Government Subsidy Strategies about The Food Post-harvest Loss Reduction Technology: Considering Quality Loss and Quantity Loss

Nan Su, Pan Liu, Jiamin Zhu, JianHua Wang, Bin Zhao

Abstract—**This study examines the government subsidy mechanism designed to encourage supply chain members to adopt advanced post-harvest loss reduction technologies. A supply chain comprising a producer, retailer, and government is analyzed. The concepts of unit quantity loss discount factor and unit quality loss improvement factor are introduced to adjust the demand function. Three models concerning food loss reduction investment and government subsidies are developed and assessed. The results indicate that: 1) Adopting loss reduction techniques positively impacts the returns of supply chain members, influenced by production subsidy factors. 2) The unit quantity loss discount factor is positively correlated with government revenue, while the unit quality loss improvement factor is positively correlated with retailer income. 3) In the ENL model, the equilibrium profit of supply chain members is maximized, and the effect of government subsidies is optimized. These findings provide theoretical support for the formulation of government subsidy policies and investment decisions by supply chain members.**

Index Terms—**subsidy mechanism; quantity loss discount; quality loss improvement; post-harvest loss reduction**

I. Introduction

FOOD supply security was crucial to a country's stable development. In the context of international turmoil, trade disruptions, and a tight domestic production and marketing balance, significant food post-harvest loss (FPHL) would severely affect the country's food security [1]. Food loss has been a persistent issue, with global food loss amounting to US$940 billion in 2013 [2]. Statistics indicate that around 30-40% of agricultural products in India are wasted [3]. Globally, about one-third of the food produced for human consumption is lost or wasted, equivalent to approximately 1.3 billion tons annually [4]. In 2020, China's FPHL reached 35 billion kg, and these food losses are directly tied to global food supply and security [5]. As the global population grows and food demand continues to increase, reducing food loss is critical to the global food supply. As one of the world's largest food producers, food loss in China affects the stability and sustainability of the global food supply chain. Reducing food losses not only enhances food supply within China but also alleviates food shortages and hunger worldwide. To address the FPHL issue, many countries have introduced various incentive policies (such as adopting advanced technological facilities, applying post-production management techniques, etc.) and formulated subsidy policies to manage the relationship between food production and FPHL. However, significant FPHL persists in developing countries. The Chinese government has also implemented a series of food loss reduction policies, as shown in Table 1 (Refer to Appendix E). However, the adoption rate of equipment and technologies remained low, according to a survey conducted by the Standing Committee of the National People's Congress of China in 2020, the national average adoption rate of scientific grain storage equipment was less than 40%, and the proportion of bulk food transportation was only 25% [6].Furthermore, China introduced a subsidy policy for reducing FPHL in 2007. To increase food production and maintain national food security, the government also implemented a related subsidy policy for FPHL, as detailed in Table 2 (Refer to Appendix E). Designing an effective subsidy policy to incentivize supply chain members to adopt loss-reducing equipment and technologies is critical for establishing a long-term mechanism for food conservation and loss reduction. The 20th National Congress of the Communist Party of China proposed building a strong-quality nation, and food quality loss is an issue that cannot be overlooked. However, much existing research has primarily focused on quantitative food loss. Therefore, designing effective subsidy policies to encourage the adoption of loss-reducing equipment and technologies requires a balanced approach to both quality and quantity loss of food.

Despite some scholars' efforts to explore the food loss reduction, most studies have focused on analyzing the

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factors influencing post-harvest food loss and the impacts of food loss and waste on food security, resource waste, and supply chain profits, as well as the multiple benefits of reducing food loss, including economic, environmental and social benefits [7]-[9]. Additionally, there has been significant focus on interventions to reduce food loss and waste [10]. However, few studies have concentrated on food quality and quantity loss and explored government production subsidies under different loss reduction input strategies. Moreover, considering efforts to reduce food post-harvest loss (FPHL), only a few researchers have discussed subsidies and investment rules for supply chain stakeholders. Therefore, this study focuses on a food supply chain consisting of producers, retailers, and the government, aiming to address both food quality and quantity loss, while exploring government production subsidies under different loss-reducing input strategies and the subsidy and investment rules for supply chain stakeholders. To account for stakeholders' efforts in reducing FPHL, the unit quantity loss discount factor and the unit quality loss improvement factor were introduced to modify the demand function. Based on government subsidy behaviors and supply chain members' investment actions in reducing FPHL, three subsidy and investment models are proposed and their respective benefits analyzed. The results provide theoretical support for the formulation of government subsidy policies and investment decisions by supply chain members.

This article presents the following innovations: 1) The concepts and functional expressions for the unit quantity loss discount factor and the unit quality loss improvement factor are introduced to reflect the loss reduction efforts of supply chain members. Given the availability of food loss cost data, food quality loss reduction costs and quantity loss reduction costs are used to represent loss reduction inputs. 2) The market demand function is modified to account for the impacts of supply chain members' reduction efforts on unit quantity and quality loss. 3) Three investment and subsidy models related to loss-reducing technologies are proposed, and the benefit functions of supply chain members are constructed and analyzed.

II. Material and Methods

A. Literature review

Quantity, quality and post-production losses of food and policy subsidies. Food is the material basis for human survival. Currently, global food security is facing major challenges due to extreme climate change and recurring COVID-19 epidemics. Reducing food loss and waste is a critical strategy to effectively prevent and respond to food crises [11]. According to the FAO, food loss or waste refers to a reduction in the quantity or quality of food along the supply chain. Food loss occurs from post-harvest to pre-retail, while food waste happens at retail and consumer levels [12]. The 20th National Congress of the Communist Party of China also proposed to build a quality power, so in addition to considering the quantity of food loss, we should also consider the quality of food loss [13]. According to the Food and Agriculture Organization of the United Nations (FAO), about 130 million tons of food is rendered unfit for consumption every year due to quality loss, which is equivalent to about 14 percent of global food production [12]. A study also showed that food quality loss significantly impacts farmers' income, with a 1% increase in quality loss leading to a 0.5% decrease in farmers' income [14]. Grain quality loss has an important impact on grain loss. Not only have a negative impact on food supplies and food security, and negative effects on the farmers' income and agricultural sustainable development. Therefore, reducing food quality loss is one of the important measures to ensure food security and farmers' income, and it is also an issue that cannot be ignored.

