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Evaluating Traceability Technology Adoption in Food Supply Chain: A Game Theoretic Approach

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Abstract: Food traceability in the supply chain is becoming increasingly important because of concerns such as fraud, adulteration, consumer requirements, and food loss. This study highlights the importance of food traceability in reducing food loss through the proper monitoring of food at every stage of the supply chain. The actions of individual players in a food supply chain affect its traceability. Moreover, the decisions made by one player influence the decisions of the other players. Thus, traceability becomes more complex as the number of players increases. Owing to the complex nature of a food chain, it is important to analyze all the possible strategies that stakeholders consider and understand the influence of those possible strategies on the traceability of a food supply chain. In this study, we deploy a game theory model to analyze the strategic combinations of all possible actions of different stakeholders to understand the complexities present in a food supply chain, as well as how these strategic combinations help in decision-making for the adoption of traceability in a food supply chain. Furthermore, we analyze the factors that may increase or decrease the probability of adopting traceability in a food supply chain.

Keywords: food traceability; game theory; multi-stage game; food supply chain

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1. Introduction

Food security is a major concern worldwide due to the increase in population, climate change, and increasing demand for food [1]. Around 30% of edible food is either converted to waste or lost in a supply chain. Similarly, around 14% of the food produced is lost in the post-harvest stages excluding the retail stage [1–4]. Food loss is referred to as the reduction of quality or quantity of food due to the decisions or actions taken by various stakeholders of the supply chain. Whereas food waste is referred to as edible food converted to waste due to purchasing decisions of customers, or decisions of retailers and other food service providers [1]. Food waste depends upon consumer behavior and societal concerns regarding food waste [5], while food loss can be monitored as well as controlled with the help of modifications in various aspects such as food policies, infrastructure, and technological investments. Food loss is considered a threat to food security. Therefore, it is essential to monitor the causes of food loss present in a supply chain. The main causes of food loss in the supply chain include lack of storage facility, improper care, inefficient post-harvest management, poor processing management, inadequate packaging, and lack of refrigerated transportation [6,7]. Most significant food quality and quantity deterioration take place in warehouses due to the collection of different seed-quality of food in one place [8]. Post-harvest stage loss is also essential to monitor and control to achieve sustainable development goals [1].

A traceability system in the food supply chain can help in monitoring the ambiguity of the food supply chain. According to [1] technological innovation is the foundation for the development of traceability. Traceability is the ability of a food chain to track and trace the history and flow of food products throughout the supply chain by using different technical innovations like RFID (radio-frequency identification), blockchain, food sensing technologies, and barcoding [7]. Seminar [3] exposed the vulnerability of the food chain. He also developed a framework for transparency and traceability in the supply chain to track food loss and waste. Sidwani et al. [9] also developed a wireless sensor network model at a grain warehouse in India to monitor the health of grains. Data collected from this study were analyzed to reduce grain loss during storage. An efficient traceable system will help to trace and track the food present in the supply chain starting from the farm and extending to the fork. Traceability is the ability to access all the information throughout the supply chain related to food [1,7]. Traceability systems are based on effective utilization of technologies such as internet of things, big data, and cloud computing [10,11]. Development of an efficient and effective traceability system is a complex process that requires not only the understanding of technical development, but also business, organizational, social, economic, and environmental perspectives [10].

Implementation of traceability throughout the supply chain is not a one stage phenomenon. This involves the decision of several players at different stages of the supply chain. The choice to develop the traceable system at every level depends upon the risk, capital investment, governmental policies, technological information, and social and environmental concerns [12]. Along with this information symmetry among multiple levels is difficult to achieve. Therefore, it becomes highly complex to understand the strategy of every player such as whether a particular player would invest their resources to develop a traceable system. Such decisions are purely based on the revenue from the traceable goods and the cost involved in this. The core players of the traceable food chain considered in this study include government, farmers, manufacturing/processing organizations, certification agencies, and consumers, exhibited in Figure 1. There might be other players such as transportation agencies for movement of food, public/private warehouse for storage of food, and distributors involved as well. However, due to mathematical complexity, this study is limited to the core players only. Based on the decisions of different stakeholders and enterprises, a traceability system throughout the food chain can be developed. Game theory is one of the most favorable tools for decision-making where multiple players at different levels are involved and decisions made by one player directly or indirectly depend upon the decisions made by others. Game theory is the study of strategic interaction among more than one player, when several choices are available to make a final decision. Considering Indian context, complexity of food supply chain can be included in a multi-stage game model, where several players are involved to discover their strategy. However, multi-stage game modelling is beyond the scope of this study.

Figure 1. Core players of a food supply chain.

Implementation of game theory model will help to elucidate the strategic decisions of multiple players and identify the factors that influence them to implement traceability in a supply chain. This study will reveal the components that will motivate the players to adopt traceability in a supply chain and follow transparent strategies to become profitable and safe. The objectives of this study are as follows: (1) Determine the possible strategies of stakeholders in a supply chain to implement traceability in a food chain; (2) Define conditions that are needed to understand the key factors that affect the decision of traceability adoption in a food chain; (3) Formulate a numerical example based on hypothetical data to show the utility of mathematical model developed.

The remainder of the paper is organized as follows. In Section 2, a literature review is presented along with research gaps and the scope of the present study. In Section 3, research methodology and mathematical notations have been included. Section 4 includes a mathematical model along with a practical example to get an understanding of the game-theoretic model. Analysis of the mathematical model is included in Section 5. Section 6 includes the implication of the research followed by concluding remarks and future directions in Section 7.

2. Literature Review

This study explores two important elements in the field of food supply chains. Section 2.1 covers the importance of food traceability in the context of food loss and the challenges in implementing traceability throughout the supply chain. Section 2.2 provides a review of the application of game theory in the food industry. Finally, Section 2.3 identifies the gaps in the scientific literature and the scope of the present study.

2.1. Traceability Needs and Implantation in the Food Supply Chain

A food supply chain is one of the most vulnerable supply chains due to the perishable nature of food that can be easily contaminated. Several incidents in the food sector are demanding an appropriate system due to its hazardous and perishable nature, and to prevent various incidents and fraudulence [5,7]. Gardas et al. [13] performed a study in the vegetable and fruits supply chain to identify the following three factors of post-harvest losses in the context of India: (1) lack of advanced technology in food processing units, (2) lack of linkage between government, industry, and institution, (3) lack of linkage between farmers and processing units. Moreover, there are several other factors such as global population, food-borne illness, and fraudulence, that demand the need for traceability in a food supply chain [8]. A fundamental transformation is also required in a food supply chain by technological investment to make it more efficient, sustainable, healthy, and credible. Due to the spread of COVID-19, customers have become more interested in knowing about what they are consuming and how the food comes to them [14,15].

Basu [15] proposed that it is necessary to improve the current policies toward modifying the facilities because they can lead to huge grain loss. Post-harvest loss is one of the major losses in a food supply chain [8]. Further, storing grain for multiple seasons due to inadequate storage systems also leads to food loss [8]. Gokarn and Kuthambalayan [16] performed a study that identifies the key challenges for reducing food loss in supply chains, and they also suggested that transparency in the supply chain can reduce food loss. Various challenges of the food chain that cause food loss, and how traceability can be deployed to overcome those challenges were also discussed [3]. Shanmugasundaram et al. [17] performed an overview of the application of traceability and information technology in vegetable supply chains to analyze the technical advancements in the Indian food market.

As per the [1] traceability provides a solution to the challenges faced in the food systems. Traceability helps in making the supply chain "visible" by facilitating complete tracking of the environmental, health, economic, and social consequences of various agricultural production processes. Additionally, traceability helps in dealing with credibility issues in the consumer's view by providing a transparent supply chain, minimizing food safety problems and costs involved in product recalls, reducing food loss, and developing an optimized food chain. Furthermore, a study conducted by [1] identified twelve transformative technologies that may affect food systems. The transformative technologies that affect traceability include food sensing technologies for tracking of food safety and quality, internet of things for tracing real-time information, and blockchain-enabled traceability.

