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ORIGINAL RESEARCH

Product safety assessment in a dairy dual-channel supply chain using game theory

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Abstract
In this paper, a supply chain including a farmer, a dairy manufacturer, and consumers is considered in which a particular product is sold through two channels, i.e., formal and informal. In the former, the dairy manufacturer buys the dairy product at a wholesale price from the farmer and sells it to consumers, whereas in the latter, the farmer sells the product directly to consumers. The farmer may add a sort of chemical additive to the product in order to increase its demand in either channel. This may be discovered only if a product safety accident happens. Furthermore, the government, as a regulator, plays an integral role in preventing the production and consumption of contaminated food. We aim to investigate the behavior of players in this supply chain and decide about safety issues and the wholesale price of the product using the game theory approach. To this end, four scenarios, including centralized structure, decentralized structure, cost-sharing contract, and safety guarantee contract, are examined. The experimental results reveal that by enacting appropriate laws, the government can prevent the supply chain players from utilizing unauthorized chemical additives. Furthermore, it is shown that the safety guarantee contract can improve the safety level of the product, which is always at a higher level in the formal channel than in the informal one. It was also revealed that fining the farmer has a greater impact on product safety than fining the manufacturer. Moreover, the farmer has less tendency to use chemical additives when the costs of the product and chemical additives are high or additives pose a high risk to consumers whereas higher product prices tempt the farmer to utilize more additives.

Keywords Food safety · Dairy supply chain · Game theory

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1 Introduction

1.1 Motivation

Food safety has been considered one of the most significant issues in food supply chains (Mangla et al., 2021). In recent years, due to food safety problems in different countries, improving the safety level of food has always been one of the goals of governments and legislators. In this context, most challenges may arise through informal food sales channels (Minot et al., 2015). Since informal channels are prevalent in dairy supply chains in some countries, it is significant to analyze the dairy supply chain in both formal and informal channels.

One of the problems in the food market is that the quality and safety of food may not be visible to consumers. Although there are several tests to evaluate the quality and safety of various foods, most of these tests are expensive and unaffordable. Therefore, buyers and even sellers of food products may not have accurate information about the quality of food products exchanged, and this can lead to problems in the food market (Hoffmann et al., 2019). Since the players in a dairy supply chain are highly likely oblivious to the safety level of the product, the government can help improve product safety through legislation and intervention in the food market. In developed countries, governments impose strict rules and regulations on food suppliers and producers to ensure product safety, leading to an increase in food health measures. However, in developing countries, due to the government's limited budget and capability, it is not possible to enact strict laws to improve food safety. Moreover, due to the low income of people and their low awareness, the propensity of consumers to pay for food safety is low. Therefore, neither the government nor the producers prioritize food safety, which can contribute to food safety accidents in these countries (Hoffmann et al., 2019). In addition, the concept of food safety in developing countries is less discussed than in developed ones (Govindan, 2018). In low-income countries, a large part of the food market share is made up of informal channels without any regulation and inspection, whereas a small amount of market share, especially in the fresh food market, is the share of formal and legal channels (Wertheim-Heck et al., 2015).

In particular, what factor that can endanger the safety of food products is unauthorized chemical additives that may be added by different members of the supply chain. Although these additives can be harmful, they are added to food products for a variety of purposes, including protecting food spoilage, providing minerals and vitamins, improving the food taste, and improving its appearance (Song & Zhuang, 2017). A real example of utilizing unauthorized chemical additives in food products is using melamine in dairy products. In order to determine the percentage of protein in dairy products, the percentage of nitrogen is measured, which is a way to measure the quality of these products (Manteghi et al., 2021). In 2008, the Sanlu company in China used melamine instead of protein to increase the percentage of nitrogen, which resulted in the death of six children (Song & Zhuang, 2017). Thanks to the lack of awareness among consumers and also the lack of adequate inspection, farmers and producers may add unauthorized substances to their products to increase their profits.

1.2 Contributions

In this study, a two-channel supply chain is investigated where a particular dairy product is produced and sold. In addition to the formal channel, an informal channel is considered where the farmer can sell its dairy product directly to consumers. We investigate the relationship

between farmer and manufacturer and determine the decisions of the players on the wholesale price as well as the safety level of the product. To this end, four scenarios are addressed so that in each of them, a relationship between different players in the supply chain is examined. These scenarios include a centralized structure, a decentralized structure, a cost-sharing contract, and a safety guarantee contract. We model each scenario using the game theory approach and find the optimal decisions. Furthermore, we investigate all scenarios and their impacts on the wholesale price and the safety level of the product. Moreover, we explore how the government as a legislator can contribute to raising the safety level of the product. Finally, we provide a set of beneficial managerial insights for decision-makers in the supply chain.

The remainder of this paper is organized as follows. The literature review is presented in Sect. 2. The problem description and modeling of the four scenarios are discussed in Sect. 3. In Sect. 4, we present a numerical example in conjunction with sensitivity analyses. We provide a set of managerial insights in Sect. 5. Finally, a summary and future research directions are given in Sect. 6.

2 Literature review

The problem addressed in this study is related to the context of food safety and quality in dairy supply chains as well as the game theory. According to this, we categorize the related research papers into two categories as follows: food safety and application of game theory in the food supply chain.

2.1 Food safety

The food safety issue is directly related to consumers' health. Nowadays, consumers' attention and need for healthy food have increased, and thanks to the existing limitations, it is difficult for consumers to be sure of it. Therefore, the importance of food safety is increasing among researchers; in the following, we will review some of the studies that have addressed this issue.

Caswell (1998) indicated that to select a quality assurance program, the decision-makers of private and public sectors should evaluate the expected benefits and costs of the programs, and he provided methods for measuring them. Henson and Caswell (1999) also concluded that if a company can achieve more expected profits and fewer costs through complying with government regulations, it prefers to comply more with these regulations. Grunert (2005) examined the relationship between food health and consumer demand and showed that it is a significant issue in the food economy. Fares and Rouviere (2010) investigated health issues in a food supply chain. In this study, contaminants were classified as high-risk and low-risk contaminants for consumers' health. It was also assumed that quality control is performed voluntarily by the manufacturer or was forcibly imposed on the manufacturer by a retailer or a regulator. The authors concluded that voluntary control is appropriate for low-risk pollution. They also concluded that when a manufacturer sells its products directly on the market, a strict monitoring system leads to the implementation of a quality control system by the manufacturer. They showed that the company's decision to add chemical additives to food products depends on government legislation. Hoffmann et al. (2019) reviewed empirical research on food safety in low and middle-income countries. They identified the factors that cause food safety problems, and some of these factors include the low awareness and low

ability of consumers to pay for food health, the lack of incentives to invest in food safety, and low legislative power. Mangla et al. (2021) studied some food industry processes and operations. Based on the opinions of industry and some academic experts, they investigated 25 challenges in the field of food safety. These challenges are divided into five main groups, including organizational, governmental, global, knowledge-related, and financial challenges.

In the field of dairy products, various contaminants can pose a serious threat to public health. Dairy product adulteration was considered a global threat concern after discovering melamine contamination in Chinese infant milk products in 2008 (Grunert, 2005). Chen et al. (2014) developed two centralized and decentralized quality control structures at different levels of a dairy supply chain, and as a case study, they addressed the 2008 case of adulterated milk in China. The supply chain consists of a supplier and a retailer, each of whom determines the quality level of the products to maximize their profits. In the decentralized structure, the retailer has more power than the supplier, and a Stackelberg game was used for modeling. In this study, the effect of different pricing and optional quality control rules was investigated.

Song and Zhuang (2018) addressed the issue of using unauthorized chemical additives in the food industry by manufacturers. They assumed that governments enact punitive laws to prevent the risky behavior of manufacturers and reduce the cost of consumer health. However, these policies may lead to a reduction in the tax revenues for governments. They assumed that manufacturers determine the maximum level of additives according to the extent of the government's fines, and the consumers' demand is determined based on the level of utilized chemical additives. Navarro et al. (2015) examined a dual-channel food supply chain, including formal and informal channels in Peru. They examined how this supply chain influences the decisions of producers at the organizational and technical levels. The relationship between formal and informal producers was established based on a combination of competition and complementarity. Furthermore, Muunda et al. (2021) studied an informal channel for milk sales in Kenya and showed that the informal channel is still the main one for milk in the market in Kenya. They indicated that the legislature is trying to increase the quality and health of products by enacting laws and licensing various producers. These rules include pasteurizing milk before selling, adopting tracking processes, and testing product quality. These measures led to an increase in the milk price and, consequently a reduction in milk consumption by children.

2.2 Application of game theory in the food supply chain

Some articles have investigated the relationship and interaction between different players in the food supply chain. These players include the government as legislators, farmers, food manufacturers, milk stations, and consumers. They strategically interact with each other and can find optimal decisions using the game theory approach, and the following papers are the most relevant ones to this issue.

Zhang et al. (2010) developed a profit distribution model in a food supply chain using game theory. They showed that the proper distribution of profit among supply chain members can improve food safety. Li and Li (2014) investigated the possible strategies of the government and food manufacturers in the field of food safety using evolutionary game theory. They indicated that the government should actively participate in food health legislation to reduce food-related accidents.

