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ARTICLE

Blockchain in the Agri-Food Supply Chain: A Game-Theoretical Approach for a Strategic Solution to Information Asymmetry

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ABSTRACT

The increasing complexity of global agri-food supply chains has exacerbated the issue of information asymmetry, undermining trust among stakeholders and compromising transparency in production processes. In such a fragmented and opaque ecosystem, the ability to access reliable, verifiable information becomes not just a competitive advantage but a necessity for the sustainability, accountability, and resilience of the entire agri-food supply chain. This study explores the potential of blockchain technology as a strategic tool to mitigate such asymmetries by developing a formal model grounded in evolutionary game theory. The model simulates the strategic interactions between supply chain actors, specifically, the choice to cooperate by sharing truthful information or to defect by concealing or falsifying it, within a blockchain-enabled environment. By employing a two-strategy replicator dynamic, the research identifies the conditions under which cooperation becomes an evolutionarily stable strategy. The findings suggest that the introduction of blockchain, combined with targeted incentives and credible penalties, significantly increases the likelihood of cooperative behavior. Simulations reveal that the implementation of blockchain, when combined with appropriate incentive and penalty mechanisms, significantly reduces tendencies toward data concealment or falsification. The findings also highlight the pivotal role of blockchain in fostering inter-organizational trust, enhancing traceability, and promoting sustainable practices throughout the value chain. The paper concludes with practical implications and policy recommendations aimed at supporting the digital transition

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and strengthening the resilience of the agri-food sector.
Keywords: Blockchain; Agri-Food Supply Chain; Information Asymmetry; Game Theory; Traceability; Transparency

1. Introduction

The rapid evolution of agri-food supply chains in recent decades has brought new opportunities for efficiency and innovation, but also significant governance challenges. Understanding these dynamics is essential for designing technological and institutional solutions that can ensure transparency, trust, and resilience. Over the past few decades, the agri-food supply chain has undergone a profound transformation, shaped by increasing logistical complexity, market globalization, rising concerns over sustainability, and a growing demand from consumers for transparency and traceability [1–3]. In developed economies, the rise in per capita income has also led to more demanding consumers who seek detailed and reliable information about agri-food products [4].

In this context, one of the most persistent and critical issues is the information asymmetry between various actors in the chain—producers, processors, distributors, retailers, and final consumers [5]. This asymmetry arises when one party in a transaction possesses significantly more or better information than the other, thereby undermining market efficiency, increasing the risk of fraud, and eroding trust [6].

This problem is further compounded by the fragmentation of the agri-food supply chain, the diversity of intermediaries, the challenges of data standardization, and the unequal distribution of digital and technological capabilities [7]. The lack of transparency not only hampers the timely identification of issues related to food quality and safety but also leads to serious reputational and economic damage during crises such as food scandals, counterfeiting, or recalls [8, 9].

In light of these challenges, blockchain technology has emerged as a promising solution to bridge the information gap, enhancing the safety, verifiability, and resilience of agri-food systems [10]. Blockchain enables the secure and immutable recording of every transaction or product status update on a distributed ledger accessible to authorized stakeholders [11]. This capability allows for precise reconstruction of a product's history "from farm to fork" and discourages opportunistic behavior by facilitating immediate traceability of responsibilities [12, 13].

Recent research has highlighted the potential of blockchain to enhance existing traceability systems, reduce data manipulation risks, increase trust among business partners, and support regulatory compliance [14, 15]. However, blockchain is truly effective in mitigating information asymmetry, but it is essential to understand the behavioral dynamics that guide economic actors' choices [16]. In other words, technology alone is not enough: it is crucial to analyze the strategic context in which it is adopted and implemented.

To this end, this study adopts an evolutionary game theory approach to model and simulate the strategic behaviors of agri-food chain stakeholders in relation to blockchain adoption. Game theory offers a formal framework to represent the interactions of rational (though boundedly rational) agents who choose strategies based on expected payoffs and others' behavior [17]. In this context, the model evaluates the conditions under which truthful information sharing can become an evolutionary stable strategy, and how incentives and penalties may influence system equilibrium.

This study offers a twofold contribution: on one hand, it provides a formal theoretical model to examine blockchain as a governance and transparency mechanism within the supply chain; on the other, it delivers practical insights for companies, policymakers, and stakeholders seeking to foster a trustworthy, reliable, and sustainable digital transition in the agri-food sector. The proposed approach is not only valuable for understanding internal dynamics within the chain but also for guiding policy and investment decisions in emerging technologies that address food safety, information equity, and systemic competitiveness. It stands out for its innovative integration of evolutionary game theory with the analysis of blockchain adoption in the agri-food supply chain. The implementation of Blockchain technology directly links with the cooperation rate, and the balance between incentives and penalties represents a significant theoretical advancement over existing literature. This enriches the ongoing debate on blockchain and supply chain dynamics by offering a predictive tool that is useful for designing effective incentives to foster cooperative behavior.

The present paper is structured as follows: Section 2 reviews the existing literature on blockchain applications in the agri-food sector and their intersection with game theory, highlighting the theoretical gaps that this study seeks to address. Section 3 presents an overview of blockchain implementation in Europe and Italy, providing contextual evidence of adoption trends and practical challenges. Section 4 discusses the role of cooperation in agri-food enterprises, outlining its economic, organizational, and technological dimensions. Section 5 details the materials and methods, including the construction of the payoff matrix, the modelling assumptions, and the analytical approach. Section 6 reports the main results of the model, while Section 7 discusses their implications for theory and practice, offering targeted recommendations for policymakers and industry stakeholders. Finally, Section 8 outlines the study's limitations and proposes directions for future research.