At the First International Day of Awareness of Food Loss and Waste, the Food and Agriculture Organization (FAO) of United Nations (http://www.fao.org/news/story/en/item/1310271/icode/, accessed on 26 June 2021) published a study that discusses the global food security issues. The study discussed that the issue of global hunger can be overcome only by reducing food loss. Further, it says that technology and innovation are the only way to reduce this food loss. According to this study, "Innovative post-harvest treatment, digital agriculture in food systems and re-modeling market channels offer huge potential to tackle the challenges of food loss and waste". FAO has built a partnership with Microsoft, IBM, and the Vatican to empower artificial intelligence techniques in food systems. This initiative will help in achieving a transparent food chain and achieving the objective of reducing food loss. Traceability provides the customer an edge to trust the company and, based on their judgmental skills, customers can develop their interests. Traceability systems are a great source to remove all the negative practices and track the source of such malpractices if present in the supply chain [18].

Pappa et al. [19] performed a study that illustrates the factors affecting the adoption of electronic traceability in the dairy sector to ensure food quality and safety. In this study, they developed a mixed model combining TAM2 (technology acceptance model 2) and TPB (theory of planned behavior). This study concludes that electronic traceability systems can be successfully integrated within food supply chains to ensure their added value. Similarly, Padmaja et al. [11] highlighted the application of information systems in the food chain to improve productivity by analyzing how internet of things has become the foundation for reducing food loss and traceability. Sidwani et al. [9] performed a study on grain warehouses where they utilize WiFi-enabled sensors to measure the real-time data of variables such as temperature, carbon dioxide concentration, relative humidity, and pressure to prevent food grain loss and predict grain quality. Rowan and Galanakis [20] discussed the role of traceability in green supply chains to achieve sustainable production of food products and considered the impact of COVID-19 on the need for a transparent supply chain and waste mitigation. Sharma et al. [21] developed conceptual guidance to know what information needs to be captured for considering traceability in the grain supply chain and how it is implemented.

Xiao et al. [22] developed a traceable framework for aquatic food products in cold chain logistics using wireless sensor networks (WSN) and QR scan codes. Cold chain logistics utilizes artificial refrigeration systems to maintain a low temperature during the storage and transportation of food products to ensure their quality and safety. The key aspects of the cold chain are temperature and pressure with the application of wireless sensors. This data can also be collected and monitored for future analysis. They also compared QR scan codes and WSN-based systems with traditional methods of monitoring the cold chain and concluded that WSN systems provide more effective results and better monitoring than traditional methods.

Li et al. [23] developed a framework for implementing traceability in the dairy supply chain. This network structure includes breeding farms, dairy processing enterprises, distributors, retailers, and consumers. They utilized barcoding and QR scan codes that can easily locate the root cause of the problem if there are any safety-related issues present in the food supply chain. The barcoding and QR scan code technologies are less expensive as compared to RFID systems because RFID systems are expensive for the supply chain having low-margin profits. Implementation of traceability leads to an increase in the effectiveness of a milk supply chain by easily tracking and tracing along with increasing value by providing a transparent supply chain to consumers with detailed information about the product.

Astill et al. [24] performed a study to provide an overview of technologies that aid in enabling a transparent supply chain. These technological enablers are data acquisition technologies (such as sensors and bio-sensors), Internet of things (technologies that provide communication between devices such as cloud computing, RFID tags, etc.), and platforms to manage collected data (including different centralized and decentralized systems such as blockchain). Other than this there are different types of chemical or bio-chemical testing that are used to check the quality of the products. Such practices should be utilized to prevent the use of hazardous chemicals in food products. Adequate effort from all the stakeholders to develop a traceable system was highlighted, as the study [24] also focuses on challenges faced in application of the mentioned data acquisition technologies, e.g., poor internet connectivity, data privacy, and security issues, consumer acceptance, and economic sustainability. Different types of sensors to monitor pressure, temperature, oxygen level, freshness, etc. are already there in practice.

Galvez et al. [25] considered blockchain technology as a true innovation and an adequate approach for assuring the quality of food products and reducing economic losses due to falsification of food products. Due to its structure and composition, blockchain technology helps in preventing counterfeiting in supply chains and provides all the information to consumers from farm to fork. Kamble et al. [26] also revealed various benefits of blockchain in the agri-food supply chain and identified thirteen enablers that help in the implementation of blockchain. These thirteen enablers are: privacy, auditable, decentralized database, immutable (unchangeable), improved risk management, provenance, lesser transaction costs, reduced lead times, secured database, shared database, smart contracts traceability, and transparency. Blockchain implementation in supply chains is at the nascent stage and it has several challenges. Iftekhar et al. [27] considered blockchain as an emerging technology that provides tamper-proof real-time data sharing and helps to ensure that all safety measures have been considered to minimize the risk of COVID-19. In this way there is an ample amount of literature present that says that traceability implementation in the food chain may help in reducing food loss, improve the productivity of the supply chain and increase the credibility of food chains for stakeholders.

2.2. Game Theory Implementation in the Food Supply Chain

Game theory is a field of mathematics that deals with situations where two or more decision-makers are involved in a decision. Game theory is a tool that is preferred in supply chain optimization and decision-making due to its structure having multiple players. There have been several studies in the literature that utilize game theory concepts in a different context to optimize the efficiency and effectiveness of supply chains. The rationality of players and common knowledge among players are two assumptions in most of the games. Vasnani et al. [28] conducted a literature review that discussed the trends and applications of game theory in supply chains. They also discussed the application of the Nash equilibrium concept and Stackelberg game model with their application in supply chains. Further, this study focuses on how game theory is different from other decision-making and optimization methodologies. Chavoshou et al. [29] introduced a fuzzy game theory model to understand customer requirements for green products. Asrol et al. [30] proposed a cooperative game theory model based on Shapley value for fair profit allocation among stakeholders in a sugarcane industry to perform a comparative analysis among the current policies and the proposed policies. Asian et al. [12] identified the role of sharing economy in the case of organic small farmers in a cooperative environment.

Song and Zhuang [31] presented a study of strategic interaction among the government, farmers, and manufacturers to analyze the risky behavior of stakeholders in food supply chains to maximize their payoffs. This study discussed three different types of interactions among stakeholders and a comparative analysis of all these models. The first one is "government against manufacturer against farmer", the second one is "a centralized government-manufacturer-farmer model", and the third one is "government vs. farmer and manufacturer model".

Li et al. [32] conducted a comprehensive analysis for developing a decision-making traceable system by utilizing game theory to establish a traceability system for fresh agricultural products. They identified revenue, cost, technological conditions, law and policies, purchase intention, and industrial environment as key factors that influence the development of a traceability system. The findings of this study also suggested that an organization adopts a traceability system if there are fewer chances of safety incidents along with less construction cost of a traceable system while more purchase intention of the consumer.

Tang [33] developed a two-echelon system for establishment of traceability in food supply chains that consists of downstream and upstream node enterprises. Assumptions made in this study included the rationality of upstream and downstream enterprises, long-term collaboration in establishing a food traceability system, and the dynamic nature of strategies. This study concluded that the chances of cooperation between upstream and downstream are positively correlated with the probability of disruption and total revenue, and negatively correlated with the cost of establishment. This study utilizes evolutionary game theory to deal with the dynamic nature of strategies. Evolutionary game theory is based on the long-term evolution of multi-agent multi-criteria decision-making techniques under consideration of uncertainty [34].