Song and Zhuang (2017) examined the behavior of farmers and a manufacturer in adding melamine to milk. Farmers use additives to improve their product appearance and taste, reduce costs and consequently increase the demand for the product. Consumers get sick if

they consume contaminated milk, and the government is responsible for it, so the government imposes penalties for using unauthorized additives. On the other hand, the government takes taxes from the manufacturer, preventing the government from enacting strict laws. In this study, equilibrium points for the optimal level of punishment by the government, the price at that the manufacturer buys the product from the farmer, and the percentage of additives have been determined using the Stackelberg method.

Hu et al. (2019) studied a four-echelon food supply chain, including a food manufacturer, a processing company, a distributor, and several consumers, and they employed the game theory as the modeling approach. They designed a combined strategy including profit sharing, quality commitment, and risk sharing for this supply chain. To encourage consumers to buy more, the manufacturer guarantees a certain level of quality, and in the event of a problem, consumers can claim damages and seek compensation from the manufacturer. They indicated that this strategy gives rise to increases in the quality of raw agricultural materials and food production. Meng et al. (2020) studied the applications of game theory in safety management and reviewed 57 articles in this field. The results showed that the game theory might contribute to discovering the reasons and motivations for the unsafe behavior of supply chain members, and it plays an integral role in guiding decision-makers in the safety management processes. Furthermore, Teng et al. (2021) addressed the relationship among the government, farmers, and consumers in improving food quality, and they developed an evolutionary game. They showed that effective inspection of the government can accelerate the transition process from traditional systems to green systems. Manteghi et al. (2021) presented three pricing models for the supply chain, including two suppliers and one manufacturer. In this study, all three aspects of sustainability have been examined including consumer health as a social goal, reducing greenhouse gas emissions as an environmental goal, and the benefit of supply chain members as an economic goal. They considered centralized and decentralized structures and modeled the problem using game theory.

3 Problem description and modeling

In this study, we address a dairy dual-channel supply chain including formal and informal channels, depicted in Fig. 1. In the formal channel, the farmer and dairy manufacturer decide on the safety level and the wholesale price of a dairy product to maximize their profits. We assume the selling prices to customers in both formal and informal channels are predetermined values because the market is not a monopoly, and no player has the power to set these prices. In this supply chain, the farmer's profit includes the total profit of sales in both formal and informal channels minus the likely penalty expected to be imposed by the government if the farmer utilizes illegal chemical additives and the government discovers it. The manufacturer's profit includes the profit obtained by the sale in the formal channel minus the expected value of the probable penalty imposed by the government due to the using illegal additives.

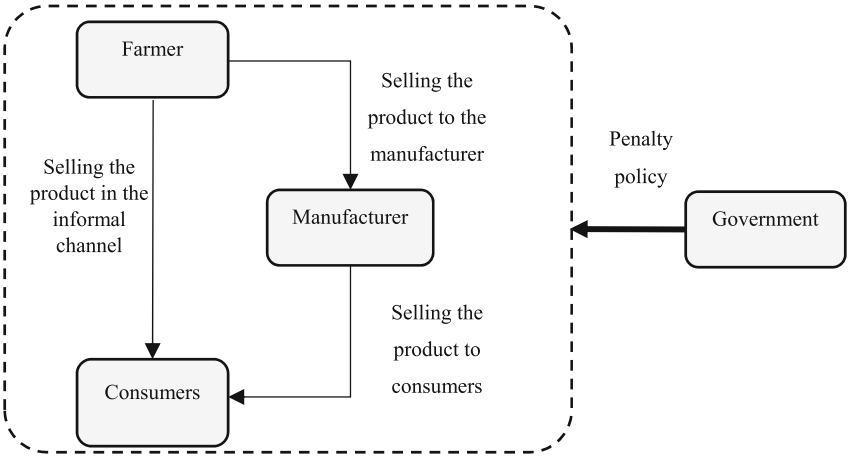


Fig. 1 The general structure of the supply chain

In the formal channel, the manufacturer processes the raw material (a dairy product) bought at the wholesale price from the farmer and then sells the product to consumers. We assume that this product is almost a type of the same dairy product but processed, and they can be used interchangeably. We assume only the farmer may add a sort of chemical additive to the product, and the manufacturer either does not inspect the product or cannot discover it. This illegal additive may be discovered only if a product safety accident happens, i.e., a consumer gets sick and sues for compensation. In this case, in the formal channel, both the manufacturer and the farmer will be penalized, and in the informal channel, only the farmer will be fined.

We also assume the product demand increases if more percentage of the additive is utilized in the product (Manteghi et al., 2021; Song & Zhuang, 2017). In this supply chain, we deal with a Stackelberg game in which the farmer and the manufacturer are the players. The notations of the model are presented in Table 1.

It is assumed that the production cost of one unit of the product is calculated based on Eq. (1). In this equation, the cost of additive is fx_{ij} and the cost of protein is qy_{ij} where the latter usually constitutes the main part of the production cost.

Table 1 The notations of the model

Indices	
i	Channel, $i \in \{1$: informal, 2: formal$\}$
j	Scenario, $j \in \{1, 2, 3, 4\}$
Parameters	
a_i	Basic market demand of channel i
α	Self-price sensitivity coefficient of demand
β	Cross-price sensitivity coefficient of demand
n	The minimum percentage of nitrogen required in one unit (1 kg) of the product
o	The amount of nitrogen in one percent of the protein available in one unit of the product
m	The amount of nitrogen in one percent of melamine available in one unit of product
f	The cost of one percent melamine in one unit of the product
q	The cost of one percent protein in one unit of the product
c_m	The process cost of one unit of the product for the manufacturer
λ	The slope for the probability of getting sickness
g_m	The penalty cost imposed on the manufacturer by the government for endangering consumer health
g_f	The penalty cost imposed on the farmer by the government for endangering consumer health
p_1	The selling price of one unit of the product to consumers in the informal channel
p_2	The selling price of one unit of the product to consumers in the formal channel
Decision variables	
p_{wj}	The wholesale price of one unit of the product in scenario j
x_{ij}	The percentage of melamine in one unit of the product in channel i and scenario j
y_{ij}	The percentage of protein in one unit of the product in channel i and scenario j
Dependent variable	
π_{fj}	The profit of the farmer in scenario j
π_{mj}	The profit of the manufacturer in scenario j
π_j	The total profit of the dual-channel supply chain in scenario j
c_{ij}	The cost function of the farmer in channel i and scenario j
D_{ij}	The demand function in channel i and scenario j

$$c_{ij} = f x_{ij} + q y_{ij};\ i = 1, 2; j = 1, \ldots, 4 \tag{1}$$

Inequality (2) indicates that the percentage of nitrogen in one unit of the product should be equal to or larger than the minimum required percentage (n).

$$m x_{ij} + o y_{ij} \geq n;\ i = 1, 2; j = 1, \ldots, 4 \tag{2}$$

From the farmer's perspective, a minimum percentage of nitrogen should be available in one unit of product. Consequently, the optimal percentage of protein is obtained using Eq. (3).

$$y_{ij} = \frac{n - m x_{ij}}{o};\ i = 1, 2; j = 1, \ldots, 4 \tag{3}$$

Using Eqs. 1 and 3, the production cost paid by the farmer is calculated as Eq. 4.

$$c_{ij} = \frac{nq + (fo - mq)x_{ij}}{o};\ i = 1, 2; j = 1, \ldots, 4 \tag{4}$$

Furthermore, the probability of a product safety accident is an increasing function of the percentage of the utilized additive in the form of λx_{ij}. Equations (5) formulates the market demand in the informal channel where it depends on the basic market demand, the safety level of the product with coefficient α as well as the safety level of the product in another channel with coefficient β. Likewise, Eq. (6) is developed for the market demand in the formal channel.

$$D_{1j} = a_1 + \alpha x_{1j} - \beta x_{2j}; j = 1, \ldots, 4 \tag{5}$$

$$D_{2j} = a_2 + \alpha x_{2j} - \beta x_{1j}; j = 1, \ldots, 4 \tag{6}$$

In this problem, four scenarios are considered for investigation in which different relationships between players of the supply chain are scrutinized. In the first and second scenarios, centralized and decentralized structures of the supply chain are investigated, respectively. Moreover, in the third and fourth scenarios, the effects of conventional contracts on the decisions of the supply chain players are examined. In the following sections, in order to simplify the representation of equations, we use some notations presented in Appendix A.

3.1 Scenario 1: the centralized structure

In this scenario, the farmer and manufacturer interact in a centralized structure. In other words, it is assumed that a single decision-maker decides in the supply chain on health safety issues and selling prices to maximize the profit of the whole supply chain. In this scenario, the demand and cost functions follow Eqs. 1, 4, 5, and 6.

The profit function of the whole supply chain is shown by Eq. (7), in which the benefits of the farmer and the manufacturer are considered jointly. It is worth noting that due to the structure of this scenario, financial transactions between the farmer and the manufacturer are neglected. As a result, the decision variables in this scenario are x_{11} and x_{21}. The profit function of the supply chain includes the profit from the sale of products in the formal and informal channels. We assume that if a consumer gets sick in the informal channel, a penalty cost of g_f is imposed on the supply chain, and if it happens in the formal channel, the extent of punishment equals $g_f + g_m$.

$$\pi_1 = (p_1 - c_{11})D_{11} + (p_2 - c_{21} - c_{\mathrm{m}})D_{21} - D_{21}\big(g_f + g_m\big)\lambda x_{21} - D_{11} g_f \lambda x_{11} \tag{7}$$

Proposition 1 *The profit function of the supply chain under the centralized structure is concave to x_{11} and x_{21}.*

Proof See Appendix B.