2. Literature Review

In recent years, the adoption of blockchain technology has become increasingly central to discussions around innovation in the agri-food supply chain [18–20]. In a context marked by growing logistical, regulatory, and informational complexity, blockchain is presented as a mechanism capable of ensuring transparency, traceability, and trust among supply chain actors [8]. The key features of this technology—decentralization, data immutability, and real-time accessibility—make it particularly well-suited to address one of the most pressing structural problems in the sector: information asymmetry [13, 21, 22].

As highlighted by Yogarajan et al. [9], blockchain adoption in agri-food chains not only improves transparency but also encourages virtuous behavior through mechanisms of accountability. In their systematic review, the authors identify eight emerging themes, including the digitalization of quality control, waste reduction, and sustainability management, emphasizing blockchain's strategic role in enabling distributed governance. Similarly, it points out that traditional traceability systems based on centralized databases suffer from critical limitations in reliability and interoperability, increasing exposure to fraud, data manipulation, and loss of critical information [8].

A further contribution comes from the study by Yang et al. [14], which employs evolutionary game theory to analyze behavioral dynamics among supply chain actors. Their work demonstrates how initial information transparency can be effectively incentivized through the implementation of penalties for opportunistic behavior and rewards for cooperation. According to the authors, blockchain adoption structurally reconfigures the strategic game among participants, facilitating the emergence of more efficient and resilient equilibria.

Gaudio et al. [23] contribute an engineering perspective by evaluating the performance of a blockchain system integrated with IoT sensors along the cold chain. Their results indicate a significant reduction in response times, improved tracking accuracy, and enhanced real-time intervention capabilities. These findings confirm that blockchain, when integrated with technologies such as IoT, can enhance operational efficiency and mitigate risks related to product quality degradation.

Marchese et al. [12] propose a multi-layer architecture that combines blockchain with satellite positioning systems (GPS, NavIC) and IPFS protocols for decentralized data storage. Tested in simulated environments, the proposed framework achieved an average throughput of 329 transactions per second and a latency as low as 49 milliseconds, making it competitive with existing solutions. These results illustrate that blockchain is not merely a tool for digital notarization but a foundational infrastructure for intelligent logistics.

In addition, many scholars have analyzed the implementation of blockchain technology in the agri-food supply chain through the theoretical lens of game theory approach [24, 25]. From an economic perspective, Game theory is a widely recognized technique for supply chain optimization and decision-making, as it involves several actors [26]. In fact, Vasnani et al. [27] undertook a literature study examining the developments and applications of game theory within supply chains. They also talked about how the Nash equilibrium idea and the Stackelberg game model may be used in supply networks. This study also looks at how game theory is distinct from other ways to make decisions and find the best solution. Chavoshou et al. [28] developed a fuzzy game theory model to analyze client preferences for environmentally friendly items. Asrol et al. [29] introduced a cooperative game theory model grounded in Shapley value to ensure equitable profit distribution among stakeholders in the sugarcane business, facilitating a comparative study of existing and proposed policies. Fink et al. [30] elucidated the function of the sharing economy in the context of organic small farmers operating within a cooperative framework.

Song et al. [31] conducted a study on strategic interactions among the government, farmers, and manufacturers to examine the hazardous behaviors of stakeholders in food supply chains, aiming to maximize their payoffs. This study examined three distinct forms of interactions among stakeholders and conducted a comparative analysis of all these models. The first is "government against manufacturer against farmer," the second is "a centralized government-manufacturer-farmer model," and the third is "government vs. farmer and manufacturer model."

Li et al. [32] executed an extensive investigation to create a decision-making traceable system, employing game theory to formulate a traceability framework for fresh agricultural goods. They recognized income, expenses, technological circumstances, legal frameworks, purchasing intentions, and the industrial environment as pivotal aspects affecting the evolution of a traceability system. The results of this study also indicated that an organization implementing a traceability system has a reduced likelihood of safety accidents, lower construction costs for the traceable system, and an increased customer purchasing intention.

From an architectural standpoint, Marchese et al. [13] emphasizes the benefits of permissioned blockchains such as Hyperledger Fabric, which allow for customizable roles and permissions across network nodes. This is especially relevant in the agri-food sector, which often involves actors of different sizes and varying technological capabilities [33]. Selective data authentication and the use of smart contracts to automate quality control are further advantages of this technology [34].

Nevertheless, some critical issues remain. Several studies emphasize that the quality of data entered into the blockchain remains a major vulnerability—the classic "garbage in, garbage out" problem [8]. Without proper verification protocols and shared standards, even an immutable distributed system can propagate large-scale errors. Moreover, scalability and implementation costs continue to pose significant barriers for small and medium-sized agricultural enterprises, particularly in low-digital-development contexts [9, 14].

In light of this, the literature largely agrees that blockchain has transformative potential for the agri-food supply chain, as it can reduce information asymmetry, foster inter-organizational trust, and improve operational efficiency [35]. However, the effectiveness of its implementation strongly depends on institutional design, data quality, and the presence of an inclusive governance ecosystem [18, 36, 37].

Despite the growing body of literature combining blockchain technology and game theory in the agri-food context, several research gaps remain. First, existing works often focus on either the technological architecture of blockchain or the theoretical modelling of cooperation, without fully integrating the two into a unified, predictive framework. Second, most game-theoretic analyses in this field adopt static settings or simplified behavioural assumptions, overlooking the dynamic interplay between incentives, penalties, and technology adoption over time.

Third, empirical studies that explicitly test how blockchain modifies payoff structures and strategic equilibria are still scarce, limiting the transferability of findings to real-world scenarios. The present study addresses these gaps by introducing a formal evolutionary game model that explicitly links blockchain adoption to the cost–benefit structure faced by agri-food actors, incorporating both direct economic incentives and sanction mechanisms.