Wang and Yang [35] implement game theory for organic tea certification in the tea industry. Along with this they also analyze the strategic decisions made by certification agencies and farmers to set up traceability systems in the industry. A further study by Wang and Yang [36] proposed a game theoretic model in the herbal product industry by including multiple stakeholders in the supply chain. In this way, the literature discusses different methodologies of game theory, and how these methodologies have been utilized in the food supply chain.

2.3. Research Gaps and Key Contributions

Supply chains involve multiple stakeholders, where decisions made by every player matter. Every decision made by different stakeholders plays an important role and may affect the decisions of others. Multiple studies have developed traceability frameworks for various food chains, but none of them considers strategic interaction among stakeholders and their contribution as an individual to the supply chain. Every stakeholder in the supply chain is a different entity and tries to maximize their utility value. In such cases, it becomes difficult to understand how different players make their decisions, either as independent players to maximize their payoffs or by cooperation with other players to maximize the utility of the whole supply chain. Several studies have been performed on decision-making and supply chain optimization, but these studies have highlighted either the overall view of a supply chain or a particular node of a supply chain.

In the current study game theory is being utilized by considering the supply chain as a multi-player game having multiple strategies. Limited studies have implemented game theory in the food supply chain by considering two or three players in the supply chain, but food supply chains involve multiple players from farmers to retailers to end consumers. The key goals of this study are to:

- Develop a multiplayer game to obtain a view of strategies that can be made by different stakeholders of the supply chain.
- Analyze the game model to understand the key factors that affect the decision of traceability adoption in the food chain.

3. Assumptions and Notations

The key purpose of food traceability is to provide detailed information on food throughout the supply chain. This is ambiguous due to the complexity as well as changing scenarios of the food chain. Causes of ambiguity may be information complexity, information asymmetry, cost–benefit tradeoff, government intervention, etc. [36].

This study considers the government, farmers, processing organizations, certification agencies, and consumers as key stakeholders of the food supply chain. The following points justify the selection of key players:

- Government authorities can be considered key players in the food supply chain by imposing policies and laws, punishing risky players and providing subsidies for establishing traceable systems [29,31]. Government can monitor food loss by implementing traceability and modifying the policies to reduce food loss in post-harvest stages.
- Farmers are the players who grow the food and transport it to markets or industries. Due to the lack of resources, major food loss can take place at this stage. In addition, use of unwanted chemicals to protect the food may affect the quality of food.

- Around 10% of food is lost either in processing or storage at warehouses of processing enterprises. Such loss may be caused by factors such as lack of infrastructure, poor methods of processing/storage, and lack of technological advancement. Therefore, processing organizations are one of the major players in a food supply chain.
- Certification agencies are the players that audit and verify the whole process and provide documentation regarding food production. If they collude with other stakeholders for false certification, this may act as a threat to the whole supply chain.
- Adoption of traceability also depends upon consumers' perception regarding traceable food products and their readiness to pay premium prices for traceable food [14] because consumers are the only source of revenue for a particular supply chain.

The current study considers key stakeholders as players of the game and the decision choices of every stakeholder act as a possible strategy of the game. The current study considers the following assumptions: All the players of this game are rational, i.e., they can decide on their choice and every player is aware of the strategies of every other player. The objective of this game is to observe the strategic combination for developing a comprehensive traceability system throughout the food chain.

Government authorities may choose either active or passive promotion of traceability. Active promotion of traceability involves modification in policies and standards of food products to enforce traceability in the supply chain. Passive promotion depends upon consumer requirements and the willingness of other stakeholders to adopt a traceable food production system without the direct involvement of authority. Farmers can choose whether to establish a traceable system. Processing organizations may also choose whether to purchase traceable food from farmers and establish a comprehensive traceable system at their enterprise. Certification agencies can choose either to maintain their independence without colluding with processing organizations or to lose their independence by colluding with processing organizations and issuing false certifications. The consumer may also choose whether to purchase traceable food products.

The following notations have been used throughout the game model.

R_a: Revenue of authority from actively promoting traceability.
R_n: Revenue of authority from passively promoting traceability.
C_a: Cost to authority for actively promoting traceability.
C_n: Cost to authority for passively promoting traceability.
R_f: Revenue of farmers generated from sales of traceable food products.
R_t: Revenue of farmers generated from sales of non-traceable food products.
F_a: Cost to farmers for establishing a traceable system.
F_c: Cost to farmers for establishing a non-traceable system.
R_f: Cost to processing enterprises in purchasing traceable food products.
R_t: Cost to processing enterprises in purchasing non-traceable food products.
F_t: Cost to processing enterprises in developing a comprehensive traceable system.
F_n: Cost to processing enterprises in developing a non-traceable system.
F_b: Certification fees for processing enterprises when developing a traceable system.
S_h: Revenue of processing enterprises generated from the sale of traceable labeled food products.
S_n: Revenue of processing enterprises generated from the sale of non-traceable labeled food products.
F_b: Revenue of certification agencies generated from certification fees paid by processing enterprises.
C_c: Revenue of certification agencies generated from collusion with processing enterprises for issuing the false certification.
W_c: Damage compensation imposed on certification agencies for issuing falsely labeled food products as traceable.
Q_a: Cost to certification agencies for finding new clients when it works independently and refuses to issue false certification. Cost of losing a client and finding a new one might be more than the cost involved in collusion ($Q_a > C_c - W_c$).

S_h: Cost to a consumer in purchasing traceable labeled food products
S_n: Cost to a consumer in purchasing non-traceable labeled food products.
U_a: Revenue of consumers in purchasing traceable labeled food products in terms of monetary value.
U_b: Revenue of consumers in purchasing traceable labeled food products in terms of monetary value.

Here,

$$R_a > R_n$$

$$C_a > C_n$$

$$F_a > F_c$$

$$R_f > R_t$$

$$F_t > F_n$$

$$S_h > S_n$$

$$U_a > U_b$$

W_g: Damage compensation imposed on authorities when the food product is falsely labeled as a traceable product and authorities promote it passively.
W_f: Damage compensation imposed on farmers when a product is falsely labeled as traceable and farmers do not develop a traceable system.

When processing organization either does not purchase traceable food from farmers or do not develop a traceable system the following costs may be involved:

C_c: Cost to processing enterprise in colluding with certification agency.
W_p: Damage compensation imposed on the processing organization when the food product is falsely labeled as a traceable food product.
Q_n: Cost to processing enterprise for switching certification agency when certification agency does not collude in issuing a false certificate.
W_a: Damage compensation imposed on the certification agency when the food product is falsely labeled as a traceable food product.
W_t: Damage compensation provided to consumers if a product is falsely labeled as traceable.

4. Mathematical Model and Practical Application

Extensive form games are specialized games that represent sequential moves of players and their strategies at every decision-making node. For example, at one stage one player might be making some decision and at the next stage, another player might be making a decision based on an action taken by the first player. In such games, each player has information about the move of other players while making their decision. These games are listed in the form of a tree. Extensive games can be classified into two categories: (1) Game with perfect information: players when making decisions know about all the actions that have previously occurred; (2) Game with imperfect information: players when making decisions may not be perfectly informed about some (or all) of the events that have previously occurred. There are two methodologies to solve an extensive form game: backward induction and sub-game equilibrium. The game is solved when the Nash equilibrium is found. Nash equilibrium in the extensive game is defined in such a way that if any player deviates from equilibrium, his/her payoff will not increase, i.e., a player has no incentive in deviating from Nash equilibrium.

Table 1 represents the 28 strategic interactions among the key players of the game and the strategic combination of authority, farmers, processing enterprises, certification agencies, and consumers.

Table 1. Strategic combinations of the game.