Theorem 1 *The optimal values of x_{11} and x_{21} under the centralized scenario are obtained using Eqs. (8) and (9):*

$$\begin{aligned} x_{11} = & \frac{-2a_1A_1A_2\alpha + 2A_2(-nq + op_1)\alpha^2 + o\lambda g_m(nq + oc_m - op_2)\alpha\beta}{4A_1A_2\alpha^2 - A_3^2\beta^2} \\ & + \frac{-\big(2fo - 2mq + o\lambda\big(2g_f + g_m\big)\big)\beta(a_2A_2 + (-nq + op_1)\beta))}{4A_1A_2\alpha^2 - A_3^2\beta^2} \end{aligned} \tag{8}$$

$$x_{21} = \frac{-2a_2A_1A_2\alpha - 2A_1(nq + oc_m - op_2)\alpha^2 + o\lambda g_m(-nq + op_1)\alpha\beta}{\left(4A_1A_2\alpha^2 - A_3^2\beta^2\right)} + \frac{-\left(2fo - 2mq + o\lambda\left(2g_f + g_m\right)\right)\beta(A_1 - (nq + oc_m - op_2)\beta))}{\left(4A_1A_2\alpha^2 - A_3^2\beta^2\right)} \tag{9}$$

3.2 Scenario 2: the decentralized structure

In this scenario, the farmer and the manufacturer compete in a decentralized structure. Furthermore, each player tries to maximize his/her profit by considering the decisions of others. It is assumed that the manufacturer is the leader and the farmer is the follower of the supply chain. Both players try to maximize their profits independently. First, the manufacturer determines the wholesale price of the product, and then the farmer decides on the percentage of the additive according to the determined wholesale price. It is assumed that if a food safety accident happens in each channel, the penalty cost imposed to the farmer is g_f, and if this risk rises in the formal channel, the manufacturer will be penalized with g_m. Equation (10) describes the farmer profit function, including profits obtained from the channels minus expected penalty costs.

$$\pi_{f2} = (p_1 - c_{12})D_{12} + (p_{w2} - c_{22})D_{22} - \lambda x_{12}D_{12}g_f - \lambda x_{22}D_{22}g_f \tag{10}$$

Proposition 2 *The profit function of the farmer under the decentralized structure is concave to x_{12} and x_{22}.*

Proof See Appedix B.

Theorem 2 *The optimal values of x_{12} and x_{22} under the decentralized structure are obtained by Eqs. (11) and (12):*

$$x_{12} = \frac{1}{4}\left(\frac{2(-nq + op_1)}{A_1} + \frac{a_1 + a_2}{-\alpha + \beta} + \frac{-a_1 + a_2}{\alpha + \beta}\right) \tag{11}$$

$$x_{22} = \frac{1}{4}\left(\frac{2(-nq + op_w)}{A_1} + \frac{a_1 + a_2}{-\alpha + \beta} + \frac{a_1 - a_2}{\alpha + \beta}\right) \tag{12}$$

The manufacturer profit function is shown in Eq. 13.

$$\pi_{m2} = (p_2 - p_{w2} - c_m)D_{22} - \lambda x_{22}D_{22}g_m \tag{13}$$

In the end, we can show the total profit of the supply chain in this scenario as $\pi_2 = \pi_{f2} + \pi_{m2}$.

Proposition 3 *The profit function of the manufacturer under the decentralized structure is concave to p_{w2}.*

Proof See Appendix B.

Theorem 3 *The optimal values of p_{w2} under the decentralized scenario are obtained using Eq. (14):*

$$p_{w2} = \frac{2(-oc_mA_1 + nqA_2 + oA_1p_2)\alpha^3}{\left(2oA_3\alpha\left(\alpha^2 - \beta^2\right)\right)} + \frac{\alpha(o\lambda a_1A_1g_m + A_3(-nq + op_1)\alpha)\beta}{\left(2oA_3\alpha\left(\alpha^2 - \beta^2\right)\right)}$$

$$+\frac{-2(-oc_m A_1 + nqA_2 + oA_1 p_2)\alpha\beta^2}{\left(2oA_3\alpha\left(\alpha^2-\beta^2\right)\right)} + \frac{A_3(nq - op_1)\beta^3 + a_2 A_1\left(-2A_1\alpha^2 + A_3\beta^2\right)}{\left(2oA_3\alpha\left(\alpha^2-\beta^2\right)\right)} \tag{14}$$

3.3 Scenario 3: the cost-sharing contract

In this scenario, we consider a cooperative game through a cost-sharing contract in which the manufacturer pays a portion (θ) of the initial production cost to the farmer in order to reduce the farmer's motivation to use the informal channel. This also encourages the farmer to increase his/her production. The demand and cost functions are similar to the previous two scenarios, and the farmer profit function is obtained by Eq. (15).

$$\pi_{f3} = (p_1 - c_{13})D_{13} + (p_{w3} - (1-\theta)c_{23})D_{23} - \lambda x_{13}D_{13}g_f - \lambda x_{23}D_{23}g_f \tag{15}$$

Proposition 4 *The profit function of the farmer under the cost-sharing contract is concave to x_{13} and x_{23}.*

Proof See Appendix B.

Theorem 4 *The optimal values of x_{13} and x_{23} under the cost-sharing contract are obtained through Eqs. (16) and (17):*

$$x_{13} = \frac{-2a_1\left(A_4B_1 - o\lambda g_f\right)A_1\alpha + 2\left(A_4B_1 - o\lambda g_f\right)(-nq + op_1)\alpha^2}{4\left(A_4B_1 - o\lambda g_f\right)A_1\alpha^2 + \left(A_4B_2 - 2o\lambda g_f\right)^2\beta^2} + \frac{-A_4\theta(nqB_1 + op_w)\alpha\beta + \left(A_4B_2 - 2o\lambda g_f\right)\beta\left(a_2\left(A_4B_1 - o\lambda g_f\right) + (nq - op_1)\beta\right)}{4\left(A_4B_1 - o\lambda g_f\right)A_1\alpha^2 + \left(A_4B_2 - 2o\lambda g_f\right)^2\beta^2} \tag{16}$$

$$x_{23} = \frac{-2a_2\left(A_4B_1 - o\lambda g_f\right)A_1\alpha - 2A_1(nqB_1 + op_w)\alpha^2)}{4\left(A_4B_1 - o\lambda g_f\right)A_1\alpha^2 + \left(A_4B_2 - 2o\lambda g_f\right)^2\beta^2} + \frac{A_4\theta(-nq + op_1)\alpha\beta - \left(A_4B_2 - 2o\lambda g_f\right)\beta(a_1A_1 + (nqB_1 + op_w)\beta)}{4\left(A_4B_1 - o\lambda g_f\right)A_1\alpha^2 + \left(A_4B_2 - 2o\lambda g_f\right)^2\beta^2} \tag{17}$$

Moreover, the manufacturer's profit function is presented in Eq. (18).

$$\pi_{m3} = (p_2 - p_{w3} - c_m)D_{23} - \lambda x_{23}D_{23}g_m - \theta c_{23}D_{23} \tag{18}$$

Let $\pi_3 = \pi_{f3} + \pi_{m3}$ as the total profit of the supply chain in this scenario 3.

Proposition 5 *The profit function of the manufacturer under the cost-sharing contract is concave to p_{w3}.*

Proof See Appendix B.

Theorem 5 *The optimal value of p_{w3} under the cost-sharing contract is obtained by Eq. (19).*

$$p_{w3} = \frac{B_{18}}{B_6} \tag{19}$$

3.4 Scenario 4: the health safety guarantee contract

In this scenario, it is assumed that the farmer guarantees health and product safety in the formal channel. In other words, if a consumer of the manufacturer gets sick, the entire penalty cost has to be paid by the farmer. In this scenario, the structure of the supply chain is similar to that in Scenario 2; i.e. the manufacturer plays the role of the leader and the farmer plays the role of the follower. Furthermore, the farmer's profit function is obtained by Eq. (20).

$$\pi_{f4} = (p_1 - c_{14})D_{14} + (p_{w4} - c_{24})D_{24} - \lambda x_{14} D_{14} g_f - \lambda x_{24} D_{24}\left(g_f + g_m\right) \tag{20}$$

Proposition 6 *The profit function of the farmer under the health safety guarantee contract is concave to x_{14} and x_{24}.*

Proof See Appendix B.