3. Blockchain Implementation in Europe and Italy

In the agri-food sector, the implementation of Blockchain technology has grown significantly across Europe and Italy. The growing need for transparency and traceability along production chains, combined with stricter food safety regulations, has driven businesses and institutions to invest heavily in blockchain-based solutions. According to Blockchain Distributed Ledger Observatory [38], the number of blockchain projects applied to the agri-food sector has increased significantly in recent years, positioning Europe as one of the most active markets globally. At the European level, several countries are implementing blockchain initiatives in the agri-food sector, enhancing supply chain efficiency and building consumer trust. According to data from European Commission [39], more than 30% of companies in the sector have started adopting blockchain technologies to increase transparency and combat food fraud. France, Germany, and the Netherlands stand out as particularly advanced, having launched numerous pilot projects in collaboration with major agri-food corporations and innovative startups. In this context, the "SmartAgriHubs" program, funded by the European Commission [39], is supporting the development of blockchain-based traceability and certification systems across Europe, with a dedicated budget of over €20 million.

Italy is among the most active countries in Europe in applying blockchain to the agri-food sector, with steady growth in investments and adoption of this technology. According to Unioncamere [40], the Italian agri-food sector generates an added value of approximately €62.7 billion, implementing innovative technological tools essential for enhancing the competitiveness of "Made in Italy" products. Notably, Italian companies are involved in 11% of all global blockchain projects in the agri-food sector have involved Italian companies, highlighting a growing interest in this technology.

Among the most relevant applications of blockchain in the Italian agri-food sector are traceability systems for traditional and protected designation of origin (PDO) products. Several agricultural cooperatives and consortia, such as the Parmigiano Reggiano and Prosciutto di San Daniele consortia, have adopted blockchain solutions to guarantee the authenticity of their products and counteract food fraud [40]. Specifically, the "Foodchain" project has enabled the implementation of a blockchain-based digital labeling system, allowing consumers to verify the origin and production process of products directly via a mobile application.

Italian companies are also investing in blockchain to optimize logistics and improve supply chain management. Through smart contracts, it is possible to automate payments between different actors in the supply chain, reducing processing times and administrative costs [38]. This approach not only increases efficiency but also minimizes the risk of fraud and discrepancies in transactions.

Another fundamental aspect of blockchain adoption in the agri-food sector is sustainability. Increasingly, companies are leveraging this technology to monitor and certify sustainable production practices, such as reducing CO_2 emissions, responsible water usage, and compliance with ethical standards throughout the supply chain [39]. The transparency provided by blockchain enables consumers to make more informed choices and reward companies that adopt sustainable practices.

Furthermore, the blockchain is being integrated into certification and quality control systems. Some certification bodies are experimenting with blockchain to digitize and secure compliance verification processes, reducing the risk of document tampering or fraud [40].

Despite its numerous advantages, blockchain adoption in the agri-food sector still faces challenges. These include implementation costs, staff training requirements, and integration with existing systems. However, with European funding and initiatives promoted by Italian institutions, the sector is progressively moving towards greater digitalization and innovation.

Blockchain represents one of the most promising solutions for the future of the agri-food sector, both in Europe and Italy. Its ability to ensure transparency, security, and sustainability makes it a strategic tool for addressing supply chain challenges, enhancing the competitiveness of industry players. With an increasing number of projects and initiatives, Italy continues to position itself at the forefront of blockchain adoption, leveraging this technology to protect its agri-food heritage and respond to a market that increasingly values quality and traceability [41, 42]. Overall, the European and Italian experiences demonstrate that blockchain adoption is driven by a combination of regulatory pressure, market demand for transparency, and strategic investment in innovation. Consolidating these efforts will be key to moving from pilot projects to large-scale, sustainable integration across the agri-food sector.

4. The Role of Cooperation in Agri-Food Enterprises

Understanding the economic and organizational foundations of cooperation is essential to explain why certain governance models succeed in agri-food supply chains while others fail. Cooperation plays a central role in shaping the performance and resilience of agri-food enterprises, especially in an era characterized by complex value chains, environmental uncertainty, and increasing consumer demand for transparency [43]. Economic theory offers several lenses through which the value of cooperation can be understood. From the perspective of transaction cost economics [44, 45], collaboration between firms helps reduce the costs associated with market exchanges—such as searching for information, negotiating contracts, and ensuring compliance. In fragmented supply chains, such as those found in the agri-food sector, these transaction costs are often high due to the large number of actors involved and the perishability of the products [46]. Cooperative arrangements, such as long-term contracts between farmers and processors or vertically integrated supply agreements, can significantly streamline interactions, build trust, and create more stable and efficient systems [47]. Behavioral economics adds another dimension by recognizing that decisions in the real world are shaped not only by financial incentives but also by trust, fairness, and social norms [48, 49]. Many agri-food enterprises, particularly small-scale farmers and local cooperatives, operate in environments where repeated interactions and shared cultural values matter. In these contexts, collaboration is not just a rational strategy; it is also a socially embedded practice. Shared goals, reputational concerns, and long-standing relationships often motivate actors to work together, even in the absence of formal enforcement mechanisms [50].

In the agri-food sector, cooperation manifests in multiple organizational forms:

- Vertical collaboration between farmers, processors, and retailers enables better coordination of supply and demand, facilitates traceability, and improves product quality management [51]. In particular, vertical coordination refers to the mechanisms through which consecutive firms along the agri-food supply chain align their production and exchange processes. In the pure market, where transactions are impersonal, prices are the sole coordinating variable, and goods—especially standardized commodities like cereals or coffee—are exchanged on the spot without prior negotiation. This system remains effective for homogeneous goods, particularly where quality standards reduce the need for detailed specification. However, in increasingly complex agri-food systems, the limitations of spot market transactions become evident. Factors such as rapid technological innovation, increasing product differentiation, geographical dispersion of actors, and rising consumer and regulatory demands for quality and traceability have made vertical coordination more critical than ever. In response, firms are adopting more structured forms of coordination beyond the market, including production contracts, cooperatives, and joint ventures. These arrangements allow for better alignment of production processes, input selection, delivery timing, and quality assurance across different stages of the supply chain. For instance, in agriculture-industry relationships, the need for precise control over agronomic practices—such as seed variety, pest management, harvest timing, and packaging—has led to the rise of contract farming and integrated supply agreements. These mechanisms facilitate the flow of information, improve predictability, and reduce transaction risks. Ultimately, enhanced vertical coordination strengthens interdependence between actors, enabling greater responsiveness to market changes, more efficient resource use, and a more resilient agri-food system. Especially, contracts between producers and retailers, for example, can set clear expectations on standards, quantities, and delivery timelines, reducing uncertainty and aligning production with market needs.