Currently, food loss reduction still faces significant challenges, with post-harvest loss being particularly severe. However, the adoption rate of equipment and technologies to reduce post-harvest losses remains low. According to a survey by the special research group of the Standing Committee of the National People's Congress in 2020, the proportion of scientific grain storage equipment in the country is less than 40% on average, and the proportion of bulk grain transportation is only 25%. In addition, China's agricultural science and technology investment intensity is less than 1%, agricultural basic research investment accounts for less than 5%, and agricultural scientific research stability support funds account for less than 60%, there is a certain gap with developed countries [12]. The low adoption rate of grain equipment reflects the low motivation of supply chain members to adopt impairment equipment, and food post-harvest service system construction is an important guarantee for loss. However, due to the lack of corresponding incentive measures, the government should actively participate and introduce subsidy policies to encourage supply chain members to adopt loss reduction technologies.

Game theory is widely used in economics, politics, biology and other fields. With the development of society, economy and science and technology, people's demand for game theory in these fields is increasing [15]. In economics, enterprises need to understand the competitive market environment, and game theory provides models for competitive strategies and pricing. As market competition intensifies, the demand for game theory models has grown, bringing more research opportunities and increasing the benefits of related studies [16].

Status of research on the food post-harvest loss. Current researches about post-harvest food loss focused on two main areas. 1) the status of post-harvest loss and its impact on food security, and 2) the factors influencing post-harvest loss and measures to reduce it at different stages of the supply chain.

1) Status of post-harvest loss and its impact on food security. Most initial research concentrated on resource wastage due to post-harvest loss, especially in regions like Africa. The FAO and the World Bank estimated that about 47% of the US $940 billion needed to eliminate hunger in sub-Saharan Africa by 2050 would be spent on post-harvest loss reduction [17][18]. In sub-Saharan Africa (SSA), rural populations are heavily dependent on food production for their income, and food purchases account for a significant portion of spending in both rural and urban areas. Reducing post-harvest losses is therefore also a key way to achieve food and nutrition security in sub-Saharan Africa [19].

However, in a study in the Near East and North Africa region, food loss and waste accounted for 34 per cent of food supply and also undermined the foundations of food security, resulting in massive depletion of resources (e.g. water, land, energy). Thus, reducing FPHL can not only improve food security, but also increase the profitability of participants in the food supply chain[20][21]. Chanchal Kumari et al. also argue that it is essential to reduce post-harvest losses of food, particularly perishable fruits and vegetables[22].

2) Influencing factors and mitigation measures of grain post-harvest losses in different links of the supply chain. Some domestic scholars have studied the post-harvest loss of grain in different provinces, considered different grain varieties, such as corn and wheat and other major grain crops, defined the post-harvest loss segment, analyzed the main factors affecting the post-harvest loss of grain, and proposed corresponding measures[23]. At the same time, many scholars also analyzed the causes of food loss and waste in different links, such as production, processing, storage, harvest and post-harvest links, and put forward measures and suggestions to reduce the loss [25]-[28]. However, WU Songjian and other scholars summarized the research progress of grain post-production loss reduction technology in our country in their article, and put forward the future development trend[29]. Wang Qiang[30] and other scholars showed that the post-harvest loss reduction policy had a certain impact on the loss reduction behavior of farmers, and put forward suggestions for policy improvement [29]. Lundy et al. explored the problems of smallholder farmers in agricultural markets and adaptation to climate change, and proposed some strategies for post-production loss of grain [31]. The review by Kolady et al. analyzed the scope and causes of post-harvest food loss in developing countries and proposed a series of policy and technical interventions [32]. In addition to post-harvest losses across provinces, varieties and segments, interventions to reduce food losses in low-and middle-income countries have been implemented, including post-harvest measures to reduce aflatoxins in maize [33]-[35].

There has been limited research on post-harvest food loss reduction subsidy policies from a supply chain perspective, and existing studies have focused on: proposing government involvement in post-harvest food loss reduction.

Since 1978, China has implemented a food subsidy policy for the circulation link (including post-production). By comparing food subsidies in China and the United States, some studies have highlighted the need for better regulation, higher subsidy amounts, and greater state funding. The situation and reasons for post-harvest corn loss in China were analyzed, concluding that the treatment of corn post-harvest loss in 2010 was outdated. The characteristics of post-harvest losses in rice, wheat, and corn—such as during harvest, transportation, drying, and storage—had limited loss reduction potential, mainly due to insufficient government support for loss reduction policies, which need to be backed by national agricultural science and technology policy [36]. Outside of China, under the background of reducing African food loss, also discussed the policy subsidies, in order to better inform food loss reduction, it is therefore necessary to integrate post-harvest management and food loss into national agricultural policies[37]. Moreover, among the five major challenges facing policies to reduce food loss and waste, As well as the need for policies to reduce food loss, including post-harvest food loss, governments are equally involved[38]. Therefore, governments should develop appropriate food security policies and strategies, improve the sustainability of food production in all its aspects, especially how to reduce post-harvest losses[39].

The above studies had made efforts on post-harvest food loss reduction as well as subsidies, but they had not proposed the concept and functional expressions of the unit quantity loss discount factor and the unit quality loss improvement factor, nor had they modified the demand function and constructed three models for analyzing food loss reduction investments and government subsidies.

B. Question Description

(1) Before the adoption of loss reduction techniques, the producer's per unit quantity loss was $\lambda_1 m$. With the use of loss reduction techniques, the producer's unit quantity loss was $\delta_1\lambda_1 m$. Therefore, the level of loss reduction was $(\lambda_1 m-\delta_1\lambda_1 \mathrm{m})/\lambda_1 m=1-\delta_1$, The cost of reducing loss was $C_1=\kappa_1(1-\delta_1)^2/2$.

(2) Before the adoption of loss reduction techniques, the retailer's per unit quantity loss was $\lambda_2 m_1$. With the use of loss reduction techniques, the retailer's unit quantity loss was $\delta_2\lambda_2 m_1$. Therefore, the level of loss reduction was $(\lambda_2 m_1-\delta_2\lambda_2 \mathrm{m}_1)/m_1=1-\delta_2$, The cost of reducing loss was $C_4=\kappa_4(1-\delta_2)^2/2$.