Theorem 6 *The optimal values of x_{14} and x_{24} under the health safety guarantee contract are obtained using Eq. (21) and (22):*

$$x_{14} = \frac{-2a_1 A_2 \alpha + 2A_2 (-nq + op_1)\alpha^2 + o\lambda g_m (nq - op_w)\alpha\beta}{\left(4A_1 A_2 \alpha^2 - \left(2fo - 2mq + o\lambda\left(2g_f + g_m\right)\right)^2 \beta^2\right)} + \frac{(-A_3\beta(a_2 A_2 + (-nq + op_1)\beta))}{\left(4A_1 A_2 \alpha^2 - A_3^2 \beta^2\right)} \tag{21}$$

$$x_{24} = \frac{-2a_2 A_1 A_2 \alpha + 2A_1 (-nq + op_w)\alpha^2 + o\lambda g_m (-nq + op_1)\alpha\beta}{4A_1 A_2 \alpha^2 - A_3^2 \beta^2} + \frac{-A_3\beta(a_1 A_1 + (-nq + op_w)\beta)}{4A_1 A_2 \alpha^2 - A_3^2 \beta^2} \tag{22}$$

The manufacturer's profit function is as below.

$$\pi_{m4} = (p_2 - p_{w4} - c_m)D_{24} \tag{23}$$

Let $\pi_4 = \pi_{f4} + \pi_{m4}$ as the total profit of the supply chain in this scenario 4.

Proposition 7 *The profit function of the manufacturer under the health safety guarantee contract is concave to p_{w4}.*

Proof See Appendix B.

Theorem 7 *The optimal value of p_{w4} under the health safety guarantee contract is as follows.*

$$p_{w4} = \frac{1}{8}\left(\frac{4nq}{o} - 4c_m + 4p_2 - \frac{2a_2 A_3}{o\alpha} + \frac{2A_3(-nq + op_1)\beta}{oA_1\alpha} + \frac{\lambda(a_1 + a_2)g_m}{-\alpha + \beta} + \frac{\lambda(a_1 - a_2)g_m}{\alpha + \beta}\right) \tag{24}$$

4 Sensitivity analyses

In this section, we provide sensitivity analyses for some significant parameters in different scenarios and present relevant managerial insights. To this end, we illustrate a numerical example, the data of which are presented in Table 2. This is a case study of a food safety accident that occurred in 2008 in a Chinese company that produced milk powder and injured three million infants. To the best of our knowledge, our problem and developed mathematical model are new and there is no paper in the literature to provide the whole parameters of Table 2. Consequently, we utilize a few relevant references, including Hu et al. (2019), Jabarzare and Rasti-Barzoki (2020), Manteghi et al. (2021) and Song and Zhuang (2017), to fix these parameters. To adjust the values of p_1, g_m and g_f, we asked the for opinion of some experts in dairy industries.

Table 3 shows the results obtained by solving the numerical example in the different scenarios.

Table 2 Data of the case study

Parameter	Value	Parameter	Value
a_2	420,000 (Manteghi et al., 2021; Song & Zhuang, 2017)	n	0.0288 (Manteghi et al., 2021; Song & Zhuang, 2017)
α	10^8(Manteghi et al., 2021)	m	66.6 (Manteghi et al., 2021; Song & Zhuang, 2017)
p_2	62.5 (Song & Zhuang, 2017)	o	16 (Manteghi et al., 2021; Song & Zhuang, 2017)
p_1	50	q	0.84 (Manteghi et al., 2021; Song & Zhuang, 2017)
λ	106.3 (Manteghi et al., 2021)	f	0.7 (Manteghi et al., 2021; Song & Zhuang, 2017)
g_m	20	a_1	280,000 (Manteghi et al., 2021; Song & Zhuang, 2017)
g_f	20	β	5×10^7(Jabarzare and Rasti-Barzoki, 2020)
c_m	5 (Hu et al., 2019)	–	–

Table 3 Comparative results of the case study

Variable	Scenario 1	Scenario 2	Scenario 3	Scenario 4
p_w	–	29.91	29.86	36.868
x_{1j}	0.0068	0.0085	0.0085	0.0076
x_{2j}	0.0043	0.0033	0.0033	0.0021
π_{fj}	–	3.808×10^7	3.809×10^7	3.85×10^7
π_{mj}	–	6680310	6702157	5227364
π_j	4.631×10^7	4.476×10^7	4.479×10^7	4.37×10^7

According to Table 3, the centralized scenario leads to the highest profit in the supply chain (Manteghi et al., 2021). The results of the decentralized and cost-sharing scenarios are very close to each other, but in the cost-sharing contract, both the farmer and manufacturer gain higher profits than in the former scenario. Furthermore, the health safety guarantee scenario results in the highest level of safety in the formal channel. In the informal channel, the centralized scenario also gives rise to a better level of health safety.

As can be seen from Table 3, the centralized structure in the formal channel can lead to a decrease in the level of product safety (Song & Zhuang, 2017). As the interests of the supply chain members become more similar, the use of unauthorized additives will be raised by the players. The wholesale price is at the highest level in the health safety guarantee scenario because the farmer takes full responsibility for paying fines. It can also be seen that in all scenarios, the level of health safety in the formal channel is at a higher level than in the informal one.

4.1 The impact of parallel channels on each other

Figure 2 plots $p_{wj}; j = 2, 3, 4$ as an increasing function of p_1, implying that the higher the price of the product in the informal channel, the higher the wholesale price of the product. If the wholesale price is low, the farmer has less incentive to sell his/her product to the manufacturer. As a result, the manufacturer is compelled to raise the wholesale price to buy the product from the farmer.

There are similar direct relationships between p_2 and $p_{wj}; j = 2, 3, 4$, and the health safety guarantee contract leads to the highest wholesale price because the farmer undertakes the penalty cost of the manufacturer.

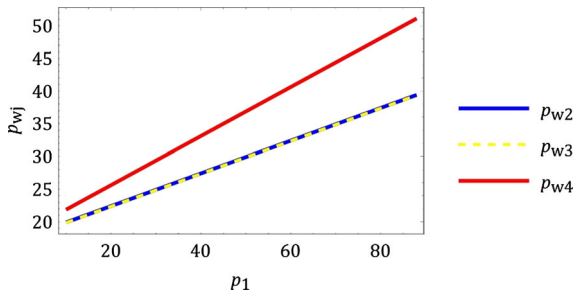


Fig. 2 The impact of p_1 on $p_{wj}; j = 2, 3, 4$

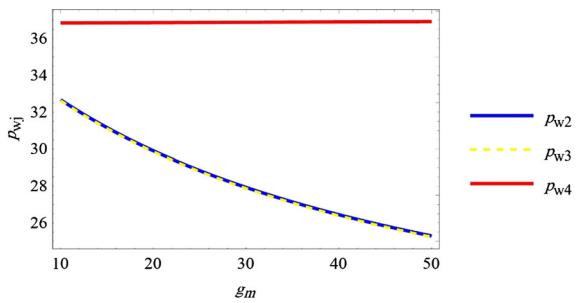


Fig. 3 The impact of g_m on $p_{wj}; j = 2, 3, 4$

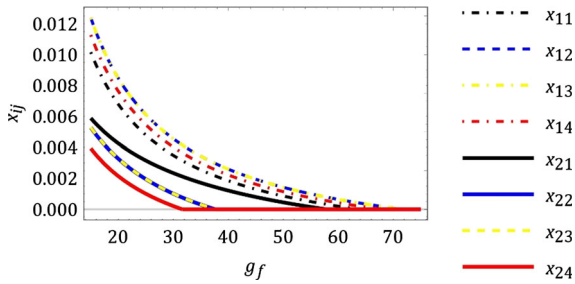


Fig. 4 The values of g_f that avoid the farmer not utilizing the additive

Furthermore, Fig. 3 plots $p_{wj}; j = 2, 3, 4$ as a function of g_m. In decentralized and cost-sharing scenarios, there is an inverse relationship between g_m and the wholesale price because the manufacturer tries to recompense his/her imposed fines through a lower payment to the farmer. In contrast to these two scenarios, g_m has no impact on the wholesale price in the health safety guarantee scenario because the farmer should pay all penalty costs.

4.2 The impact of g_f on the percentage of the chemical additive

Figure 4 indicates the relationship between g_f and $x_{ij}; i = 1, 2; j = 1, 2, 3, 4$. According to this figure, the more intense the punishment policy is, the less percentage of the chemical additive is used by the farmer. Furthermore, it is also observed that in all scenarios, the product in the formal channel has a higher level of safety than the informal one, thanks to the interference of the manufacturer. This interference is applied through the wholesale price adjusted by the manufacturer to avoid being penalized. Moreover, the farmer knows that should a food safety accident happen in either channel, he/she will be unable to get away and will be penalized. In addition to this, the steeper slope of curves pertinent to the informal channel than the formal one indicates that the punishment policy is more intense in this channel.

Figure 4 displays that the government can enact heavy penalties against the farmer so that he/she had better not utilize the chemical additive in any channel. In the formal channel, the health safety guarantee scenario leads to the highest level of product safety because the farmer has to pay the manufacturer's fine as well as his, and this discourages the farmer from utilizing the chemical additive. Furthermore, in the informal channel, the centralized scenario results in the highest level of product safety. Additionally, the decentralized and cost-sharing scenarios have a similar level of product safety because the manufacturer is able to determine the wholesale price.