Strategic Combination	Node 1 (Authority's) Action	Node 2 (Farmer's) Action	Node 3 (Processing Organization's) Action	Node 4 (Certification Agency's) Action	Node 5 (Consumer's) Action
1	Actively promoted traceability system in food chain	Farmer developed a comprehensive traceability system	Processing organization purchased traceable food from farmers and established a traceability system	Certification agency issued traceable labeled certificate	Consumer purchased "Traceable Labeled Food Product"
2					Consumer did not purchase "Traceable Labeled Food Product"
3		Farmer did not Develop a comprehensive traceability system	Processing organization did not purchase traceable food from farmers, but establish a traceability system at enterprise	Certification agency colluded with other stakeholders and issued false certificate	Purchased "Traceable Labeled Food Product"
4					Did not purchase "Traceable Labeled Food Product"
5				Certification agency refused to issue falsely labeled traceable food product	Purchased "Traceable Labeled Food Product"
6					Did not purchase "Traceable Labeled Food Product"
7				Switched current certification agency when certification agency refused to collude with processing organization for falsely labeled food product as traceable	Purchased "Traceable Labeled Food Product"
8					Did not purchase "Traceable Labeled Food Product"
9			Processing organization neither purchased traceable food from farmers, nor establish a traceability system at enterprise	Certification agency colluded with other stakeholders and issued false certificate	Purchased "Traceable Labeled Food Product"
10					Did not purchase "Traceable Labeled Food Product"
11				Certification agency refused to issue falsely labeled traceable food product	Purchased "Traceable Labeled Food Product"
12					Did not purchase "Traceable Labeled Food Product"
13				Switched current certification agency when certification agency refused to collude with processing organization for falsely label food product as traceable	Purchased "Traceable Labeled Food Product"
14					Did not purchase "Traceable Labeled Food Product"

Table 1. *Cont.*

Strategic Combination	Node 1 (Authority's) Action	Node 2 (Farmer's) Action	Node 3 (Processing Organization's) Action	Node 4 (Certification Agency's) Action	Node 5 (Consumer's) Action
15	Passively promoted traceability system in food chain	Farmer developed a comprehensive traceability system	Purchased traceable food from farmers and also established a traceability system	Certification agency issued traceable labeled certificate	Purchased "Traceable Labeled Food Product"
16					Did not purchase "Traceable Labeled Food Product"
17		Farmer did not develop a comprehensive traceability system	Processing organization did not purchase traceable food from farmers, but established a traceability system at enterprise	Certification agency colluded with other stakeholders and issued false certificate	Purchased "Traceable Labeled Food Product"
18					Did not purchase "Traceable Labeled Food Product"
19				Certification agency refused to issue falsely labeled traceable food product	Purchased "Traceable Labeled Food Product"
20					Did not purchase "Traceable Labeled Food Product"
21				Switched current certification agency when certification agency refused to collude with processing organization for falsely label food product as traceable	Purchased "Traceable Labeled Food Product"
22					Did not purchase "Traceable Labeled Food Product"
23			Processing organization neither purchased traceable food from farmers, nor established a traceability system at enterprise	Certification agency colluded with other stakeholders and issued false certificate	Purchased "Traceable Labeled Food Product"
24					Did not purchase "Traceable Labeled Food Product"
25				Certification agency refused to issue falsely labeled traceable food product	Purchased "Traceable Labeled Food Product"
26					Did not purchase "Traceable Labeled Food Product"
27				Switched current certification agency when certification agency refused to collude with processing organization for falsely label food product as traceable	Purchased "Traceable Labeled Food Product"
28					Did not purchase "Traceable Labeled Food Product"

Figure 2 represents the steps required for the calculation of payoff values for all the stakeholders. Here, sub-game perfect equilibrium has been utilized for the calculation of Nash equilibrium. After the calculation of payoff values the next step is to identify the optimum strategy for the players to develop a traceable system throughout the food chain. Sub-games are considered as a sub-set of a game which is broken into a sub-game. Sub-games are extracted from backward induction. Figure 3 represents the steps for obtaining the best strategy using sub-game perfect equilibrium. Figure 4 represents all 28 combinations of strategies obtained from the interaction of all the players.

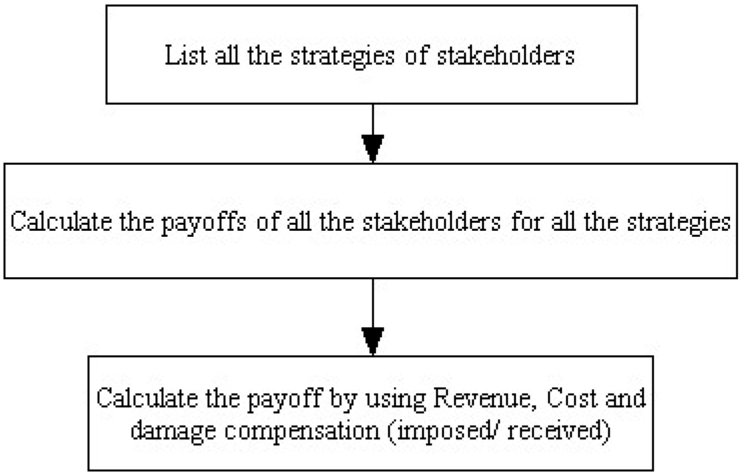

Figure 2. Steps to calculate profits of all the stakeholders.

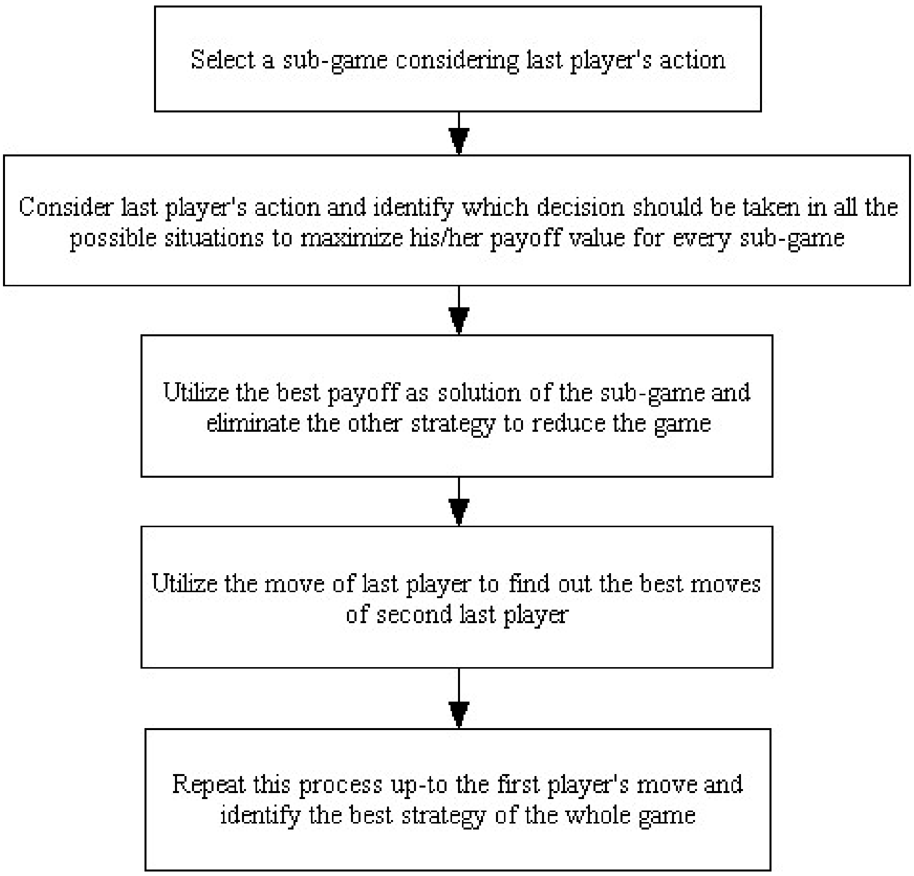

Figure 3. Steps to determine the best strategies of the game by sub-game equilibrium.