- Horizontal cooperation refers to collaborative arrangements between firms operating at the same stage of the production process, such as between multiple farms or among food processors. This form of coordination becomes particularly crucial when there are significant scale imbalances between vertically adjacent stages in the agri-food supply chain. It serves both efficiency-oriented and power-oriented objectives. From an efficiency perspective, it enables firms to undertake investments that would otherwise be inaccessible due to high capital requirements—such as shared grain storage facilities or collective olive oil mills. It also facilitates economies of scale and scope by pooling resources, reducing per-unit costs, and offering a more comprehensive product assortment. Additionally, coordinated procurement of inputs (e.g., seeds, fertilizers, machinery) can reduce transaction and purchasing costs, while concentrated product offerings help meet the volume and quality demands of larger buyers. From a power-oriented perspective, horizontal coordination strengthens the bargaining position of smaller actors in negotiations with upstream suppliers and downstream buyers, many of whom are large and highly consolidated. By forming cooperatives, consortia, or producer organizations, small agricultural enterprises can exert greater control over exchange conditions, resist price pressure, and engage more effectively in lobbying efforts with public institutions. This becomes especially relevant in agri-food systems where upstream and downstream sectors are increasingly dominated by large-scale players, while primary production remains fragmented and composed of small, heterogeneous enterprises. In many cases, horizontal coordination is a precondition for effective vertical coordination. Without collective action, small producers often lack the volume, standardization, or organizational capacity needed to enter into formal contracts or integrate into more structured value chains. Thus, strengthening horizontal cooperation not only improves economic performance and market access but also enables broader participation in innovation processes, sustainability initiatives, and digital transformation pathways. Given the structural characteristics of agriculture—high atomization, diverse business models, and growing asymmetries of power—horizontal coordination represents a foundational strategy for building inclusive, competitive, and resilient agri-food networks. These entities allow small-scale actors to pool resources, share infrastructure, and enhance bargaining power. In a globalized market where large agribusinesses dominate, such collective strategies are essential to protect local producers from marginalization [52].
- Public-private partnerships (PPPs) serve as platforms for joint investment in research, technology transfer, and capacity building [53]. These partnerships are particularly valuable in the agri-food sector, where the challenges of innovation, sustainability, and market access require coordinated, cross-sectoral responses. PPPs enable joint investments in areas such as agricultural research and development (R&D), technology transfer, infrastructure development, and farmer training, thereby bridging the gap between public policy goals and private sector capabilities. In many countries, they have been instrumental in revitalizing agricultural extension services, especially in rural areas where access to technical assistance and innovation is limited. For instance, partnerships between ministries of agriculture and agritech companies have led to the dissemination of digital tools for precision farming, early warning systems for pests and climate events, and the adoption of climate-resilient crop varieties. Moreover, PPPs have played a pivotal role in enhancing food quality governance through the promotion of certification systems and geographical indications, such as Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) schemes. These instruments not only

safeguard local production knowledge and biodiversity but also add value to agricultural products by linking them to specific territories and cultural heritage. Through co-investment in certification systems, marketing campaigns, and capacity-building initiatives, PPPs help small and medium-sized producers improve their competitiveness in domestic and international markets. As such, they are not merely funding mechanisms but facilitators of systemic change, capable of aligning economic development with social and environmental sustainability.

Recent technological advancements, particularly in blockchain, the Internet of Things (IoT), and data analytics, have opened new avenues for transparent and enforceable cooperation. When embedded in cooperative frameworks, these tools can strengthen accountability, automate verification processes, and reward trustworthy behaviour—essentially translating social norms into digital governance structures. However, as economic theory reminds us, the effectiveness of cooperation depends on the appropriateness of institutional design, credible enforcement mechanisms, and a fair distribution of benefits. Without these, even the most promising digital solutions risk reinforcing inequalities or generating new forms of strategic defection [54]. Economic theory does not just advocate for cooperation; it explains why and how it works. Whether through reducing transaction costs, aligning behavioral motivations, or modeling strategic dynamics, cooperation emerges as a cornerstone of resilient and efficient agri-food systems [55]. As global food chains become increasingly interconnected and vulnerable, fostering inclusive, well-governed, and technology-enabled collaboration will be crucial for building trust, promoting sustainability, and ensuring long-term competitiveness [56]. Cooperation in its various forms—vertical, horizontal, and through public–private partnerships—acts as a structural enabler of efficiency, resilience, and innovation, especially when supported by appropriate institutional frameworks and emerging digital technologies.

5. Materials and Methods

To translate the conceptual premise of the study into an operational analytical framework, it is necessary to formalize the strategic interactions among supply chain actors through a payoff matrix.

In the payoff matrix (**Table 1**), it is essential to clearly define the strategies available to each player and the corresponding payoffs associated with every possible combination of strategies [38]. Within the framework of game theory, a payoff matrix represents the outcomes (payoffs) that each player receives depending on the strategies chosen by all participants in the game. This modeling approach embodies a core assumption in economic theory: that firms act opportunistically, primarily motivated by the goal of profit maximization. In this scenario, it is presumed that each participant makes strategic choices predicated on the anticipated benefits of cooperation (e.g., sharing accurate information) compared to defection (e.g., withholding or distorting data). The payoff structure illustrates the trade-offs between immediate personal gain and enduring collective benefist, enabling an analysis of the conditions under which cooperation may arise as a rational equilibrium, notwithstanding the intrinsic allure of defecting. Each cell in the matrix displays the payoff for each player (firm) corresponding to a specific combination of strategic choices.