4.3 The impact of g_m on the percentage of the chemical additive

Figure 5 indicates that in all scenarios if the fine imposed on the manufacturer rises, the percentage of the chemical additive utilized by the farmer in the formal channel decreases. Additionally, in the centralized and health safety guarantee scenarios and the informal channel, product safety increases if more punishment is considered against the manufacturer. However, in the informal channel, punishing the manufacturer in the decentralized and cost-sharing scenarios fails to raise product safety. Overall, product safety is higher in the formal channel than in the informal one in all scenarios. In the formal channel, we cannot reach zero

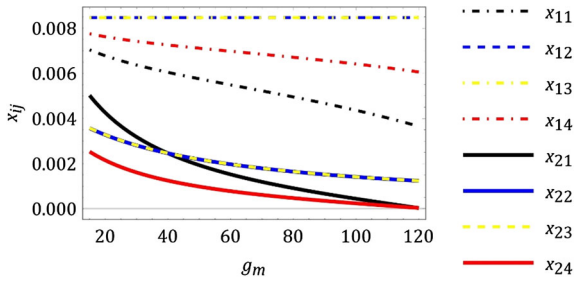


Fig. 5 The effect of g_m on product safety

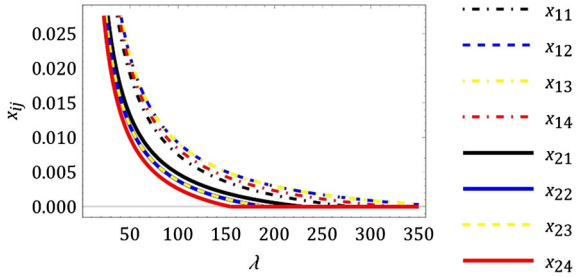


Fig. 6 The impact of λ on x_{ij}

percent of the chemical additive by penalizing only the manufacturer. To achieve this, we also need to consider penalties for the farmer.

In light of the fact that the manufacturer determines the wholesale price and considering the relationship between g_m and p_{wj} in Fig. 4, he/she does it in such a way that the farmer has less or no motivation for using the chemical additive. However, the comparison of Figs. 5 and 7 reveals that punishment policies imposed against the farmer rather than the manufacturer have more influence on product safety.

According to Fig. 5, in the formal channel, the health safety guarantee scenario gives rise to the utilization of the minimum percentage of the chemical additive. Furthermore, for the small values of the penalty cost, the centralized structure results in the highest percentage of the chemical additive because there is perfect coordination between the farmer and the manufacturer, and because of low fines, a low risk is shared between them.

4.4 The impact of additive dangerousness on the percentage of utilization

Figure 6 shows that in both formal and informal channels, as the risk of the unauthorized additive surges, the farmer would rather use less amount of this substance. If the risk goes beyond a certain level, the farmer prefers not to utilize it because the possibility of safety accidents and consequently expected penalty costs surges.

4.5 The impact of the product price on the additive percentage

Figure 7 plots $x_{1j}; j = 1, \ldots, 4$ as a function of p_1. As can be seen in all scenarios, if the selling price of the product is less than a threshold value, the farmer does not bear the risk of utilizing the additive. After that, $x_{1j}; j = 1, \ldots, 4$ is a strictly increasing function of p_1, implying high selling prices in the informal channel tempt the farmer more to increase the

Fig. 7 The impact of p_1 on x_{1j}

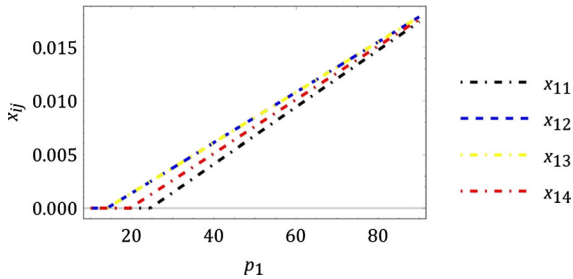


Fig. 8 The impact of p_2 on x_{1j}

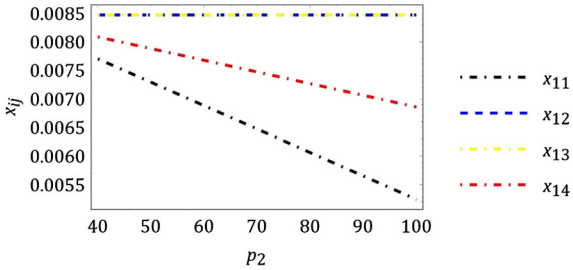
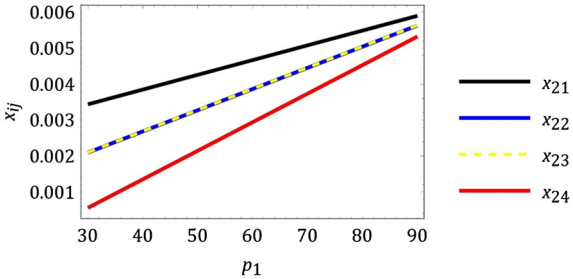


Fig. 9 The impact of p_1 on x_{2j}



demand and sales of the product by adding a higher percentage of the additive. Although it increases the penalty risk, more sale compensates for it.

Figure 8 displays how p_2 influences $x_{1j}; j = 1, 2, 3, 4$. As the product price rises in the formal channel, the farmer would rather utilize fewer percentages of the chemical additive in the informal channel because he/she prefers to sell the product in the formal channel.

Likewise, Fig. 9 shows how in each scenario, p_1 affects the percentage of the additive in the formal channel. As can be seen, the higher the price of the product in the informal channel is, the higher percentage of the additive will be used in the formal channel. Since p_{wj} is an increasing function of p_1, if p_1 and consequently p_{wj} rise, the farmer has more enticement to increase his/her sales in the formal channel through adding more percentage of the additive. It is worth noting that p_2 has a similar impact on $x_{2j}; j = 1, 2, 3, 4$.

4.6 The impact of additive hazardousness on the profit of the supply chain

Figure 10 indicates how λ might influence the total profit of the supply chain in each scenario. According to this figure, there is a kind of inverse relationship between them; the highest

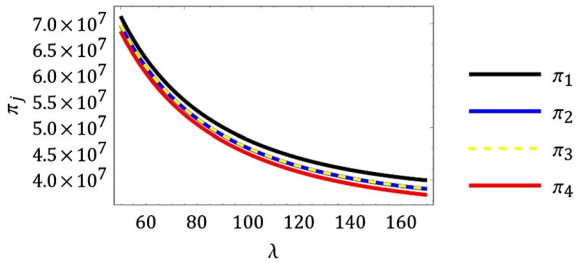


Fig. 10 The impact of λ on π_j

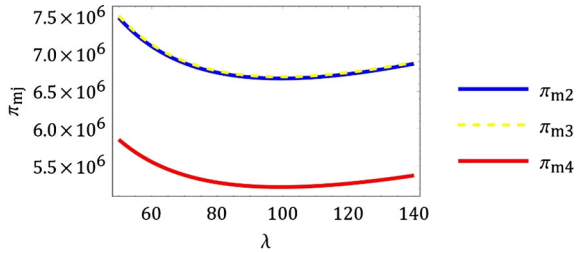


Fig. 11 The effect of λ on π_{mj}

profit is related to the centralized scenario, whereas the lowest profit is related to the safety guarantee scenario.

Moreover, Fig. 11 displays how λ can affect the manufacturer's profit. As can be seen, for $\lambda \leq 100$, the more dangerous the additive is, the lower profit is gained by the manufacturer. However, if the additive is more dangerous than a certain amount, the farmer would rather not use the additive. As a result, the manufacturer will no longer face fines, and its profits will increase.

4.7 The impact of g_f on the profit of the supply chain

Figure 12 indicates that there is an inverse relationship between g_f and $\pi_j; j = 1, 2, 3, 4$. This would appear that the more intense laws imposed by the government contribute to the less total profit of the supply chain.

As shown in Fig. 13, if g_f is going to increase, $\pi_{mj}; j = 1, 2, 3, 4$ rises. Overall, the fine imposed against the farmer in the case of product safety accidents is in favor of the manufacturer because the punishment policy contributes to less utilization of the additive by the farmer; hence the manufacturer accepts a lower risk.

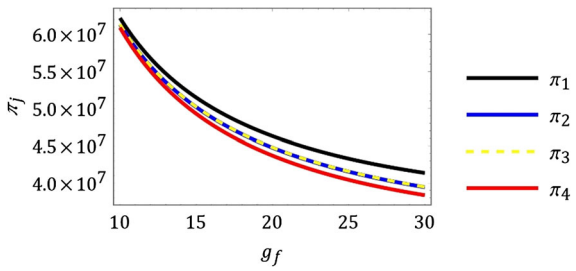


Fig. 12 The effect of g_f on π_j

Fig. 13 The impact of g_f on π_{mj}

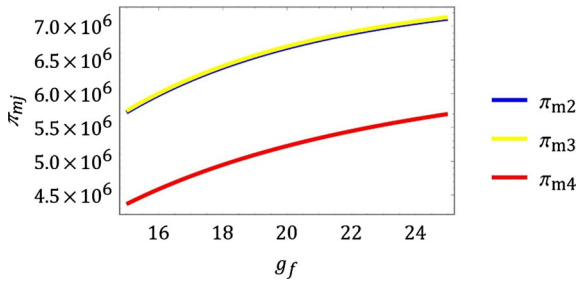
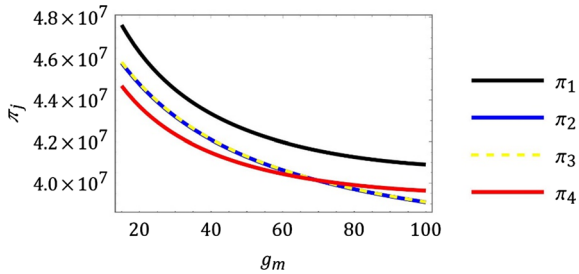


Fig. 14 The impact g_m on π_j



4.8 The impact of g_m on the profit of the supply chain

Figure 14 plots $\pi_j; j = 1, .., 4$ as a function of g_m. According to this figure, as g_m increases, the total profit of the supply chain is diminished. Moreover, the large values of g_m result in a better performance of the health safety guarantee scenario than the decentralized and cost-sharing scenarios.