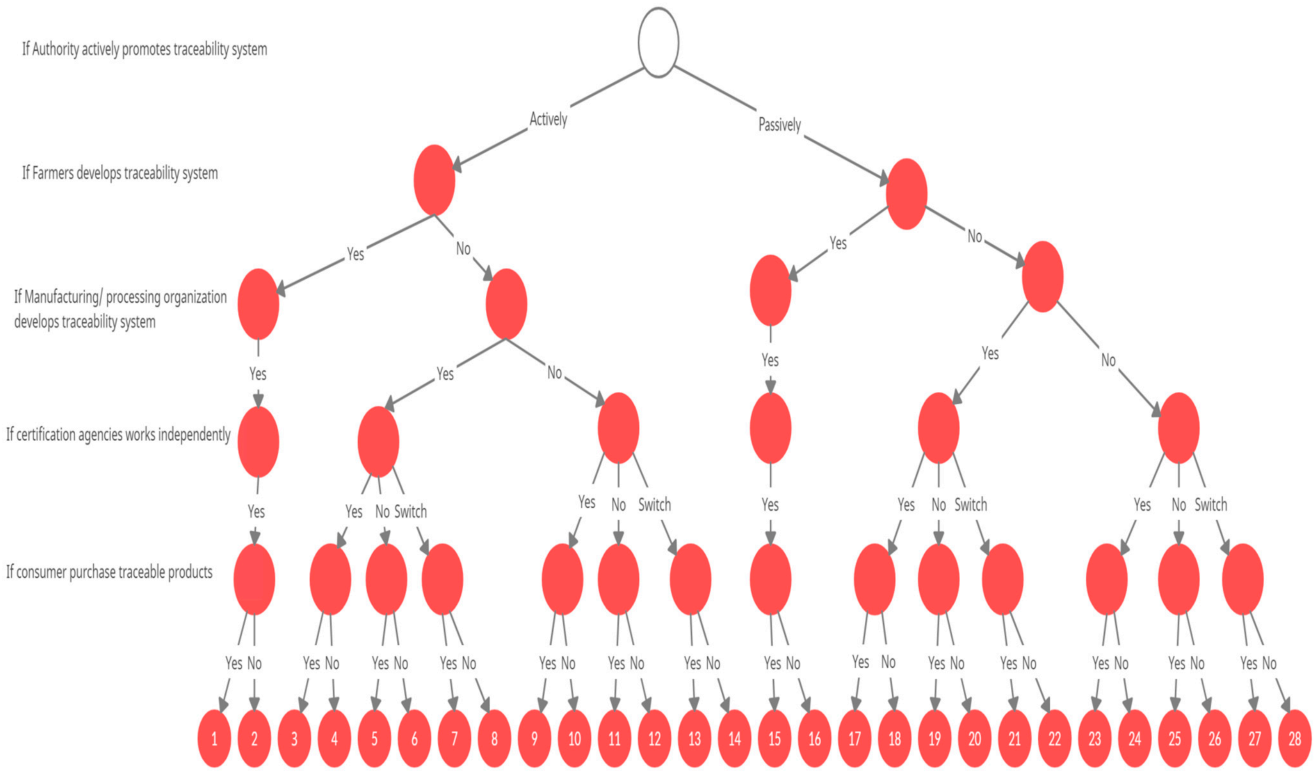

Figure 4. Multi-stage game model representing strategies of stakeholders in supply chain.

Table 2 represents the payoff values of authority, farmers, processing enterprises, certification agencies, and consumers that are obtained from the above flow charts. The backward induction method has been used for the calculation of payoffs in this game model.

Table 2. Payoff matrix of the multi-stage game model.

Strategic Combination	Authority	Farmers	Processing Enterprises	Certification Agencies	Consumers
1	$R_a - C_a$	$R_f - F_a$	$S_h - \left(R_f + F_t\right) - F_b$	F_b	$U_a - S_h$
2	$-C_a$	$-F_a$	$-\left(R_f + F_t\right) - F_b$	F_b	0
3	$R_a - C_a - W_g$	$R_t - F_c - W_f$	$S_h - (R_t + F_t) - F_b - C_c - W_p$	$F_b + C_c - W_a$	$U_b - S_h + W_t$
4	$-C_a$	$-F_c$	$-(R_t + F_t) - F_b - C_c - W_p$	$F_b + C_c$	0
5	$R_a - C_a - W_g$	$R_t - F_c - W_f$	$S_n - (R_t + F_t) - F_b$	F_b	$U_a - S_n$
6	$-C_a$	$-F_c$	$-(R_t + F_t) - F_b$	F_b	0
7	$R_a - C_a - W_g$	$R_t - F_c - W_f$	$S_h - (R_t + F_t) - F_b - C_c - W_p - Q_n$	$F_b - Q_a$	$U_b - S_h + W_t$
8	$-C_a$	$-F_c$	$-(R_t + F_t) - F_b - C_c - W_p - Q_n$	$F_b - Q_a$	0
9	$R_a - C_a - W_g$	$R_t - F_c - W_f$	$S_h - (R_t + F_n) - F_b - C_c - W_p$	$F_b + C_c - W_a$	$U_b - S_h + W_t$
10	$-C_a$	$-F_c$	$-(R_t + F_n) - F_b - C_c - W_p$	$F_b + C_c$	0
11	$R_a - C_a - W_g$	$R_t - F_c - W_f$	$S_n - (R_t + F_n) - F_b$	F_b	$U_b - S_n$
12	$-C_a$	$-F_c$	$-(R_t + F_n) - F_b$	F_b	0
13	$R_a - C_a - W_g$	$R_t - F_c - W_f$	$S_h - (R_t + F_n) - F_b - C_c - W_p - Q_n$	$F_b - Q_a$	$U_b - S_h + W_t$
14	$-C_a$	$-F_c$	$-(R_t + F_n) - F_b - C_c - W_p - Q_n$	$F_b - Q_a$	0

Table 2. *Cont.*

Strategic Combination	Authority	Farmers	Processing Enterprises	Certification Agencies	Consumers
15	$R_n - C_n$	$R_f - F_a$	$S_h - \left(R_f + F_t\right) - F_b$	F_b	$U_a - S_h$
16	$-C_n$	$-F_a$	$-\left(R_f + F_t\right) - F_b$	F_b	0
17	$R_n - C_n - W_g$	$R_t - F_c - W_f$	$S_h - (R_t + F_t) - F_b - C_c - W_p$	$F_b + C_c - W_a$	$U_b - S_h + W_t$
18	$-C_n$	$-F_c$	$-(R_t + F_t) - F_b - C_c - W_p$	$F_b + C_c$	0
19	$R_n - C_n - W_g$	$R_t - F_c - W_f$	$S_n - (R_t + F_t) - F_b$	F_b	$U_b - S_n$
20	$-C_n$	$-F_c$	$-(R_t + F_t) - F_b$	F_b	0
21	$R_n - C_n - W_g$	$R_t - F_c - W_f$	$S_h - (R_t + F_t) - F_b - C_c - W_p - Q_n$	$F_b - Q_a$	$U_b - S_h + W_t$
22	$-C_n$	$-F_c$	$-(R_t + F_t) - F_b - C_c - W_p - Q_n$	$F_b - Q_a$	0
23	$R_n - C_n - W_g$	$R_t - F_c - W_f$	$S_h - (R_t + F_n) - F_b - C_c - W_p$	$F_b + C_c - W_a$	$U_b - S_h + W_t$
24	$-C_n$	$-F_c$	$-(R_t + F_n) - F_b - C_c - W_p$	$F_b + C_c$	0
25	$R_n - C_n - W_g$	$R_t - F_c - W_f$	$S_n - (R_t + F_n) - F_b$	F_b	$U_b - S_n$
26	$-C_n$	$-F_c$	$-(R_t + F_n) - F_b$	F_b	0
27	$R_n - C_n - W_g$	$R_t - F_c - W_f$	$S_h - (R_t + F_n) - F_b - C_c - W_p - Q_n$	$F_b - Q_a$	$U_b - S_h + W_t$
28	$-C_n$	$-F_c$	$-(R_t + F_n) - F_b - C_c - W_p - Q_n$	$F_b - Q_a$	0

Strategic combination 1 can be considered as Nash equilibrium for the game when authority promotes actively traceable food products and Strategic combination 15 can be considered as Nash equilibrium when authority promotes traceable food products passively. Figure 5 gives a detailed view of the steps included in obtaining the optimum strategy using sub-game equilibrium.