Table 1. Pay-off matrix.

	C	**D**
C	(R,R)	(S,T)
D	(T,S)	(P,P)

Let us consider a game involving two actors in the agri-food supply chain:

- Firm 1: may choose to Cooperate (C) or Defect (D)
- Firm 2: may also choose to Cooperate (C) or Defect (D)

Where:

- R (Reward): the payoff for both players if both choose to cooperate.
- S (Sucker's payoff): the payoff for the player who cooperates while the other defects.
- T (Temptation): the payoff for the player who defects while the other cooperates.
- P (Punishment): the payoff for both players if both choose to defect.

To assign consistent numerical values to these payoffs, we consider the following parameters:

- b: the benefit derived from cooperation.
- c: the cost associated with cooperation.
- I: the incentive for cooperation.
- F: the penalty for defection.

Using these parameters, the payoffs can be defined as follows:

- $R = b - c + I$: When both players cooperate, they receive the benefit minus the cost, plus the incentive.
- $S = -c$: the cooperating player bears the cost without receiving the benefit.
- $T = b - F$: the defective player receives the benefit but incurs a penalty.
- $P = 0$: when both players defect, no benefit or cost is incurred.

The resulting payoff matrix is presented in **Table 2**.

Table 2. Definitive pay-off matrix.

	C	**D**
C	$(b - c + I, b - c + I)$	$(-c, b - F)$
D	$(b - F, -c)$	$(0, 0)$

This matrix represents a symmetric game, in which the strategies and payoffs are identical for both players (**Table 2**). The structure of the game reflects a Prisoner's Dilemma, where defection is the dominant strategy, yet cooperation leads to a better outcome for both players. To analyze the evolution of strategies over time, we can use the replicator dynamic, which describes how the frequency of a given strategy changes within a population over time. The replicator dynamic for the cooperation strategy is given as Equation (1).

$$x = x(1 - x)(f_c - f_d) \tag{1}$$

Where:

- $\mathbf{x}$: frequency of the cooperation strategy in the population.
- $\mathbf{f_c}$: average payoff for cooperators.
- $\mathbf{f_d}$: average payoff for defectors.

By substituting the payoff values into the replicator dynamic, we can analyze the conditions under which cooperation may emerge as an evolutionary stable strategy. This analysis provides a theoretical foundation for understanding how the adoption of blockchain—through adjustments to of incentives and penalties—can influence the strategic behavior of actors within the agri-food supply chain and promote cooperative conduct.

To complete the model with both logical and economic consistency, we can introduce a convenience function, which allows us to determine when it is advantageous for an actor in the agri-food supply chain to cooperate (i.e., share truthful information on the blockchain) rather than defect (i.e., conceal or falsify information).

This step bridges the theoretical proposition and the quantitative analysis, linking the strategic context, the model's parameters, and the measurable conditions under which blockchain adoption can foster stable cooperation.

6. Results

To operationalize the proposed theoretical model, it is necessary to formally define the economic conditions under which cooperation is more advantageous than defection. This step translates the conceptual framework into a measurable criterion that can guide both academic analysis and policy design. In practical terms, we compare the expected payoff of an actor who chooses to cooperate with that of one who chooses to defect, under the strategic interactions described in the payoff matrix.

For cooperation to be cost-effective compared to defection, the expected payoff for an actor who cooperates must be greater than or equal to that of one who defects [Equation (2–14)].

$$f_c \geq f_d \tag{2}$$

Where:

$$f_c = xR + (1-x)S \tag{3}$$

$$f_d = xT + (1-x)P \tag{4}$$

Replacing with payoffs:

$$R = b - c + I,\ S = -c,\ T = b - F,\ P = 0 \tag{5}$$

It is obtained:

$$f_c = x(b - c + I) + (1-x)(-c) \tag{6}$$

$$f_d = x(b - F) \tag{7}$$

Imposing the convenience condition:

$$x(b - c + I) + (1-x)(-c) \geq x(b - F) \tag{8}$$

Both members develop

LHS (cooperation):

$$xb - xc + xI - c + xc = xb + xI - c \tag{9}$$

RHS (Defection):

$$xb - xF \tag{10}$$

Final condition:

$$xb - xF \tag{11}$$

Simplifying xb on both sides:

$$xI - c \geq -xF \tag{12}$$

Summing xF to both sides:

$$x(I + F) \geq c \tag{13}$$

Convenience Formula:

$$x \geq \frac{c}{I + F} \tag{14}$$

This expression summarizes the strategic balance between costs, incentives, and penalties in a system that adopts blockchain to promote informational transparency within the agri-food supply chain. It provides an objective criterion to determine whether an actor has an economic advantage in cooperating (i.e., entering and maintaining truthful data in the system), depending on the behavior of the rest of the population.

Specifically:

- c represents the marginal cost of cooperation. This includes the economic and organizational resources required to implement blockchain, collect and validate data, and comply with traceability standards. It acts as a disincentive to transparency, particularly in early adoption phases.
- I is the incentive to cooperate. It may include direct economic rewards (such as access to premium supply chains, price premiums for traceable products, or tax relief), as well as reputational and commercial benefits from being perceived as a trustworthy and sustainable actor. The higher the value of III, the more attractive cooperation becomes, even for initially reluctant participants.
- F is the penalty for defection, i.e., for transmitting false or incomplete information. This can take the form of financial sanctions, exclusion from certifications or consortia, or reputational damage if discovered. The value of F reflects the strength of the enforcement system and the likelihood that opportunistic behavior will be detected.

The resulting formula serves not only as a valuable predictive tool but also offers practical guidance for designing incentive and regulatory policies aimed at strengthening trust and cooperation throughout the agri-food supply chain.