4.9 The effect of q on the supply chain

In this section, we investigate the impact of q on π_j and $x_{2j}; j = 1, \ldots, 4$. According to Fig. 15, it seems that there is an inverse relationship between q on π_j in all scenarios. The centralized and health safety guarantee scenarios show the best and worst performances, respectively. Furthermore, as q increases, the cost-sharing contract outperforms the decentralized scenario. Figure 16 indicates a similar relationship between q and $x_{2j}; j = 1, \ldots, 4$. It should be noted that we see a similar impact of q on $x_{1j}; j = 1, \ldots, 4$. Furthermore,

Fig. 15 The effect of q *on* π_j

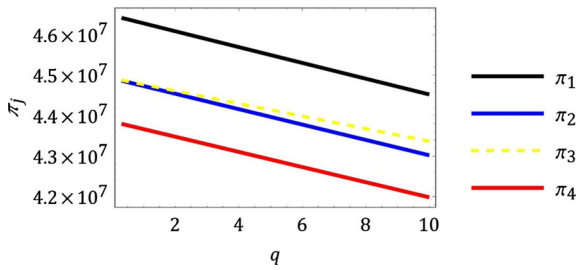


Fig. 16 The effect of q *on* x_{2j}

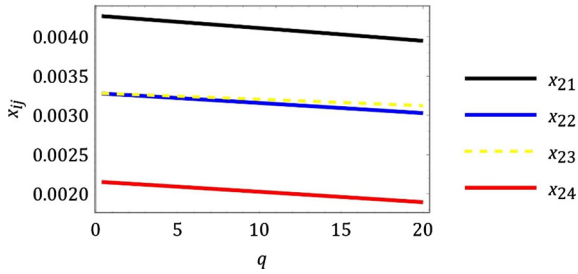
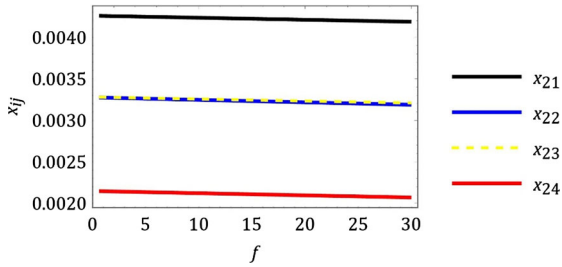


Fig. 17 The effect of q *on* x_{2j}



if q increases, the chemical additive is utilized more in the cost-sharing scenario than the decentralized one.

4.10 The effect of f on the product safety level

Figure 17 indicates that the price of the chemical additive has a mild decreasing impact on the utilization percentage of this substance. On account of this, if the unauthorized additive is more accessible, the farmer will be more enticed to use it in the product. Furthermore, in all scenarios, $x_{2j}; j = 1, \ldots, 4$ decreases when f increases.

4.11 The impact of the health safety guarantee contract on the product safety

In this section, we intend to show the effect of the health safety guarantee contract on the safety level of the product. To this end, we need to compare scenarios 2 and 4 because they only differ in the health safety guarantee issue. Figures 18 and 19 compare these two scenarios in the informal and formal channels, respectively. As can be seen, for all values of g_f and g_m, the health safety guarantee contract leads to a lower percentage of the chemical additive used in the product and a higher level of product safety.

4.12 The impact of the supply chain structure: centralized versus decentralized

In this section, we are going to investigate the impact of cooperation among the players of the supply chain on the safety level of the product. To do this, we compare the centralized and decentralized structures in the formal channel. Figure 20 shows that in the formal channel, the centralized scenario results in a higher safety level of the product than the decentralized scenario but for the large values of g_m and small values of g_f. In this case, the manufacturer

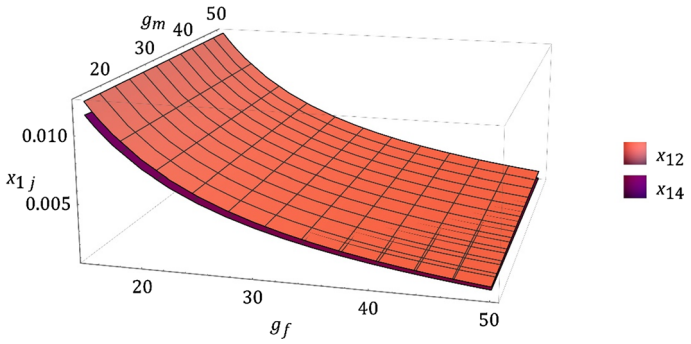


Fig. 18 The comparison of scenarios 2 and 4 in the informal channel

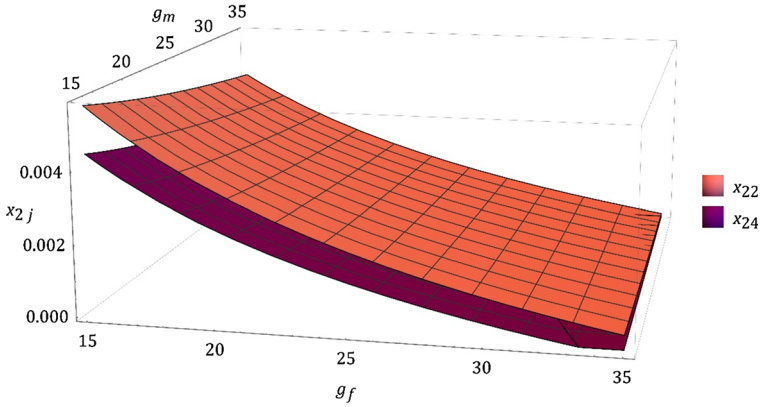


Fig. 19 The comparison of scenarios 2 and 4 in the formal channel

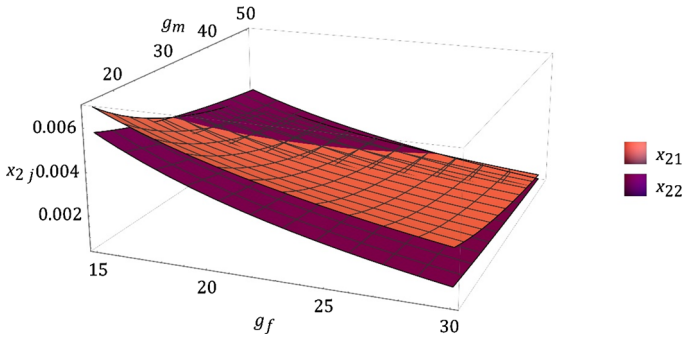


Fig. 20 The comparison of scenarios 1 and 2 in the formal channel

has to accept more responsibility and risk than the farmer if a product safety accident happens, and this encourages the farmer to utilize a higher percentage of the chemical additive in the product. Consequently, the safety level of the product in the supply chain decreases.

5 Insights

In this section, we derive several managerial insights based on the experimental results as follows.

Insight 1 If the government considers more intense punishment policies for the farmer and manufacturer, the possibility of using unauthorized additives decreases (Manteghi et al., 2021; Song & Zhuang, 2017). This also leads to a decline in the total profit of the supply chain.

Insight 2 The safety guarantee contract contributes to product safety improvement in both formal and informal channels. Furthermore, the product safety level in the formal channel is always higher than in the informal one.

Insight 3 Fining the farmer has a greater impact on product safety than fining the manufacturer. Moreover, penalty policies have a greater impact on the informal channel than the formal one.

Insight 4 The higher the basic demand is in the market, the less the farmer needs to use the additive in the product.

Insight 5 If the additive poses a high risk to consumer's health, the farmer utilizes less or zero percent of this substance in the product and gains less profit.

Insight 6 The farmer prefers not to use the chemical additive if the product cost is high, whereas cheap chemical additives temp the farmer to buy and use it. Consequently, the government should enact policies that prevent easy access to these substances.

Insight 7 The higher the product price, the more incentive the farmer has to use the chemical additive to increase his/her sales. In all scenarios, if the selling price of the product is less than a certain amount, the farmer does not accept the risk of using the unauthorized additive in production.

6 Summary and outlook on further research

In this study, a dual-channel dairy supply chain including formal and informal channels was studied. In this supply chain, a farmer determines the safety level of the product through the percentage of an unauthorized chemical additive used in it. The farmer can sell the product either directly to consumers in the informal channel or to a manufacturer at a wholesale price. The manufacturer processes the product to sell it to consumers, but he/she uses no additive. To investigate this supply chain, we address four scenarios, including the centralized, decentralized, cost-sharing contract and safety guarantee. In each scenario, we need to decide on the percentage of the additive in the formal and informal channels along with the wholesale price. To this end, we develop a model using the game theory approach to find the optimal value of each decision variable. The proposed models were examined by a set of real data, and the results were presented to decision-makers. Some of the significant results of this research are given below.