(3)For post-harvest quality loss, we assumed that before the adoption of loss reduction techniques, the initial quality of the food at the harvest time was q_0 . In Figure 1, through the manufacturer’s transport, air-drying and storage , when the food reached the retailer, we assumed that before and after the adoption of loss reduction techniques, the food quality declined by $(1-\alpha_1)q_0$ and $\beta_1(1-\alpha_1)q_0$ respectively. Her, $1\geq\beta_1(1-\alpha_1)\geq(1-\alpha_1)\geq 0$. Similarly, through the retailer's transportation and storage, when the food reached the consumer, we assumed that the food quality before and after the adoption of loss reduction techniques decayed as $(1-\alpha_2)(1-\alpha_1)q_0$ and $\beta_1\beta_2(1-\alpha_2)(1-\alpha_1)q_0$, respectively. Here, $1\geq\beta_2\beta_1(1-\alpha_2)(1-\alpha_1)\geq(1-\alpha_2)(1-\alpha_1)\geq 0$.

(4) The reduction in quality loss was Δq , $\Delta q/(1-\alpha_1)q_0=(\beta_1-1)$, and the reduction degree in quality loss was $(\beta_1-1)(1-\alpha_1)q_0$. Similar to Chen, Shih-Pin and Molin Liu [40][41], we assumed that the producer's loss reduction cost was $c_2=\kappa_2(\beta_1-1)^2/2$. Similarly, the loss reduction cost for retailers was $c_3=\kappa_3(\beta_2-1)^2/2$.

(5) Similar to[42][43][56][57], assuming that the demand equation was $D^i=a-p_i+e(\beta_1)^{z_1}(\beta_2)^{z_2}(1-\alpha_1)^{z_3}(1-\alpha_2)^{z_4}q_0$. when $i=\{NEL\}$, z_4=1 , z_3=1 , z_2=0 和 z_1=0 . when $i=\{ENL\}$, z_4=1 , z_3=1 , z_2=0 and z_1=1 , when $i=\{ELB\}$, z_4=1 , z_3=1 , z_2=1 , z_1=1 .

(6) In addition, in order to stimulate the producer and the retailer to adopt loss reduction techniques to reduce post-harvest loss, the government would provide subsidies by a factor of s_1 and s_2 .

(7) Consumer surplus was an important indicator of consumer welfare for governments. The consumer surplus was the difference between the maximum price that a consumer was willing to pay for a given quantity of a good and the actual market price of that good. Thus, the consumer surplus was as follows.

$$CS = \int_{p_i}^{p_{\max}} D_i dp = \frac{D_i^2}{2};$$

Assume that food demand is in a tight equilibrium, output was available for sale.

The specific meaning of the parameter function is shown in Table I.

TABLE I
DESCRIPTION OF THE VARIABLES INVOLVED

Parameter	EXPLANATION
a	Potential market demand.
q_0	The initial quality of the food at the harvest time.
β	Production subsidy factor.
m	Unit production of food.
m_1	The number of units of food received by a retailer.
λ_1	Before adopting loss reduction techniques, producer's unit quantity loss rate.
λ_2	Before adopting loss reduction techniques, retailers' unit quantity loss rate.
δ_1	After adopting loss reduction technology, producer's unit quantity loss discount factor. $0 < \delta_1 < 1$.
δ_2	After adopting loss reduction technology, retailer's unit quantity loss discount factor. $0 < \delta_2 < 1$
k_1	The producer's reduction loss of cost factor.
k_2	Cost factor for producers to reduce quality loss.
k_3	Cost factor for retailers to reduce quality loss.
k_4	The retailer's reduction loss of cost factor.
α_1	Producers' food quality decay factor. $1 \ge \alpha_1 \ge 0$
α_2	Retailers' food quality decay factor. $1 \ge \alpha_2 \ge 0$
β_1	After adopting loss reduction technology, producer's unit quanlity loss improvement factor. $\beta_1 \ge 1$ .In this paper, we use it to reflect the extent of the producer's derogation efforts.
β_2	After adopting loss reduction technology, retailer's unit quanlity loss improvement factor. $\beta_2 \ge 1$ .In this paper, we use it to reflect the extent of the retailer's derogation efforts.
i	$i = \{NEL, ENL, ELB\}$ In the NEL model, neither the food producer nor the retailer invests in post-harvest loss reduction technology. In the ENL model, food producers will invest in post-harvest reduction technology, while retailers will not invest in reduction technology, and the government will subsidize this investment. In the ELB model, both food producers and retailers will invest in post-harvest reduction technology, and the government will subsidize this investment.
p_i	The retail price of food in the i model.
$p_{\max}$	The price when market demand equals zero.
s_1	Producer's loss reduction subsidy factor $0 < s_1 \le 1$.
s_2	Retailer's loss reduction subsidy factor $0 < s_2 \le 1$.

III. THEORY AND CALCULATION

A. Analysis of Subsidies

The NEL model. In the NEL model, the food producer and the retailer do not adopt techniques to reduce food loss. The profit functions for the food producer, the retailer and government are as follows.

$$\pi_p^{NEL} = (w^{NEL} - c + \beta) D^{NEL} (1 - \lambda_1) \tag{1}$$

$$\pi_r^{NEL} = (p^{NEL} - w^{NEL}) D^{NEL} (1 - \lambda_2)(1 - \lambda_1) \tag{2}$$

$$\pi_g^{NEL} = \pi_p^{NEL} + \pi_r^{NEL} + CS^{NEL} - \beta D^{NEL} \tag{3}$$

From equations (1), (2) and (3), we can obtain Proposition 1 (see Appendix A-1 for the analysis process).

Proposition 1: In the NEL model, the equilibrium decisions regarding the interests of the retailer, the food producer and the government are as follows.

$$\begin{cases} p^{NEL*} = \dfrac{c - \beta + 3[a + eq_0(\alpha_1 - 1)(\alpha_2 - 1)]}{4} \\ w^{NEL*} = \dfrac{a - \beta + c + eq_0(\alpha_1 - 1)(\alpha_2 - 1)}{2} \\ D^{NEL*} = a - \dfrac{c - \beta + 3[a + eq_0(\alpha_1 - 1)(\alpha_2 - 1)]}{4} \\ \quad + e(1 - \alpha_1)(1 - \alpha_2) q_0 \end{cases} \tag{4}$$

$$\begin{cases} \quad (\lambda_1 - 1)(\lambda_2 - 1)[a + \beta - c + eq_0(\alpha_1 - 1)(\alpha_2 + 2)] \\ \pi_r^{NEL*} = \dfrac{[a + \beta - c + eq_0(\alpha_1 - 1)(\alpha_2 - 4)]}{16} \\ \quad -(\lambda_1 - 1)[a + \beta - c + eq_0(\alpha_1 - 1)(\alpha_2 - 1)] \\ \pi_p^{NEL*} = \dfrac{[a + \beta - c + eq_0(\alpha_1 - 1)(4\alpha_2 + 5)]}{8} \\ \pi_g^{NEL*} = \dfrac{a + \beta - c + eq_0(\alpha_1 - 1)(\alpha_2 + 2)}{4} \{\beta - (\lambda_1 - 1)(\lambda_2 + 1) \\ \quad [\dfrac{a + \beta - c + eq_0(\alpha_1 - 1)\alpha_2}{4} - \lambda_2 + \dfrac{1}{2}]\} \end{cases} \tag{5}$$