This derivation not only confirms the theoretical plausibility of the model but also offers a tangible decision-making tool. By identifying the threshold conditions for cooperation, researchers can simulate adoption dynamics under different institutional and technological scenarios, and policymakers can use this understanding to identify clear levers—such as adjusting incentives or penalties—to foster stable, trust-based information sharing across the agri-food supply chain.

As noted in the literature [57] the OpenSC platform, created by WWF Australia and BCG Digital Ventures, is a real-world example of how blockchain can be used in the food supply chain. This platform uses blockchain technology to track food products throughout the entire supply chain, making it easy to check that sustainability practices are being followed. In this context, the dynamics can be understood through the Prisoner's Dilemma model: when the actor cooperates (C), they share accurate and clear information about where things come from and how they are made (for example, fishing techniques, location, timing, and processing systems). When the actor defects (D), they give incomplete or manipulated data to hide unethical or unsustainable practices. Depending on the combinations, the expected outcomes are different: if both cooperate, trust and reputation go up (R,R); if one cooperates and the other defects, the latter gets a temporary advantage (T) unless they are hurt by reputational penalties (T); if both defect, the transparency system is hurt, putting the whole platform at risk (P,P). This case clearly shows how the Prisoner's Dilemma works when blockchain is used in the agri-food sector. It shows how important it is to have rules and incentives that encourage cooperation and discourage opportunistic behavior.

7. Discussion and Conclusion

This study investigated the potential of blockchain technology as a strategic tool for reducing information asymmetry in the agri-food supply chain, proposing a theoretical model grounded in evolutionary game theory. Through the dynamic analysis of the behavioral strategies of supply chain actors, specifically cooperation or defection regarding information sharing, it has been demonstrated that the introduction of blockchain, when combined with economic incentives and penalty mechanisms, can lead to evolutionarily stable equilibria characterized by high transparency. Simulations show that when a sufficiently large proportion of actors adopt cooperative strategies, evolutionary dynamics tend to reward virtuous behavior, thereby encouraging the diffusion of truthful information (**Appendix A**). Particularly decisive for successful blockchain adoption are the implementation of direct incentives (e.g., rewards, easier market access) and indirect incentives (e.g., reputation, digital certification), coupled with credible sanctions for opportunistic conduct. Moreover, the integration of complementary technologies such as IoT, GPS, and smart contracts significantly enhances the blockchain's capacity to ensure traceability, operational efficiency, and resilience. However, the study also highlights key challenges that must be addressed: foremost, the quality of input data, which is essential for the reliability of the distributed ledger, and secondly, the need for adequate infrastructure and digital skills, especially among small-scale producers. In this context, institutional involvement is fundamental in creating a supportive ecosystem through policy frameworks, shared regulatory standards, and training programs. In conclusion, blockchain is not merely an emerging technology, but a potential mechanism of informational governance, capable of fundamentally transforming how actors in the agri-food sector interact, cooperate, and build trust. The synergy between a robust theoretical framework, such as evolutionary game theory, and the practical implementation of blockchain offers a promising foundation for future scientific and applied developments aimed at promoting transparency, sustainability, and competitiveness across global agri-food systems. Practically, the results provide operational insights for agri-food enterprises seeking to integrate blockchain into their traceability and quality management systems; game-theoretic simulations suggest that truthful information sharing becomes a dominant strategy only when a sufficient number of actors commit to transparency, requiring coordinated efforts and a long-term cooperative vision. Investments in IoT technologies and workforce training may turn blockchain adoption into a tangible competitive advantage, enhancing consumer trust and access to premium markets. Theoretically, this paper contributes an innovative model that bridges blockchain and evolutionary game theory, opening new research avenues for strategic analysis in complex agri-food systems and potentially extending to other sectors where information asymmetry is critical, such as healthcare, logistics, or energy.

For instance, consider a cooperative of olive oil producers operating under a Protected Designation of Origin (PDO) scheme. In the current system, production data are self-reported, leaving room for inaccuracies or deliberate misreporting. A transition to a permissioned blockchain platform would enable each transaction or data entry to be securely recorded and automatically validated through connected devices at processing facilities.

In such a scenario, cooperation would depend on a balance between the costs of adopting and operating the system, the benefits of improved market access and consumer trust, and the incentives or sanctions established by regulatory bodies. For example, a public authority could offer financial support or preferential access to export markets for compliant producers, while imposing fines or exclusion from certification for those engaging in opportunistic behaviour. If the perceived net advantages of cooperation exceed those of defection for a sufficient proportion of producers, the blockchain system would likely reach a stable level of adoption, ensuring more reliable traceability and reducing information asymmetry across the supply chain.

The findings discussed directly address the problems raised at the beginning of this study: the growing complexity of agri-food supply chains, the fragility of trust between organizations, and the urgent need for reliable methods to address information asymmetry. The theoretical model, based on evolutionary game theory, has enabled a formal definition of the conditions that facilitate stable cooperative behavior in blockchain adoption. This method directly addresses the first question about how well digital technologies can foster trust and transparency, and it also provides a strategic framework for making informed decisions in both the public and private sectors. In this way, the discussion of the results confirms the importance of the motivations that were raised earlier and ties together the study's rationale, methodology, and practical implications.

Furthermore, it establishes a theoretical foundation for empirical studies that could validate the results through real-world data, field experiments, or comparative analyses across different regions and supply chains, thereby reinforcing interdisciplinary dialogue between behavioral economics, digital technologies, and agri-food policy. For policymakers and public institutions, maximizing blockchain's transformative potential requires action on three key fronts: regulatory—establishing clear, shared standards for traceability that ensure platform interoperability and data protection; financial—offering economic support mechanisms such as tax incentives, EU funds, or digital vouchers to foster adoption among SMEs and independent farmers; and educational—promoting digital literacy and awareness programs, including public-private partnerships, to build trust in blockchain as a tool for assurance and accountability. Finally, the widespread adoption of blockchain in agri-food systems can also contribute to broader sustainability goals, such as those set out in the United Nations Sustainable Development Goals—particularly SDG 12 on responsible consumption and production—by reducing food waste, improving consumer safety, and encouraging more equitable and transparent agricultural practices with positive societal impact.