Table 3 illustrates every node of the game model after performing a derivation and comparison of Table 1. This table gives the conditions of every node for the establishment of the traceable food production system.

Table 3. Decision point conditions of the game.

Decision Point	Strategy	Conditions
(5) If a consumer buys traceable food products	Purchase	(a) The certification agency is not working independently: $U_b - S_h + W_t > 0$ (b) The certification agency is working independently: $U_b - S_n > 0$ (for not developing a traceability system) $U_a - S_h > 0$ (for developing a traceability system)
(4) What is the strategy adopted by certification agency?	Issue the certification	$C_c - W_a > 0$ (for not developing a traceability system)
	Do not issue the certification	$C_c - W_a < 0$ (for not developing a traceability system)
(3) If processing enterprises develop comprehensive traceability system?	Do not develop	(a) Certification agency is not working independently $S_n - S_h + C_c + F_b + \left(R_f + F_t\right) - (R_t + F_n) - W_p < 0$ (b) Certification agency is working independently $S_n - S_h + F_b + \left(R_f + F_t\right) - (R_t + F_n) > 0$
	Develop	(a) Certification agency is not working independently $S_n - S_h + C_c + F_b + \left(R_f + F_t\right) - (R_t + F_n) - W_p < 0$ (b) Certification agency is working independently $S_n - S_h + F_b + \left(R_f + F_t\right) - (R_t + F_n) < 0$

Table 3. *Cont.*

Decision Point	Strategy	Conditions
(2) If farmers adopts traceability practices?	Do not develop	(a) Certification agency is not working independently $R_t + F_a - R_f - F_c - W_f > 0$ (b) Certification agency is working independently $R_t + F_a - R_f - F_c > 0$
	Develop	(a) Certification agency is not working independently $R_t + F_a - R_f - F_c - W_f < 0$ (b) Certification agency is working independently $R_t + F_a - R_f - F_c < 0$
(1) If authority actively promotes traceability system?	Actively	(a) Certification agency is not working independently $R_n - R_a + C_a - C_n - W_g < 0$ (b) Certification agency is working independently $R_n - R_a + C_a - C_n < 0$
	Passively	(a) Certification agency is not working independently $R_n - R_a + C_a - C_n - W_g > 0$ (b) Certification agency is working independently $R_n - R_a + C_a - C_n > 0$

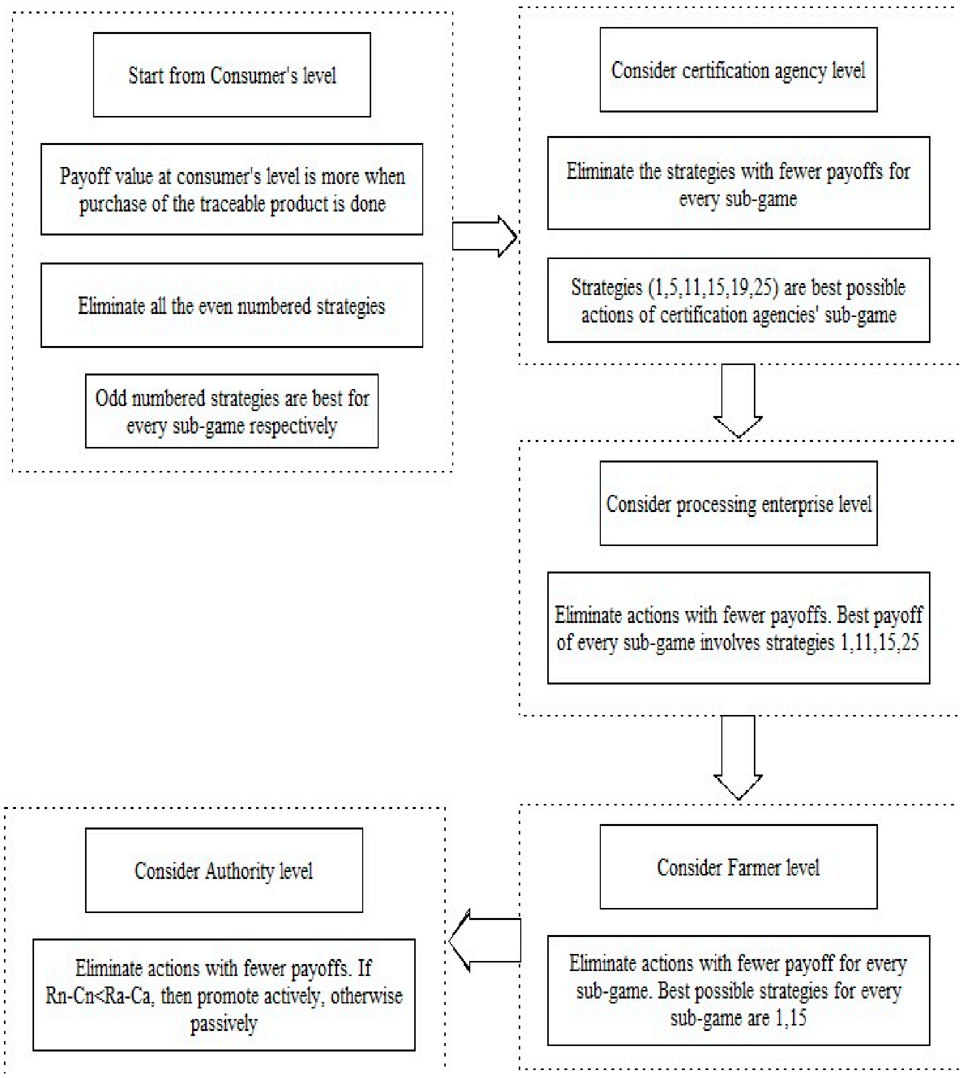

Figure 5. Framework to find Nash-equilibrium using sub-game equilibrium.

5. Analysis of Mathematical Model

This section highlights the decisions made by all the stakeholders and analyzes the conditions mentioned in the above table. Here we will analyze the factors of every player in the food chain that encourage them to establish a traceability system.

Factors affecting government authorities for actively promoting a food traceability system:

i. An increase in value of R_a, C_h and W_g represents high chances of authorities promoting the food traceability system actively.
ii. An increase in value of R_n and C_a represents low chances of authorities going for active promotion of traceability system.