Based on Proposition 1, Partial derivative of the yield subsidy coefficient β ,we can obtain Inference 1 (see Appendix B-1 for the analysis process):

Inference 1: From (i) in Inference 1, the coefficient for production subsidies, under specific conditions, influences the trends of equilibrium prices and profit margins for both retailers and the government, as well as impacting the revenues of producers. As this coefficient increases, both retail and wholesale prices of grain decline. Concurrently, the profits of producers, retailers, and the government rise with the increase in the subsidy coefficient. Therefore, when the government increases grain subsidies, the average unit price of grain decreases. In a market with tightly balanced demand, the profits of retailers and producers will rise to some extent as the subsidy coefficient increases. Whether the government's profits increase depends on the difference between the subsidies granted to producers and retailers, and the societal benefits gained by the government from the increased profits of producers and retailers.

The ENL model. In the ENL model, the producer will adopt loss reduction techniques, but the retailer will not adopt loss reduction techniques. The revenue functions of the food producer, the retailer and government are as follows.

$$\pi_p^{ENL} = (w^{ENL} - c + \beta) D^{ENL} (1 - \delta_1 \lambda_1) - \frac{(1 - s_1)[k_1(\delta_1 - 1)^2 + k_2(\beta_1 - 1)^2]}{2} \tag{6}$$

$$\pi_r^{ENL} = (p^{ENL} - w^{ENL}) D^{ENL} (1 - \delta_1 \lambda_1)(1 - \lambda_2) \tag{7}$$

$$\pi_g^{ENL} = \pi_p^{ENL} + \pi_r^{ENL} + CS^{ENL} - \beta D^{ENL} - \frac{s_1[k_1(\delta_1 - 1)^2 + k_2(\beta_1 - 1)^2]}{2} \tag{8}$$

From equations (6), (7) and (8), we can obtain Proposition 2 (see Appendix A-2 for the analysis process).

Proposition 2: In the ENL model, the equilibrium decisions regarding the interests of the retailer, the food producer and the government are as follows.

$$\begin{cases} w^{ENL*} = \dfrac{a - \beta + c + \beta_1 eq_0 - \beta_1 eq_0 \alpha_1 - \beta_1 eq_0 \alpha_2 + \beta_1 eq_0 \alpha_1 \alpha_2}{2} \\ p^{ENL*} = \dfrac{3a - \beta + c + 3\beta_1 eq_0 - 3\alpha_1 \beta_1 eq_0 - 3\alpha_2 \beta_1 eq_0 + 3\alpha_1 \alpha_2 \beta_1 eq_0}{4} \\ D^{NEL*} = \dfrac{a + \beta - c + \beta_1 eq_0 - \alpha_1 \beta_1 eq_0 - \alpha_2 \beta_1 eq_0 + \beta_1 eq_0 \alpha_1 \alpha_2}{4} \end{cases} \tag{9}$$

$$\begin{cases} \pi_p^{ENL*} = \dfrac{[k_2(\beta_1 - 1)^2 + k_1(\delta_1 - 1)^2 * (s_1 - 1)]}{2} - 2(\delta_1 \lambda_1 - 1) R^2 \\ \pi_r^{ENL*} = \dfrac{(\lambda_1 - 1)(\lambda_2 - 1)}{16} R^2 \\ \pi_g^{ENL*} = [B + j(\alpha_1 - 1)(\alpha_2 - 1) - \dfrac{3j\alpha_1 \alpha_2}{4}]^2 / 2 - \\ \quad \dfrac{k_2(\beta_1 - 1)^2 + k_1(\delta_1 - 1)^2}{2} - \beta R - 2(\delta_1 \lambda_1 - 1) R^2 \\ \quad + (\lambda_1 - 1)(\lambda_2 - 1) R + \dfrac{j\alpha_1 \alpha_2}{4} E \end{cases} \tag{10}$$

Based on Proposition 2, Take the partial derivative of β 、 s_1 、 β_1 、 δ_1, we can obtain Inference 2 (see Appendix B-2 for the analysis process).

Inference 2:

① From ① in Inferences 1 and 2 (proof provided in Appendix B-2), it can be understood that when producers adopt loss-reduction technologies, the coefficient for production subsidies impacts retail and wholesale prices in the same manner as when such technologies are not employed. Specifically, whenever the government increases subsidies, both retail and wholesale prices decrease to a certain extent. Similarly, under certain conditions, the coefficient for production subsidies affects the profits of producers, retailers, and the government. The retailer's profits increase as the subsidy coefficient rises and decrease when it falls, with the same pattern applying to the producer's profits. The government's profits follow this trend as well, increasing with a higher subsidy coefficient and decreasing otherwise, consistent with the conclusions drawn in Inference 1.

② From inference 2, it can be seen that the producer's loss reduction subsidy factor is solely related to the producer's benefits. When the producer adopts the loss-reduction technology, the higher the loss reduction subsidy factor, the greater the benefit the producer receives from it. In this case, when the producer adopts the loss-reduction technology, the benefits of the retailer and the government do not change. The government subsidies provided to the producer are equal to the social benefits received by the government.

③ As stated in ③ of Inference 2 (proof provided in Appendix B-2), after producers adopt loss-reduction technologies, the coefficient for improving the unit quality of grain impacts both wholesale and retail prices. With the adoption of these technologies, the cost of grain production increases, leading to an increase in the unit price of grain. Furthermore, this coefficient, under certain conditions, affects the profits of supply chain members. Specifically, the profits of retailers decrease as the cost of investing in loss-reduction technologies rises. Conversely, the profits of producers rise with increased investment in these technologies. Meanwhile, the government's benefits increase due to the loss-reduction technologies adopted by producers, as the increased production volume results in higher social benefits for the government.

④ From Inference 2, after the producer adopts loss-reduction techniques, the unit food quantity loss discount factor decreases, thereby reducing the food loss rate. As a result, without changing the unit price, the profits of both the producer and the government increase due to the increased production of food, as they meet the respective conditions.