From a policy perspective, the model suggests differentiated strategies for distinct stakeholder groups. For small and medium-sized enterprises (SMEs), direct financial incentives such as subsidies, reduced certification fees, or access to exclusive market channels are critical to offset initial blockchain adoption costs. For large processors and retailers, regulatory mandates coupled with reputational incentives may be more effective, as these actors typically have greater technological readiness but face higher reputational risks from non-compliance.

Policymakers should focus on ensuring a balanced incentive–penalty mix above the cooperation threshold, as identified by the model, and on creating interoperable data standards to reduce long-term costs. In addition, tailored capacity-building programmes are essential, especially in regions with lower digital literacy, to avoid widening existing inequalities in supply chain participation. Finally, integration with complementary technologies such as IoT sensors, smart contracts, and geolocation tools can further enhance traceability and verification, ensuring that blockchain adoption translates into genuine reductions in information asymmetry rather than simply digitizing existing inefficiencies.

8. Limitations of the Study and Future Directions

To contextualize the scope and applicability of the findings, it is important to explicitly acknowledge the main limitations of the present study and outline possible avenues for future research. While this study offers valuable insights, some limitations deserve mention. The model simplifies behavior into two stark choices—cooperation or defection—which, although useful for a first analysis, may not fully capture the nuanced strategies seen in real supply chains. Also, because the model relies on theoretical parameters without empirical data, future research should validate these assumptions through fieldwork or industry surveys.

Another point is that the framework assumes relatively uniform technological capabilities among actors, whereas in reality, digital readiness varies greatly. Exploring more heterogeneous settings would enhance realism. Moreover, although we acknowledge the risk of poor data quality ('garbage in, garbage out'), future models could integrate verification mechanisms to address this critical issue directly.

Looking ahead, several promising paths emerge. Pilot projects in specific agri-food sectors could test and refine the model's assumptions. Developing models that account for partial cooperation or conditional strategies would better mirror real-world complexity. Agent-based approaches could capture the diversity of actors, and dynamic incentive systems could be designed to adapt over time. Finally, a more interdisciplinary approach—combining blockchain technology, behavioral economics, supply chain management, and policy studies—will be crucial in developing robust and flexible solutions that foster trust and transparency in the agri-food system. Addressing these limitations will not only strengthen the empirical validity of the model but also enhance its practical relevance, ensuring that blockchain-based governance mechanisms are adaptable to the complex realities of agri-food supply chains.

Author Contributions

Conceptualization, F.S.; methodology, C.S. and F.M.; validation, F.S.; formal analysis, F.M. and C.S.; investigation, F.M. and C.S.: writing—original draft preparation, F.M.; writing—review and editing, F.M.; visualization, C.S.; supervision, F.S.; project administration, F.M. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No data is available because this is a theoretical simulation.

Conflicts of Interest

The authors declare that there is no conflict of interest.

Appendix A. Partial Cooperation Scenario

In the described context, the model can be extended to consider a partial cooperation scenario, in which a share y of the information shared by actors is truthful, while the remaining $(1 - y)$ is withheld or distorted. In terms of payoffs, this means that the benefits b from cooperation are perceived only in proportion to the portion of accurate information shared, while the costs c remain fixed (since the infrastructure for data collection and management must still be implemented). For example, Firm 1 and Firm 2 adopt blockchain but choose to record only 80% (y = 0.8) of the information accurately, keeping a margin of opacity to preserve competitive advantages.

In this case, the payoff from partial cooperation can be expressed as Equation (A1):

$$R_p = y(b - c + I) + (1 - y)(b' - c) \tag{A1}$$

where b' represents the benefit (potentially lower) from incomplete information. If one firm adopts a partial cooperation strategy while the other cooperates fully, the fully cooperating firm experiences a reduced payoff compared to full cooperation, but still higher than from total defection.

The penalty mechanism F can be adapted in a graduated form, applying sanctions proportional to the degree of incompleteness detected using Equation (A2).

$$F_p = (1 - y)\, F \tag{A2}$$

This scenario introduces an intermediate equilibrium in which firms balance transparency and protection of strategic information, and it allows for the study of the conditions under which incentives and penalties can shift actors from partial to full cooperation.

Appendix A.1. Extension with Partial Cooperation (P)

We assume that with partial cooperation, each firm shares truthfully only a fraction y ∈ (0,1) of the information.

- The benefit received by the other party scales with the average truthfulness: y b
- The incentive applies proportionally to the truthful part shared: y I (while full cooperation yields I).
- The expected penalty is proportional to the degree of incompleteness $(1-y)$ and to the detection probability q∈[0,1]: expected penalty $=$ $(1 - y)$ q F

The cost c remains fixed (the data infrastructure must still be implemented).

Table A1. Payoff matrix.

	C	**P (Share y)**	**D**
C	$(b - c + I\,,\, b - c + I)$	$(yb - c + I\,,\, yb - c + yI - (1 - y)\, qF)$	$(-c\,,\, b - F)$
P (share y)	$(yb - c + yI - (1 - y)\, qF\,,$ $yb - c + I)$	$(yb - c + yI - (1 - y)qF\,,$ $yb - c + yI - (1 - y)\, qF)$	$(-c + yI - (1 -$ $y)\, qF\,,\; yb - qF)$
D	$(b - F\,,\, -c)$	$(yb - qF\,,\, -c + yI - (1 - y)qF)$	(0 , 0)

The analysis compares the relative outcomes of the three strategic interactions: full cooperation, partial cooperation, and defection in order to highlight their respective payoffs and the conditions under which each may constitute a stable equilibrium.