According to the game model and every decision of the game, various scenarios in which government authorities promote traceable production of food actively can be illustrated as the following inequalities:

When the certification agency is not working independently, and the farmers and processing enterprises do not develop a comprehensive traceability system:

$$R_n - R_a + C_a - C_n - W_g < 0$$

When the certification agency is working independently:

$$R_n - R_a + C_a - C_n < 0$$

Here, positive and negative relations among several parameters influence the decision of authorities (i.e., the authority will promote traceability actively or not). Revenue of authorities when promoting traceable production of food actively (R_a); cost to authorities when promoting traceable production of food passively (C_h); damage compensation imposed on authorities when authorities passively promote traceability and food products are falsely labeled as traceable (W_g); represents a positive relationship with the active promotion of traceability (i.e., increases in the value of these parameters represent a high chance of active promotion of traceability. Revenue of authorities for the passive promotion of traceability (R_n); cost to authorities in active promotion of traceability of food products (C_a) represents a negative relationship with the active promotion of traceability i.e., increase in the value of these parameters represents low chances of active promotion of traceability. In short, the decision of authorities to promote traceability depends upon the revenue, cost, and damage compensation. If the damage compensation is higher as compared to the cost involved, the authority is more likely to promote traceability actively.

Factors affecting farmers to establish a traceable production of food:

i. Increase in the values of R_f, F_c, W_f represent high chances for farmers to develop a food traceability system.
ii. Increase in values of R_t, F_a represent low chances for farmers to develop a food traceability system.

According to game model derivation conclusions and every decision of the game (Table 2), various scenarios in which farmers establish a comprehensive traceable food production system can be illustrated as the following inequalities:

When the certification agency is not working independently:

$$R_t + F_a - R_f - F_c - W_f < 0$$

When the certification agency is working independently:

$$R_t + F_a - R_f - F_c < 0$$

Here positive and negative relations among several parameters influence farmers either to establish comprehensive food traceability or not. Revenue of farmers from the sale of traceable food products (R_f); Cost to farmers to develop a non-traceable system (F_c); damage compensation imposed on farmers when a product is falsely labeled as traceable and the farmer does not develop a traceable system (W_f); represents a positive relationship with the development of traceability i.e., increase in the value of these parameters represents a high chance of adopting traceability by farmers. Revenue of farmers from the sale of non-traceable food products (R_t); cost to farmers in establishing a traceability system of food products (F_a) represents a negative relationship with the establishment of a traceability system i.e., increase in the value of these parameters represents low chances of adopting traceability by farmers. In short, revenue generated by the farmer, the cost involved in growing traceable crops and the value added/risk involved in developing a traceable product/betraying the customer by taking false certification respectively. If the compensation for false certification is high then the farmer is more likely to avoid false certification and go for an honest strategy based on the profitability of the product.

Factors affecting processing enterprises to purchase traceable food and develop a comprehensive traceability system:

i. Increases in values of $S_h,\ R_t,\ F_n,\ W_p$ represent high chances of processing organizations purchasing traceable food from farmers and establishing a food traceability system at enterprises.
ii. Increases in values of $S_n,\ C_c,\ F_b,\ R_f,\ F_t$ represent low chances of processing organizations purchasing traceable food from farmers and establishing a food traceability system at enterprises.

According to game model derivation conclusions and every decision of the game, various scenarios in which the processing enterprise purchases traceable food from farmers and establishes a comprehensive traceable food production system can be illustrated as the following inequalities:

When the certification agency is not working independently:

$$S_n - S_h + C_c + F_b + \left(R_f + F_t\right) - (R_t + F_n) - W_p < 0$$

When certification agencies are working independently:

$$S_n - S_h + F_b + \left(R_f + F_t\right) - (R_t + F_n) < 0$$

Here positive and negative relations among several parameters influence whether processing enterprises purchase and establish a comprehensive food traceability system. Revenue of processing enterprises from the sale of traceable labeled food products (S_h); cost of purchasing non-traceable products from farmers (R_t); cost of a non-developing traceable system at enterprise (F_n); damage compensation imposed on processing enterprises when a product is falsely labeled as traceable (W_p); represents a positive relationship between the purchase of traceable food from farmers and the development of a comprehensive food traceability system at the organization (i.e., increases in the value of these parameters lead to a high probability of processing enterprises adopting traceable methodologies). Revenue of processing enterprises from the sale of non-traceable labeled food products (S_n); cost of purchasing traceable products from farmers (R_f); cost of developing a traceable system at the enterprise (F_t); cost of collusion with certification agencies (C_c); certification fees paid to certification agency (F_b); represent a negative relationship between the purchase of traceable food from farmers and the development of a comprehensive food traceability system at the organization (i.e., increases in the value of these parameters indicate a low probability of processing enterprises adopting traceable methodologies).

Factors influencing certification agencies to work independently and refuse false certification

i. Increased value of W_a represents a high chance that the certification agency will work independently.

ii. Increased value of C_c represents low chances that the certification agency will work independently.

Evidence: According to game model derivation conclusions and every decision of the game (Table 2), when the farmer or processing organization does not develop a food traceability system, the following inequality indicates that certification agencies work independently and maintain their integrity by refusing to issue falsely labeled traceable food products:

$$C_c - W_a < 0$$

Here, positive and negative relations among several parameters influence certification agencies to work independently without losing their integrity. Damage compensation for issuing false certification (W_a) represents a positive relationship with certification agencies working independently (i.e., the higher the damage compensation, the higher the chances that the certification agency will not issue a false certificate). Collusion costs with processing enterprises (C_c) represent a negative relationship with the issuance of true certification (i.e., the higher the collusion cost certification agency will obtain, the higher the chance of losing independence and issuing the false certificate).

Factors influencing consumers to purchase traceable labeled food products:

i. Increases in values of U_b, U_a, W_t represent a high chance that consumers will purchase traceable labeled food products.
ii. Increases in values of S_h, S_n represent low chances that consumers will purchase traceable labeled food products.

Evidence: According to game model derivation conclusions and every decision of the game (Table 2), when a food product is labeled as traceable (maybe truly or falsely labeled), the following inequalities represent the conditions that consumers purchase the traceable labeled food product:

When a certification agency is not working independently:

$$U_b - S_h + W_t > 0$$

When a certification agency is working independently and refuses to issue a false certificate, and the food production system does not have a comprehensive traceable system:

$$U_b - S_n > 0$$

When the certification agency is working independently, and the food production system has a comprehensive traceable system:

$$U_a - S_h > 0$$

Here, positive and negative relations among several parameters influence consumers to purchase traceable labeled food products. Revenue generated from the sale of traceable labeled food product U_a; revenue generated from the sale of non-traceable labeled food product U_b; damage compensation received by consumers W_t; represents a positive relationship with consumers' choice to purchase a traceable labeled product. The cost paid by the consumer to purchase a traceable labeled food product S_h; cost paid by the consumer to purchase a non-traceable labeled product S_n; indicates a negative relationship with the consumer's choice to purchase a traceable labeled product.

Numerical Example

In this study, we have included a numerical example to obtain an understanding of the mathematical model developed in this study. Table 4 represents the parameter values for the numerical example:

Table 4. Parameter values for the numerical example.

Decision Node	Parameter	Numerical Value
Authority	R_a	100
	R_n	90
	C_a	80
	C_n	70
	W_g	10
Farmers	R_f	50
	R_t	40
	F_a	30
	F_c	20
	W_f	10
Processing Enterprises	F_t	30
	F_n	20
	S_h	150
	S_n	140
	F_b	15
	C_c	10
	W_p	10
	Q_n	5
Certification Agency	W_c	10
	Q_a	5
Consumer	U_a	170
	U_b	160
	W_t	10

Table 5 represents the payoff values of different stakeholders based on the methodology proposed. Further, we will utilize Gambit Software to calculate the Nash equilibrium (NE) of the game model. Gambit software is very easy to use and helps in providing all the strategies and their payoff values along with their decision tree. This software provides Pure NE as well as Mixed NE. A mixed strategy contains probability for the selection of a particular strategy.

Table 5. Payoff values of numerical example.