The ELB model. In the ELB model, both the food producer and the retailer will implement loss reduction techniques. The revenue functions of the food producer, the retailer, and government are listed below.

$$\pi_p^{ELB} = (w^{ELB} - c + \beta) D^{ELB} (1 - \delta_1 \lambda_1) - \frac{(1 - s_1)[k_1(1 - \delta_1)^2 + k_2(\beta_{\cdot} - 1)^2]}{2} \tag{11}$$

$$\pi_r^{ELB} = (p^{ELB} - w^{ELB}) D^{ELB} (1 - \delta_1 \lambda_1)(1 - \delta_2 \lambda_2) - \frac{(1 - s_2)[k_4(1 - \delta_2)^2 + k_3(\beta_2 - 1)^2]}{2} \tag{12}$$

$$\pi_g^{ELB} = \pi_p^{ELB} + \pi_r^{ELB} + CS^{ELB} - \beta D^{ELB} - \frac{s_1[k_1(1 - \delta_1)^2 + k_2(\beta_{\cdot} - 1)^2]}{2} - \frac{s_2[k_4(1 - \delta_2)^2 + k_3(\beta_2 - 1)^2]}{2} \tag{13}$$

From equations (11), (12) and (13), we can obtain Proposition 3 (see Appendix A-3 for the analysis process).

Proposition 3: In the ELB model, the optimal decision regarding the interests of the retailer, the food producer and the government is as follows.

$$\begin{cases} w^{ELB*} = \dfrac{a - b + c + \beta_1 \beta_2 eq_0 - \beta_1 \beta_2 eq_0 \alpha_1 - \beta_1 \beta_2 eq_0 \alpha_2 + \beta_1 \beta_2 eq_0 \alpha_1 \alpha_2}{2} \\ p^{ELB*} = \dfrac{3a - b + c + 3\beta_1 \beta_2 eq_0 - 3\beta_1 \beta_2 eq_0 \alpha_1 - 3\beta_1 \beta_2 eq_0 \alpha_2 + 3\beta_1 \beta_2 eq_0 \alpha_1 \alpha_2}{4} \\ D^{NLB*} = \dfrac{a + b - c + \beta_1 \beta_2 eq_0 - \beta_1 \beta_2 eq_0 \alpha_1 - \beta_1 \beta_2 eq_0 \alpha_2 + \beta_1 \beta_2 eq_0 \alpha_1 \alpha_2}{4} \end{cases} \tag{14}$$

$$
\begin{cases}
\pi_p^{ELB*} = \dfrac{(s_1-1)(k_2\beta^2-2k_2\beta+k_1\delta_1^{\ 2}-2k_1\delta_1+k_1+k_2)}{2} - 2(\delta_1\lambda_1-1)D^2 \\
\pi_r^{ELB*} = \dfrac{(s_2-1)(k_3\beta_2^{\ 2}-2k_3\beta_2+k_4\delta_2^{\ 2}-2k_4\delta_2+k_3+k_4)}{2} \\
\quad +(\delta_1\lambda_1-1)(\delta_2\lambda_2-1)D^2 \\
\pi_g^{ELB*} = -\dfrac{(k_2\beta^2-2k_2\beta+k_1\delta_1^{\ 2}-2k_1\delta_1+k_1+k_2)}{2} \\
\quad -\dfrac{(k_3\beta_2^{\ 2}-2k_3\beta_2+k_4\delta_2^{\ 2}-2k_4\delta_2+k_3+k_4)}{2} \\
\quad -\dfrac{\beta D}{4}+\dfrac{D^2}{2}+(\delta_1\lambda_1-1)(\delta_2\lambda_2-1)D^2 \\
\quad -2(\delta_1\lambda_1-1)D+\dfrac{\beta_1\beta_2 e q_0\alpha_1\alpha_2 D}{2}
\end{cases}
\tag{15}
$$

Based on Proposition 3, Take the partial derivative of β , s_1 , β_1 , δ_1 , s_2 , β_2 , δ_2 ,we can obtain Inference 3 (see Appendix B-3 for the analysis process).

Inference 3:

① As derived from ① in Inferences 2 and 3 (proof provided in Appendix B-3), the coefficient for production subsidies, under certain conditions, influences the equilibrium prices and profit trends of both retailers and the government, as well as the income of producers. However, in the scenario where loss-reduction technologies are adopted by all parties, it does not affect the price of grain. The profits of producers, retailers, and the government increase with the rise in the subsidy coefficient and decrease otherwise. Therefore, when both producers and retailers adopt loss-reduction technologies and the government provides production subsidies, the profits of all three parties increase. This situation aligns with the conclusions in Inference 2, leading to the inference that when producers solely receive production subsidies from the government without adopting loss-reduction technologies, they may obtain higher profits compared to when they do adopt such technologies. Conversely, retailers experience an increase in profits when producers adopt loss-reduction technologies.

② From Inferences 2 and 3, the producer's loss reduction subsidy factor only affects the producer's earnings. When the subsidy factor is larger, the producer receives more government subsidies, resulting in increased benefits for the producer, in agreement with the conclusion in Inference 2.

③ As derived from Inference 2 and 3, after producers adopt loss-reduction technologies, the higher the coefficient for improving the unit quality of grain, the higher the unit price of grain becomes, due to the increased input costs associated with these technologies. Retailers, on the other hand, experience an increase in total revenue as the reduction in grain quality loss leads to higher sales volumes. Additionally, producers also see an increase in total income after adopting loss-reduction technologies, as the reduced quality loss of grain translates to more marketable product. Lastly, despite providing subsidies, the government’s revenue still increases due to the heightened profits of both producers and retailers.

④ As derived from Inference 2 and 3 (proof provided in Appendix B-3), after producers adopt loss-reduction technologies, the discount coefficient for unit quantity loss of grain does not affect the unit price of grain but does impact the profits of all three parties involved. For retailers, a higher discount coefficient means receiving fewer grains, and under conditions of market value fluctuations, less supply leads to higher prices and potentially larger marginal returns. However, in reality, their profits decrease due to the scarcity effect on sales volume. For producers, a smaller discount coefficient indicates less grain loss, which translates to more grain revenue at a constant unit price. The trend in the government's profits aligns with that of producers; when producers or retailers earn more, the government’s revenue increases due to higher taxes and enhanced social benefits.

⑤ From Inference 3, the retailer's loss reduction subsidy factor only has an impact on the retailer's benefits, when the subsidy factor is larger, the retailer receives more government subsidies and therefore the benefits to the retailer occur to increase.