- The government can contribute to higher product safety by imposing appropriate penalty policies against the farmer and the manufacturer and preventing them from utilizing the unauthorized additive.
- The safety guarantee scenario can help to increase the safety level of the products in both the formal and informal channels.
- The safety level of the product in the formal channel is always higher than in the informal one.
- The highest profit of the supply chain is gained by the centralized scenario in which the players of the supply chain can earn more profit if they are integrated.
- The more dangerous the additive is, the less motivation the farmer has to utilize it.
- If the government imposes strict rules on the manufacturer, the members of the supply chain will move towards using the safety guarantee contract, and this can lead to a higher level of product safety.

For further research, there are a number of possibilities. For example, one might consider a similar supply chain with several competing players at each level of the chain. It is also possible to address some other policies of the government in the field of food safety such as encouraging laws for the production of healthy products and inspection of chain members by the government. Finally, we encourage studying the situation in which all producer players can utilize unauthorize additives in the product.

Author contributions All authors contributed to the study conception and design. Material preparation, modelling and analysis were performed by EZN, SS and MR. The first draft of the manuscript was written by EZN and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Availability of data and materials We have not used particular data, and we have just generated data to evaluate and analyze our developed solution approaches. Nevertheless, all date we have use are available based on request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical approval This paper has been written originally by Emad Zamiri-Noghreh, Soroush Safarzadeh and Mohammad Ranjbar, and has not be submitted to any other journal simultaneously. We declare that the results of this research work have been presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation. No data, text, or theories by others are presented as if they are our own.

Consent for publication We (all authors of this paper) agree with the content and that we give explicit consent to submit and publish this research work at ESPR Journal. Moreover, we obtained consent from the responsible authorities at the institute/organization where the work has been carried out.

Appendix A

$$A_1 = fo - mq + o\lambda g_f \tag{A.1}$$

$$A_2 = fo - mq + o\lambda(g_f + g_m) \tag{A.2}$$

$$A_3 = 2fo - 2mq + o\lambda(2g_f + g_m) \tag{A.3}$$

$$A_4 = fo - mq \tag{A.4}$$

$$A_5 = o\lambda(2g_f + g_m) \tag{A.5}$$

$$A_6 = o\lambda(g_f + g_m) \tag{A.6}$$

$$B_1 = -1 + \theta \tag{A.7}$$

$$B_2 = -2 + \theta \tag{A.8}$$

$$B_3 = nq - nq\theta + op_2 \tag{A.9}$$

$$B_4 = -4 + \theta \tag{A.10}$$

$$B_5 = -8 + \theta \tag{A.11}$$

$$B_6 = 4oA_1\alpha(\alpha^2 - \beta^2)(2A_1(2A_4B_1 - A_5)\alpha^2 + (A_4B_2 - 2o\lambda g_f)(A_4B_2 - A_5)\beta^2) \tag{A.12}$$

$$B_7 = -A_4B_2 + 2o\lambda g_f \tag{A.13}$$

$$B_8 = (A_4B_1 - o\lambda g_f) \tag{A.14}$$

$$B_9 = -A_4B_2 + o\lambda g_f \tag{A.15}$$

$$B_{10} = (A_4B_2 - A_5) \tag{A.16}$$

$$B_{11} = A_4(-2noqB_4B_1\lambda g_m - A_4(8 + B_5\theta)B_3) \tag{A.17}$$

$$\begin{aligned} B_{12} = \Bigg(& -A_4^3B_2\Big(8 + B_5\theta\Big) + o\lambda\Big(2g_f\Big(A_4^2\Big(24 + \theta\Big(-24 + 5\theta\Big)\Big) + 4o\lambda g_f\Big(-3A_4B_2 \\ & + 2o\lambda g_f\Big)\Big) + \Big(A_4^2\Big(8 + B_4\theta\Big) + 4o\lambda g_f\Big(-A_4B_4 + 2o\lambda g_f\Big)\Big)g_m\Big)\Big)\Big(-nq + op_1\Big)\Bigg)\alpha^2\beta^3 \end{aligned} \tag{A.18}$$

$$\begin{aligned} B_{13} = -B_7\Bigg(& \Big(A_1\Big)\alpha\beta^3\Big(a_1\Big(-2o\lambda g_f\Big(A_4\theta + o\lambda g_m\Big) + A_4\Big(A_4B_2\theta \\ & - o\Big(2 + \theta\Big)\lambda g_m\Big)\Big) + 2\Big(-oc_mB_7 - nqB_1\Big(-A_4B_2 + 2A_6\Big) + oB_7p_2\Big)\beta\Bigg) \end{aligned} \tag{A.19}$$

$$\begin{aligned} B_{14} = & -8A_1^2(oc_mB_8 - nqB_1(-A_4B_1 + A_6) - oB_8p_2)\alpha^5 \\ & + 4A_1\left(A_4^2B_2B_1 + o\lambda\left(g_f\left(-A_4(-4 + 3\theta) + 2o\lambda g_f\right) + A_1g_m\right)\right)(nq - op_1)\alpha^4\beta \end{aligned} \tag{A.20}$$

$$B_{15} = B_7^2B_{10}(-nq + op_1)\beta^5 \tag{A.21}$$

$$B_{16} = 2A_1\alpha^3\beta\Bigg(2A_1\Big(A_4^2B_1\theta + o\lambda\Big(A_4\theta g_f - A_1g_m\Big)\Big) - \Big(oc_m\Big(A_4\Big(8 + B_5\theta\Big) + 8o\lambda g_f B_9\Big) - 8o^2\lambda^2g_f^2\Big(-nqB_1 + op_2\Big) + 8o\lambda g_f\Big(noqB_1\lambda g_m + A_4B_2B_3\Big) + B_{11}\Big)\beta\Bigg) \tag{A.22}$$

$$B_{17} = a_2A_1\Bigg(8B_8^2A_1\alpha^4 + 2\Big(A_4^3B_4B_2B_1 + o\lambda\Big(g_f\Big(-A_4^2\Big(24 + 7B_4\theta\Big) - 2o\lambda g_f\Big(-A_4\Big(-12 + 7\theta\Big) + 4o\lambda g_f\Big)\Big) - \Big(A_4^2\Big(2 + B_2\theta\Big) + 2o\lambda g_f B_9\Big)g_m\Big)\Big)\alpha^2\beta^2 - B_7^2B_{10}\beta^4\Bigg) \tag{A.23}$$

$$B_{18} = B_{12} + B_{13} + B_{14} + B_{15} + B_{16} + B_{17} \tag{A.24}$$

Appendix B

Proof of Proposition 1 *To investigate the concavity condition in the supply chain profit function, we develop the Hessian matrix as follows.*

$$\begin{bmatrix} -\frac{2(fo-mq+o\lambda g_f)\alpha}{o} & \frac{(2fo-2mq+o\lambda(2g_f+g_m))\beta}{o} \\ \frac{(2fo-2mq+o\lambda(2g_f+g_m))\beta}{o} & -\frac{2(fo-mq+o\lambda(g_f+g_m))\alpha}{o} \end{bmatrix} \tag{B.1}$$

Examining the concavity conditions, we come to the following feasibility conditions.

$$q \geq \frac{fo}{m} \& g_f > \frac{-2fo + 2mq - o\lambda g_m}{2o\lambda} + \frac{1}{2}\sqrt{-\frac{g_m^2\alpha^2}{-\alpha^2 + \beta^2}} \tag{B.2}$$

Proof of Proposition 2 *To investigate the concavity condition of the farmer's profit function, we constitute the Hessian matrix as shown in Eq. (B.3).*

$$\begin{bmatrix} -\frac{2(fo-mq+o\lambda g_f)\alpha}{o} & \frac{2(fo-mq+o\lambda g_f)\beta}{o} \\ \frac{2(fo-mq+o\lambda g_f)\beta}{o} & -\frac{2(fo-mq+o\lambda g_f)\alpha}{o} \end{bmatrix} \tag{B.3}$$

The initial condition for the concavity of the farmer's profit function is shown in Eq. (B.4).

$$\frac{\partial^2\pi_f}{\partial x_1^2} = -\frac{2\big(fo - mq + o\lambda g_f\big)\alpha}{o} < 0 \tag{B.4}$$

The determinant of the Hessian matrix must also be greater than zero. Thus, according to Eq. (B.5), we have:

$$\frac{4\big(fo - mq + o\lambda g_f\big)^2\big(\alpha^2 - \beta^2\big)}{o^2} > 0 \tag{B.5}$$

where the assumption $\alpha > \beta$ in Eq. (B.5) is always held.