Strategic Combination	Authority	Farmers	Processing Enterprises	Certification Agency	Consumers
1	20	20	55	15	20
2	−80	−30	−95	15	0
3	10	10	45	15	20
4	−80	−20	−105	25	0
5	10	10	55	15	20
6	−80	−20	−85	15	0
7	10	10	40	10	20
8	−80	−20	−110	10	0

Table 5. *Cont.*

Strategic Combination	Authority	Farmers	Processing Enterprises	Certification Agency	Consumers
9	10	10	55	15	20
10	−80	−20	−95	25	0
11	10	10	65	15	20
12	−80	−20	−75	15	0
13	10	10	50	10	20
14	−80	−20	−100	10	0
15	20	20	55	15	20
16	−70	−30	−95	15	0
17	10	10	35	15	20
18	−70	−20	−105	25	0
19	10	10	55	15	20
20	−70	−20	−85	15	0
21	10	10	40	10	20
22	−70	−20	−110	10	0
23	10	10	55	15	20
24	−70	−20	−95	25	0
25	10	10	65	15	20
26	−70	−20	−75	15	0
27	10	10	50	10	20
28	−70	−20	−100	10	0

This game solution, Figure 6, concludes that strategic combinations 1 and 15 are Pure Nash Strategies if authority promotes a traceability system actively and passively, respectively. This also validates the proposed framework.

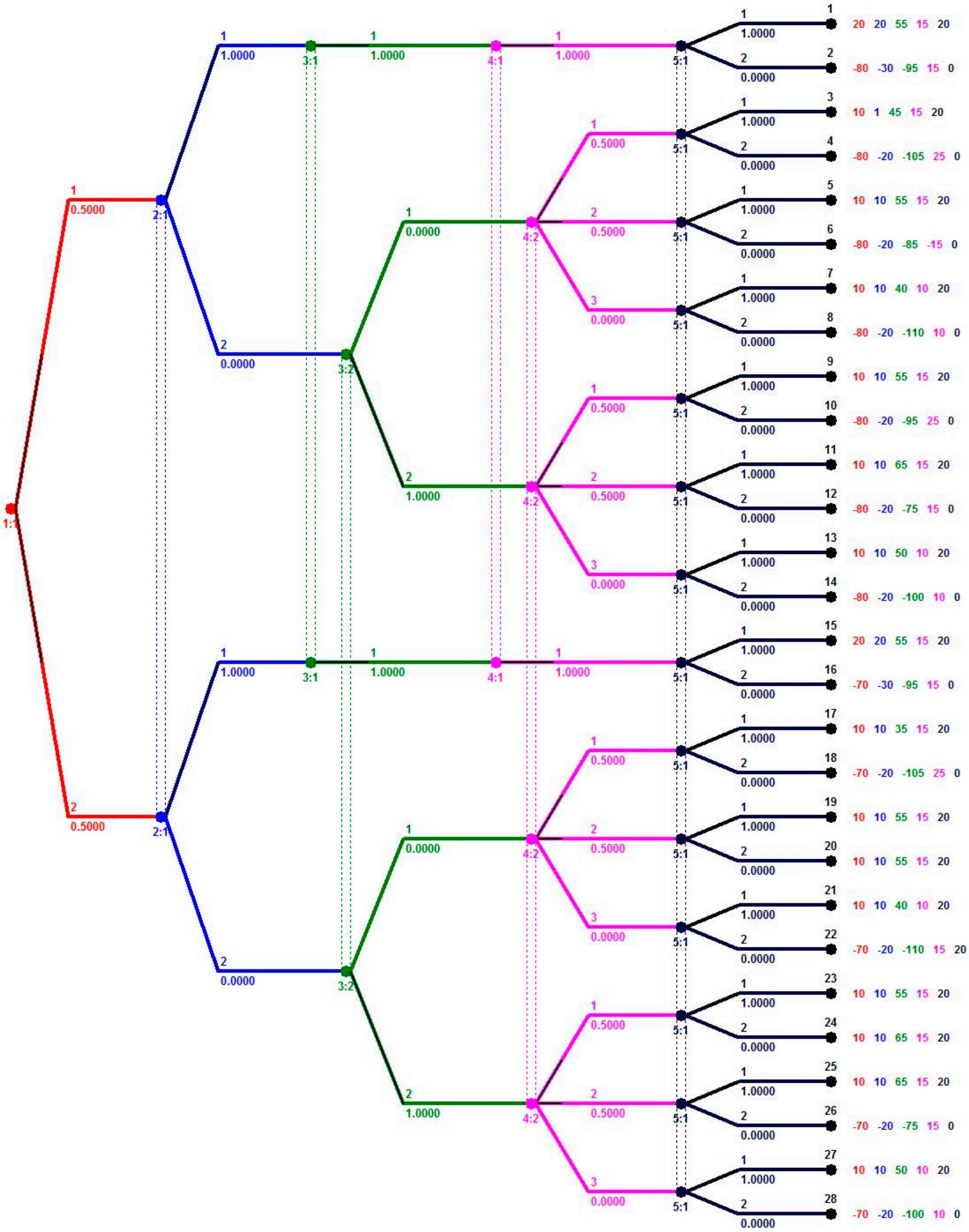

Figure 6. Numerical example solution using Gambit Software.

6. Research Implication

Analysis of the game-theoretic model highlights that strategic interaction among stakeholders plays an important role in a food supply chain. Since every stakeholder tries to optimize their payoff values, there is a high possibility of conflict among stakeholders while making their decisions. For example, the increased cost of traceable food products leads to high chances for processing enterprises to adopt traceability, but low chances for consumers to purchase traceable labeled food products. Similarly, increased collusion costs represent high chances for processing organizations to establish comprehensive food traceability systems, but low chances for certification agencies to work independently.

Reddy et al. [37] also suggested that consideration of tradeoffs among different levels of supply chain helps in deciding the scenario that might occur in supply chain.

In this way, there might be several circumstances where one player wants to maximize a particular cost, while the other wants to minimize it. In such situations, the decision should be made by trade-off among players. This research can be utilized where several players are involved in such a way that decisions made by one player influence the decision of other players. A similar framework may be utilized by a government authority or managerial level to get a strategic view of possible outcomes before making any decision. Here, the key findings are the strategic view by a combination of different strategies of different stakeholders in a food supply chain. The current research highlights real-time circumstances for developing a traceability system in a food supply chain. Zhou et al. [38] also conclude in their research the importance of traceability in terms of sustainable performance. Traceability adoption can make a supply chain more efficient and reliable.

7. Conclusions

The current study contributes to understanding the strategies of stakeholders present in the application of traceability throughout the food supply chain by application of game theory. This gives a broad view of factors that may affect the food chain. The game developed in this study gives a comprehensive view of possible strategies of players to make a decision in the supply chain, how every player can maximize their utility, and how decisions taken by one player affect the decisions of another player to maximize their payoffs. Further, a practical case has been solved to show how this model can be utilized in real-life problems.

The key findings of this research are as follows. The decision to be made in this study is whether a particular level of the supply chain is going to adopt traceability. The key factors are cost inflow, the cost of establishing a traceable supply chain, damage compensation in case of false traceable certification, and costs related to certification agencies providing certification. As the cost associated with establishing the traceable system reduces, farmers and processing organizations are more likely to adopt an honest traceable supply chain. Along with costs, damage compensations imposed on the individual level of the supply chain to take/give false certification play a very important role. Higher damage compensation is more likely to act adopt traceability based on profitability.

This study has been performed to understand the strategic interaction of players while implementing traceability in the food chain, however, it excludes several other players of the supply chain such as logistics, warehouses, etc. that can be the direction for future research. This study can also be extended by considering the after-impacts of traceability development since the food supply chain is highly time dependent. Such a situation can also play a great contribution to the literature. Observation of the dynamic nature can be a great idea for future research as well.

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