⑥ As derived from Inference 3, after adopting loss-reduction technologies, the discount coefficient for unit quantity loss on the part of retailers has no impact on the unit price of grain. This indicates that the price of grain is determined by the wholesale price set by producers. Furthermore, a lower discount coefficient for quantity loss translates to fewer losses per unit, resulting in increased profits for retailers. At this point, the discount coefficient adopted by retailers for loss-reduction technologies has no effect on producers, so the producer's profits remain stable. With a smaller discount coefficient for quantity loss, there is less grain loss, leading to an increase in the total profits of both producers and retailers. Consequently, even after implementing subsidies, the government's revenue still increases.

⑦ As derived from Inference 3 (proof provided in Appendix B-3), the greater the improvement in the unit quality of grain after retailers adopt loss-reduction technologies, the better the loss-reduction effect. Therefore, as the coefficient for improving quality loss increases after adopting these technologies, so does the price of grain. A higher coefficient for improving quality loss leads to increased profits for both retailers and producers, which, in turn, results in increased government revenue.

B. Analysis of Subsidy Strategies

Compare the benefits of the three models, get the range in which the subsidy factor is feasible for investment and feasible for subsidy.

Inference 4. According to Appendix C-1, when $0<\beta<1$, to conduct production subsidies, the benefits to the producer and the retailer increase with the subsidy factor, and also to the extent that the benefits to the government increase with the increase in the subsidy factor, under government subsidies, the government's revenues will not decline, and the benefits to other members of the supply chain rise. A multi-win situation is achieved. Therefore, the government subsidizes production to any degree to supply chain members, the government's income will not be reduced, and the benefits of supply chain members have increased, the government should provide production subsidies to supply chain members.

Inference 5. Based on ② in Appendix B-2 and ④ in Appendix B-3, it is clear that when $s_1>0$, the producer will adopt the loss-reducing technology, the producer's benefits increase with the increase of the subsidy factor, and after adopting the loss-reducing technology, the government benefits are not negatively affected by subsidizing the producer. When $0<\beta<1$, the benefits of the producer increases with the adoption of loss reduction technologies, so in this case it is feasible for the producer to invest in loss reduction technologies and for the government to subsidize them with loss reduction technologies on any terms. Because producers of earnings with increase with the increase of the coefficient of subsidies, after the loss reduction technology, and will not reduce the government's revenue. After adopting the loss reduction technology, in the case that the benefit of the producer increases, the producer should invest in the loss reduction technology, and the government subsidize the producer, they should promote the loss reduction.

Inference 6. When $s_1>0, s_2>0$, the producer and the retailer adopt loss reduction techniques. According to Appendix B-3, after adopting loss reduction techniques, the benefits to the producer and the retailer at this point increase as the subsidy factor increases, and the benefits to the government are not negatively affected by subsidies to the producer. On the basis of Inference 4, the producer and the retailer adopt loss-reducing technologies, the benefits to both increase, and the benefits to the government increase as well. Therefore, it is feasible for the producer and the retailer to invest in loss-reducing technologies and for the government to subsidize them with loss-reducing technologies on arbitrary terms. Therefore, both producers and retailers should actively adopt the loss reduction technology, and the government directly subsidize the production of both.

C. Case Simulation

Food loss and waste threaten a country's food security. To reduce loss all the food supply chain, the Chinese government has also introduced a series of policies, however, for profit-driven supply chain members, their effort and enthusiasm are insufficient about reducing FPHL. Considering the effort level of FPHL reduction, we discussed the relevant subsidy policies. Some interesting inferences are obtained. To test the validity of these inferences, we implement this case simulation. We set $e_0=0.1$ and $\beta=0.02$. According to previous studies on food loss, food quantity loss varies for different farmers or producers. For producers who use the outdated harvesting and storage equipment, the average rates of food quantity loss and food quality loss ranged from 8% to 18% and 6% to 20%, respectively. For producers who use the advanced harvesting and storage equipment, the average rates of food quantity loss and food quality loss were less than 3% and 2%, respectively. For retailers who use outdated storage equipment, the average rates of food quantity loss and food quality loss were 3% to 8% and 5% to 15%, respectively. For retailers who adopt the advanced storage equipment, the average rates of food quantity loss and food quality loss were less than 1% and 1%, respectively.

Therefore, we set $\alpha_1=0.1$, $\alpha_2=0.05$, $s_1=0.2$, $s_2=0.2$ $\beta_2=0.2$, $\beta_1=0.6$, $\lambda_1=0.1$, $\lambda_2=0.04$, $\delta_1=0.6$ a $\delta_2=0.7$. In addition, we assume that $q_0=2$, $c=0.02$, $a=3$, $k_1=0.8$, $k_2=0.7$, $k_3=0.7$, $k_4=0.8$. Based on the above values and the proposed propositions and inferences, we obtain the following.

Figure (1) shows the trends of equilibrium prices and benefits with β in the NEL model. The figure shows that under certain conditions, the production subsidy factor affects the trends of equilibrium prices and benefits about the retailer and government, and also affects producer's revenues. At the same time, as the subsidy coefficient increases, the producer's earnings increases. Therefore, production subsidies can stimulate the producer to adopt loss reduction techniques.

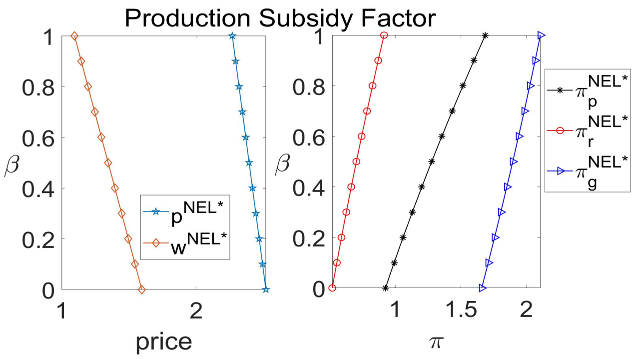

Fig 1. Variation trends of equilibrium prices and benefits with β in NEL model.

Figure (2) shows the trends of balance prices and benefits with β in the ENL model. The figure shows that under certain conditions, the production subsidy factor affects the trends of balance prices and benefits about the retailer and government, and also affects producer's revenues. At the same time, as the subsidy coefficient increases, the producer's earnings increases. Based on these, production subsidies can also stimulate producers to adopt loss reduction techniques.