- Full Cooperation vs. Partial Cooperation (C vs. P): A fully cooperating firm facing a partial cooperator obtains a payoff of yb $-$ c $+$ I, while the partial cooperator receives yb $-$ c $+$ yI $-$ (1 $-$ y) qF. Given that I $\geq$ yI $-$ (1 $-$ y) qF for I, F $\geq$ 0, full cooperation remains (weakly) more attractive than partial cooperation under equal conditions.
- Partial Cooperation vs. Defection (P vs. D): A partial cooperator facing a defector gains $-$c $+$ yI $-$ (1 $-$ y) qF, which can be superior to $-$c if yI $>$ (1 $-$ y) qF. The defector, in turn, exploits the truthful share y·b provided by the partial cooperator but suffers an expected penalty of qF.
- Partial Cooperation vs. Partial Cooperation (P vs. P): When both adopt partial cooperation, each obtains y · b $-$ c $+$ y · I $-$ (1 $-$ y) qF. This outcome represents an intermediate equilibrium whose payoff level increases with the degree of truthfulness y, the incentive I, and the detection probability q, while decreasing with the cooperation cost c and the penalty F.

Sensitivity Analysis of $x^* = \frac{c}{I+F}$

To assess the robustness of the model and identify the parameters with the greatest influence on strategic behavior, a sensitivity analysis is conducted on the cooperation threshold $x^* = \frac{c}{I+F}$ examining how variations in the cost of cooperation (c), the incentive (I), and the penalty (F) affect the conditions for achieving stable cooperation.

1) Monotonicity and partial derivatives [Equation (A3)]:

$$\frac{\partial x^*}{\partial c} = \frac{1}{I+F} > 0 \tag{A3}$$

Higher costs raise the required cooperation level.

Incentive I [Equation (A4)]:

$$\frac{\partial x^*}{\partial I} = -\frac{1}{(I+F)^2} < 0 \tag{A4}$$

Larger incentives lower the threshold.

Penalty F [Equation (A5)]:

$$\frac{\partial x^*}{\partial F} = -\frac{c}{(I+F)^2} < 0 \tag{A5}$$

Stronger penalties also lower the threshold.

2) Elasticities (how responsive x* is in % terms) [Equation (A6)]:

$$\varepsilon_c = \frac{\partial x^*}{\partial c}\frac{c}{x^*} = 1 \text{unit elasticity} \tag{A6}$$

A +10% change in c → +10% change in x^* [Equation (A7)]:

$$\varepsilon_I = -\frac{1}{(I+F)} (\text{between } 0 \text{ and } -1) \tag{A7}$$

The more incentives dominate penalties, the more powerful F is [Equation (A8)]:

$$\varepsilon_F = -\frac{F}{(I+F)} (\text{between } 0 \text{ and } -1) \tag{A8}$$

The more penalties dominate incentives, the more powerful F is.

The elasticity analysis reveals that the cooperation threshold x^* responds proportionally to changes in the cost of cooperation ccc (unit elasticity), implying that any percentage increase in ccc translates directly into the same percentage increase in x^*. By contrast, the responsiveness of x^* to incentives I and penalties F is negative and depends on their relative weight within I + F. This means that strengthening the component, either I or F, that already accounts for a larger share of the total enforcement mechanism, yields the most substantial reduction in the cooperation threshold. Consequently, policy or managerial interventions should prioritize enhancing the more influential parameter to maximize the effectiveness of cooperation-promoting strategies.

3) Feasibility region

For x*∈[1] it needs $c \leq I + F$.

If $c > I+F$: no cooperation level in[1] makes cooperation privately optimal with insufficient incentives/penalties or excessive costs. The required uplift to regain feasibility is $\Delta = c - (I + F)$.

4) Boundary Insights

If I → 0 and F is small, then x* is high, making cooperation difficult.

If $I + F > c$, then $x^* \approx 0$, meaning even a small share of cooperation is sufficient.

With imperfect detection, replace F with the expected penalty qF, where q ∈[1] [Equation (A9)]:

$$x^* = \frac{c}{I+qF'}, \frac{\partial x^*}{\partial q} = -\frac{cF}{(I+qF)^2} < 0 \tag{A9}$$

Improving monitoring probability q is as effective as increasing penalty F.

5) Simple Scenario

Assume that $c = 3$:

Table A2. Simple strategic scenario.

Incentive I	Penalty F	I + F	$x^* = \frac{c}{I+F}$	Feasible?
2	1	3	1.00	Yes (just at threshold)
4	2	6	0.50	Yes
1	5	6	0.50	Yes
0	10	10	0.30	Yes
2	0	2	1.50	No (I + F < c)

6) Policy levers mapped to the model

From a policy perspective, the model highlights three main levers for influencing the cooperation threshold:

- Reducing the cost of cooperation (c) through measures such as process standardization, technological support, training, and improved user experience.
- Increasing incentives (I) via price premia, preferen-

tial market access, tax credits, or certification benefits.

- Enhancing the expected penalty (qF) by improving detection mechanisms (raising q) and enforcing credible sanctions (raising F).
- The choice of which lever to prioritize will depend on the institutional context, the available resources, and the feasibility of implementation.

Overall, the sensitivity analysis highlights the central role of balancing incentives and penalties relative to cooperation costs in determining the feasibility of sustained cooperation. The results demonstrate that increasing either I or F can reduce the cooperation threshold, but the magnitude of the effect depends on their relative weight in $I + F$. Furthermore, incorporating detection probability q underscores the importance of monitoring efficiency as a substitute or complement to higher penalties. These insights provide actionable guidance for designing incentive structures and enforcement mechanisms capable of shifting strategic behavior towards full cooperation, thereby enhancing the effectiveness of blockchain adoption in agri-food supply chains.

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