Proof of Proposition 3 *The concavity condition of the manufacturer's profit function is shown in Eq. (B.6).*

$$\frac{\partial^2 \pi_m}{\partial p_w^2} < 0 \tag{B.6}$$

The feasible region of the problem is presented in Eq. (B.7).

$$q > \frac{fo}{m} \& g_f > \frac{-fo + mq}{o\lambda}) \tag{B.7}$$

Proof of Proposition 4 *To investigate the concavity condition of the farmer's profit function, we form the Hessian matrix as Eq. (B.8).*

$$\begin{bmatrix} -\frac{2(fo-mq+o\lambda g_f)\alpha}{o} & \frac{(-(fo-mq)(-2+\theta)+2o\lambda g_f)\beta}{o} \\ \frac{(-(fo-mq)(-2+\theta)+2o\lambda g_f)\beta}{o} & \frac{2((fo-mq)(-1+\theta)-o\lambda g_f)\alpha}{o} \end{bmatrix} \tag{B.8}$$

The initial condition for the concavity farmer's profit function is as Eq. (B.9).

$$\frac{\partial^2 \pi_f}{\partial x_1^2} = -\frac{2(fo - mq + o\lambda g_f)\alpha}{o} < 0 \tag{B.9}$$

The determinant of the Hessian matrix must also be greater than zero, so we have (Eq. B.10):

$$-\frac{1}{o^2}\Bigg(4\left((fo - mq)(-1+\theta) - o\lambda g_f\right)\left(fo - mq + o\lambda g_f\right)\alpha^2 + \left((fo - mq)(-2+\theta) - 2o\lambda g_f\right)^2 \beta^2\Bigg) > 0 \tag{B.10}$$

Proof of Proposition 5 *The concavity condition of the manufacturer's profit function is shown in Eq. (B.6). Accordingly, we obtain Eq. (B.11).*

$$q > \frac{fo}{m} \& g_f > \frac{-4fo + 4mq + 2fo\theta - 2mq\theta - o\lambda g_m}{4o\lambda} + \frac{1}{4}\sqrt{\left(\frac{1}{o^2\lambda^2\left(-\alpha^2 + \beta^2\right)}\right)\left(-4f^2o^2\theta^2\alpha^2 + 8fmoq\theta^2\alpha^2 - 4m^2q^2\theta^2\alpha^2 + 4fo^2\theta\lambda g_m\alpha^2 - 4moq\theta\lambda g_m\alpha^2 - o^2\lambda^2 g_m^2\alpha^2 + o^2\lambda^2 g_m^2\beta^2\right)} \tag{B.11}$$

Proof of Proposition 6 *To investigate the concavity condition of the farmer's profit function, we form the Hessian matrix as Eq. (B.12).*

$$\begin{bmatrix} -\frac{2(fo-mq+o\lambda g_f)\alpha}{o} & \frac{(2fo-2mq+o\lambda(2g_f+g_m))\beta}{o} \\ \frac{(2fo-2mq+o\lambda(2g_f+g_m))\beta}{o} & -\frac{2(fo-mq+o\lambda(g_f+g_m))\alpha}{o} \end{bmatrix} \tag{B.12}$$

The initial condition for the concavity of the farmer's profit function is shown in Eq. (B.13).

$$\frac{\partial^2 \pi_f}{\partial x_1^2} = -\frac{2\left(fo - mq + o\lambda g_f\right)\alpha}{o} < 0 \tag{B.13}$$

The determinant of the Hessian matrix must also be greater than zero, so we have the following equation.

$$\frac{4\left(fo - mq + o\lambda g_f\right)\left(fo - mq + o\lambda\left(g_f + g_m\right)\right)\alpha^2 - \left(2fo - 2mq + o\lambda\left(2g_f + g_m\right)\right)^2\beta^2}{o^2} > 0 \tag{B.14}$$

Proof of Proposition 7 *The concavity condition of the manufacturer's profit is given in Eq. (B.15).*

$$\frac{\partial^2 \pi_m}{\partial p_w^2} = \frac{4o\left(fo - mq + o\lambda g_f\right)\alpha\left(\alpha^2 - \beta^2\right)}{\left(2fo - 2mq + o\lambda\left(2g_f + g_m\right)\right)^2\beta^2 - 4\left(fo - mq + o\lambda g_f\right)\left(fo - mq + o\lambda\left(g_f + g_m\right)\right)\alpha^2} < 0 \tag{B.15}$$

Examining the concavity conditions, we come to the following feasibility conditions.

$$q \geq \frac{fo}{m} \& g_f > \frac{-2fo + 2mq - o\lambda g_m}{2o\lambda} + \frac{1}{2}\sqrt{-\frac{g_m^2\alpha^2}{-\alpha^2 + \beta^2}} \tag{B.16}$$

References

Caswell, J. A. (1998). Valuing the benefits and costs of improved food safety and nutrition. *Australian Journal of Agricultural and Resource Economics, 42*(4), 409–424. https://doi.org/10.1111/1467-8489.00060

Chen, C., Zhang, J., & Delaurentis, T. (2014). Quality control in food supply chain management: An analytical model and case study of the adulterated milk incident in China. *International Journal of Production Economics, 152*, 188–199. https://doi.org/10.1016/j.ijpe.2013.12.016

Fares, M., & Rouviere, E. (2010). The implementation mechanisms of voluntary food safety systems. *Food Policy, 35*(5), 412–418. https://doi.org/10.1016/j.foodpol.2010.05.008

Govindan, K. (2018). Sustainable consumption and production in the food supply chain: A conceptual framework. *International Journal of Production Economics, 195*, 419–431. https://doi.org/10.1016/j.ijpe.2017.03.003

Grunert, K. G. (2005). Food quality and safety: Consumer perception and demand. *European Review of Agricultural Economics, 32*(3), 369–391. https://doi.org/10.1093/eurrag/jbi011

Henson, S., & Caswell, J. (1999). Food safety regulation: An overview of contemporary issues. *Food Policy, 24*(6), 589–603. https://doi.org/10.1016/S0306-9192(99)00072-X

Hoffmann, V., Moser, C., & Saak, A. (2019). Food safety in low and middle-income countries: The evidence through an economic lens. *World Development, 123*, 104611. https://doi.org/10.1016/j.worlddev.2019.104611

Hu, J.-y, Zhang, J., Mei, M., min Yang, W., & Shen, Q. (2019). Quality control of a four-echelon agri-food supply chain with multiple strategies. *Information Processing in Agriculture, 6*(4), 425–437. https://doi.org/10.1016/j.inpa.2019.05.002

Jabarzare, N., & Rasti-Barzoki, M. (2020). A game theoretic approach for pricing and determining quality level through coordination contracts in a dual-channel supply chain including manufacturer and packaging company. *International Journal of Production Economics, 221*, 107480. https://doi.org/10.1016/j.ijpe.2019.09.001

Li, Z., Li, H., (2014). Analysis on food quality and safety supervision based on game theory, in *Proceedings of the Eighth International Conference on Management Science and Engineering Management* (pp. 1541–1549). Springer. https://doi.org/10.1007/978-3-642-55122-2_133

Mangla, S. K., Bhattacharya, A., Yadav, A. K., Sharma, Y. K., Ishizaka, A., Luthra, S., & Chakraborty, R. (2021). A framework to assess the challenges to food safety initiatives in an emerging economy. *Journal of Cleaner Production, 284*, 124709. https://doi.org/10.1016/j.jclepro.2020.124709

Manteghi, Y., Arkat, J., Mahmoodi, A., & Farvaresh, H. (2021). Competition and cooperation in the sustainable food supply chain with a focus on social issues. *Journal of Cleaner Production, 285*, 124872. https://doi.org/10.1016/j.jclepro.2020.124872

Meng, Q., Tan, S., Li, Z., Chen, B., & Shi, W. (2020). A review of game theory application research in safety management. *IEEE Access, 8*, 107301–107313. https://doi.org/10.1109/ACCESS.2020.2999963

Minot, N., Stringer, R., Umberger, W. J., & Maghraby, W. (2015). Urban shopping patterns in Indonesia and their implications for small farmers. *Bulletin of Indonesian Economic Studies, 51*(3), 375–388. https://doi.org/10.1080/00074918.2015.1104410

Muunda, E., Mtimet, N., Schneider, F., Wanyoike, F., Dominguez-Salas, P., & Alonso, S. (2021). Could the new dairy policy affect milk allocation to infants in Kenya? A best-worst scaling approach. *Food Policy, 101*, 102043. https://doi.org/10.1016/j.foodpol.2021.102043

Navarro, E. F., Faure, G., Cortijo, E., De Nys, E., Bogue, J., Gomez, C., Mercado, W., Gamboa, C., & Le Gal, P.-Y. (2015). The impacts of differentiated markets on the relationship between dairy processors and smallholder farmers in the Peruvian Andes. *Agricultural Systems, 132*, 145–156. https://doi.org/10.1016/j.agsy.2014.10.003

Song, C., & Zhuang, J. (2017). Modeling a Government-Manufacturer-Farmer game for food supply chain risk management. *Food Control, 78*, 443–455. https://doi.org/10.1016/j.foodcont.2017.02.047

Song, C., & Zhuang, J. (2018). Regulating food risk management—a government-manufacturer game facing endogenous consumer demand. *International Transactions in Operational Research, 25*(6), 1855–1878. https://doi.org/10.1111/itor.12269

Teng, Y., Chen, X., Yu, Z., & Wei, J. (2021). Research on the evolutionary decision-making behavior among the government, farmers, and consumers: Based on the quality and safety of agricultural products. *IEEE Access, 9*, 73747–73756. https://doi.org/10.1109/ACCESS.2021.3078561

Wertheim-Heck, S. C., Vellema, S., & Spaargaren, G. (2015). Food safety and urban food markets in Vietnam: The need for flexible and customized retail modernization policies. *Food Policy, 54*, 95–106. https://doi.org/10.1016/j.foodpol.2015.05.002

Zhang, K., Qi, H. F., & Shi, C. H. (2010). Safety on food supply chain game basing on profit distribution. *Advanced Materials Research*. https://doi.org/10.4028/www.scientific.net/AMR.121-122.710

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