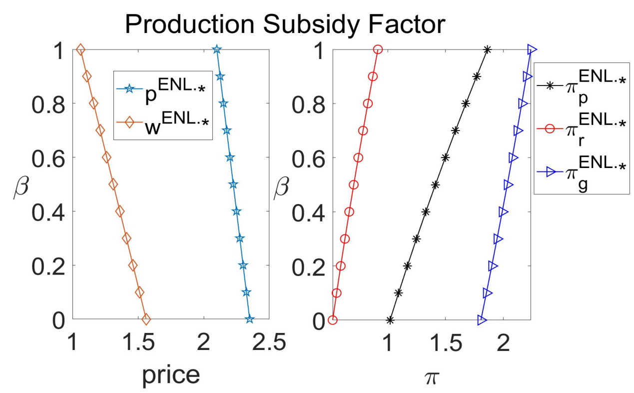

Fig 2. Variation trends of balance prices and benefits with β in ENL model.

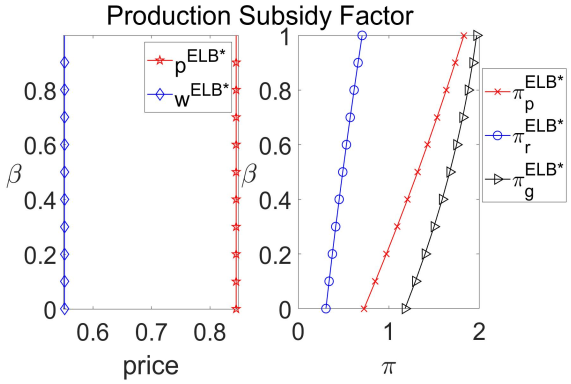

Fig 3. Variation trends of balance prices and benefits with β in ELB model.

Figure (3) shows the trend of balance prices and benefits with β in the ELB model. The figure shows that the production subsidy factor affects the trend in equilibrium prices and benefits for the retailer and government under certain conditions, and also affects producer's revenues, but has no effect on the price of food when loss reduction techniques are both used.

Figure (4) shows the trends of balance prices and returns with s_1 in the ENL model. The figure shows that the producer's loss reduction subsidy factor is only related to the producer's benefits, and when the producer adopts a loss reduction technology and the government offers a higher loss reduction subsidy factor, the more benefits the producer receives from it.

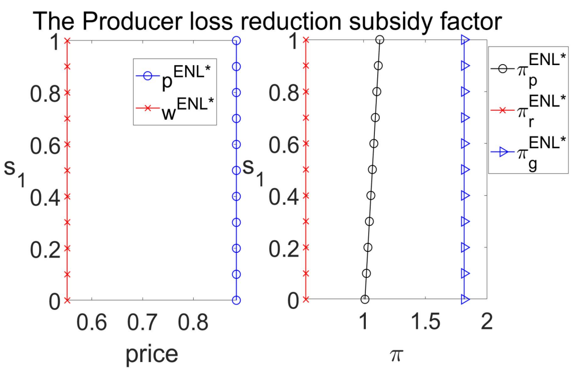

Fig 4. Variation trends of balance prices and benefits with s_1 in ENL model.

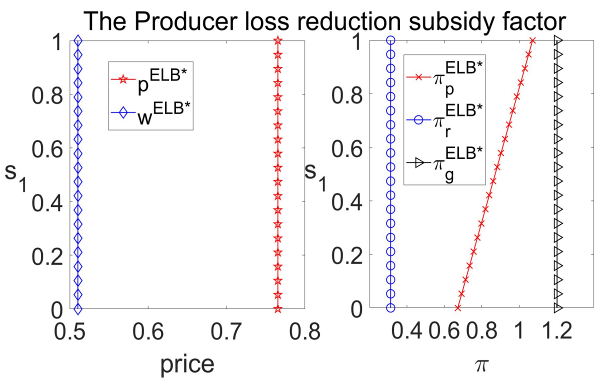

Fig 5. Variation trends of balance prices and benefits with s_1 in ELB model.

Figure (5) shows the trend of balance prices and returns with s_1 in the ELB model. The figure shows that the producer's loss reduction subsidy factor only has an impact on the producer's returns. When the subsidy factor is larger, the producer receives more government subsidies and therefore the benefits to the producer occur to increase, in line with the findings in Inference 2.

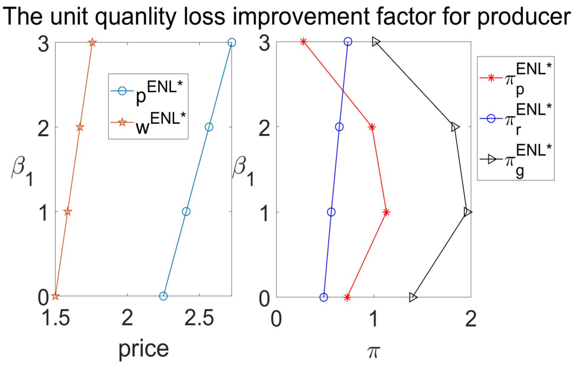

Fig 6. Variation trends of balance prices and benefits with β_1 in ENL model.

Figure (6) shows the trends of the balance prices and revenues with β_1 in the ENL model. The figure shows that the unit quality loss improvement coefficient has an impact on the wholesale price and the retail price when producers adopt loss reduction techniques, and that the coefficient also has an impact on the benefits of supply chain members under certain conditions.

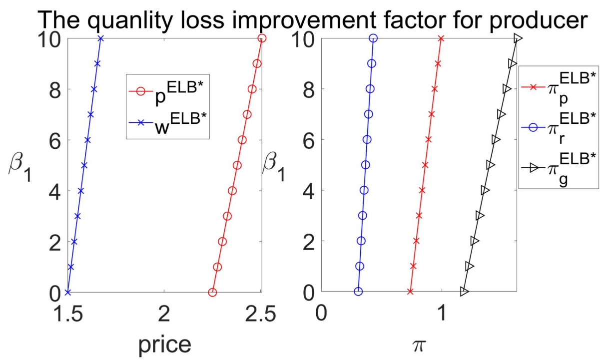

Fig 7. Variation trends of balance prices and benefits with β_1 in ELB model.

Figure (7) shows the trend of balance prices and returns with β_1 in the ELB model. The figure shows that the adoption of loss reduction techniques by the producer and the factor of improvement in quality loss per unit of food have an impact on prices and the returns of supply chain members.

