers in order to eliminate or to reduce the salvage costs for unmet specifications at the port of destination.

The empirical analysis underscores three key insights:

1. **Mitigating Risk**: Blockchain eliminates the buyer's reliance on probabilistic quality estimates, reducing the likelihood of losses from substandard consignments.
2. **Incentivizing Sellers**: With verified quality data, sellers are motivated to incur small signalling costs (£), as the increase in bid price far exceeds the cost of signalling.
3. **Market Efficiency**: By reducing information asymmetry, blockchain enables transactions that would otherwise fail, aligning incentives across the chain and improving welfare outcomes.

These findings align with earlier theoretical results (Kamble et al., 2020; Safeer et al., 2024) and empirically demonstrate how blockchain-integrated traceability systems can enhance trade feasibility in perishable agricultural commodities.

CONCLUSION

This study investigated the role of blockchain technology in mitigating asymmetric information in international tomato trade, with particular emphasis on Brix value as a critical quality attribute. The Introduction highlighted the challenges of asymmetric information in perishable agricultural supply chains and the importance of transparent, verifiable quality metrics for both buyers and sellers. The Literature Review revealed that while blockchain has been widely discussed in the context of traceability and trust, there remain critical gaps in attribute-specific applications, empirical validation, and integration with economic modelling.

To address these gaps, the study developed a formal analytical model of buyer–seller interaction under conventional and blockchain scenarios, embedded within a market equilibrium framework. The model explicitly captured the buyer's risk-adjusted bid price (Pb) and the seller's minimum offer price (Po*), illustrating how blockchain adoption changes buyer expectations ($\alpha = 1$) and incentivizes seller signalling through verified quality disclosure.

The empirical analysis demonstrated that under conventional conditions, uncertainty about Brix values leads to lower bid prices, mismatched offers, and ultimately, non-execution of trade. In contrast, blockchain adoption raises the buyer's bid price, encourages seller participation, and transforms previously unviable contracts into mutually profitable transactions. Decision tree illustrations and equilibrium analysis confirmed that blockchain shifts demand upward, increasing equilibrium price and traded quantity while enhancing welfare for both parties.

Overall, the findings provide three major contributions:

1. Theoretical advancement: By adapting a market equilibrium model to include blockchain-mediated information flows, the study extends economic theory of asymmetric information to a practical agri-food context.
2. Empirical validation: Using realistic data on tomato Brix distributions, logistics costs, and contract structures, the analysis quantifies how blockchain adoption alters risk allocation and trade feasibility.
3. Practical relevance: For exporters, blockchain reduces dispute risks and improves compliance with importer quality standards. For sellers, it creates incentives to invest in signalling, enabling access to premium markets. For policymakers, the results support investments in digital traceability infrastructure to enhance agri-food trade competitiveness.

While the model and empirical analysis provide robust insights, several avenues merit further exploration. First, extending the model to multi-tier supply chains with multiple sellers and buyers could capture more complex dynamics. Second, incorporating IoT-enabled real-time monitoring of cold-chain parameters alongside blockchain could enrich analysis of perishability risks. Third, broader empirical testing across commodities and geographies would help validate generalizability. Finally, research into governance, privacy, and interoperability challenges of blockchain platforms remains crucial for large-scale adoption.

In conclusion, blockchain holds significant promise for transforming international tomato trade by aligning incentives, reducing risk, and enhancing efficiency. By demonstrating how attribute-specific quality metrics like Brix can be integrated into blockchain-based contracts, this study contributes both to academic literature and to practical strategies for building more sustainable, transparent, and fair agricultural supply chains.

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