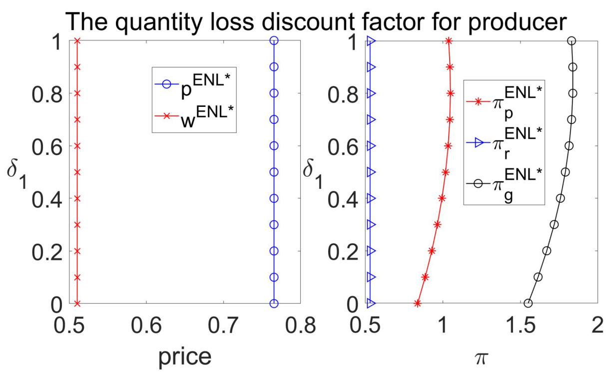

Fig 8. Variation trends of balance prices and benefits with δ_1 in ENL model.

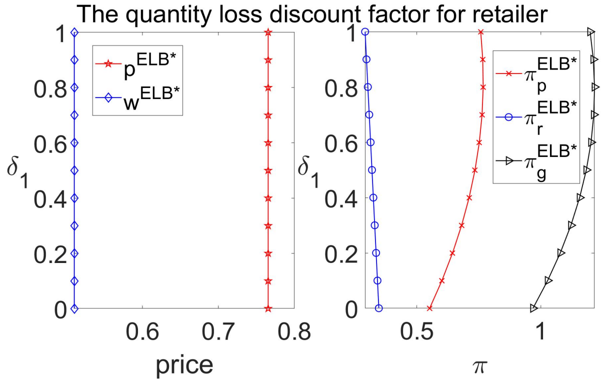

Fig 9. Variation trends of balance prices and benefits with δ_1 in ELB model.

Figure (8) shows the trend of balance prices and returns with δ_1 in the ENL model. The figure shows that the loss discount factor per unit of quantity decreases as the producer adopts loss reduction techniques, so that with no change in unit price, the producer and the government receive a consequent increase in profits as the output of the food rises and therefore both meet the respective corresponding conditions.

Figure (9) shows the trend in balance price and yield with δ_1 in the ELB model. The figure shows that the producer's use of the loss reduction technique has no effect on the unit price of food with the unit quantity loss discount factor, and has an effect on the returns of all three.

Fig 10. Variation trends of balance prices and benefits with s_2 in ELB model.

Figure (10) shows the trend of balance price and revenues with s_2 in the ELB model. The figure shows that the retailer's loss reduction subsidy factor only has an impact on the retailer's returns; as the subsidy factor becomes larger, the retailer receives more government subsidies and therefore the benefits to the retailer occur to increase.

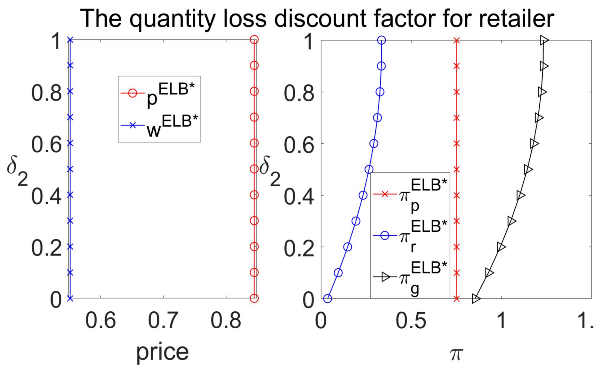

Fig 11. Variation trends of balance prices and benefits with δ_2 in ELB model.

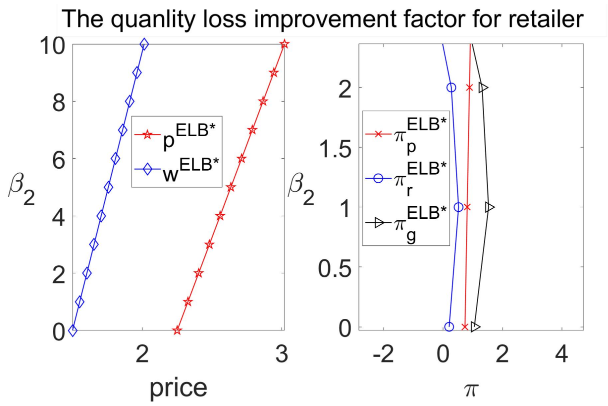

Fig 12. Variation trends of balance prices and benefits with β_2 in ELB model.

Figure (11) shows the trend of balance price and revenues with δ_2 in the ELB model. The figure shows that the loss discount factor per unit quantity of food has no effect on the unit price of food and no effect on producer's returns when the retailer adopt loss reduction techniques.

Figure (12) shows the trend of balance price and revenues with β_2 in the ELB model. It can be seen from the graph that the unit quality loss improvement factor with the adoption of loss reduction techniques by the retailer has no effect on the unit price of food and has an effect on the returns of all three.

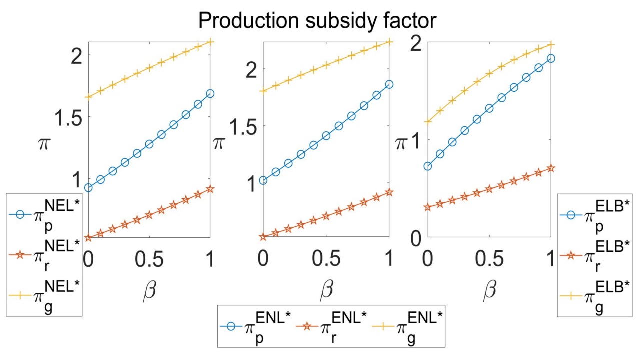

Fig 13. Variation trends of benefits with β in NEL/ENL/ELB model.

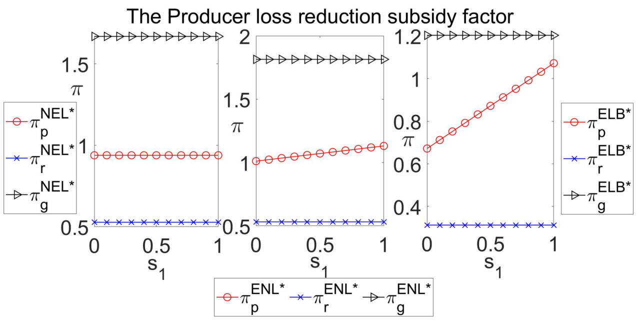

Fig 14. Variation trends of benefits with $s1$ in NEL/ENL/ELB model.

Figure (13) shows the trend of supply chain members' returns with β under the three models. The figure shows that whenever the government subsidises their output, then the supply chain members' returns all increase with the increase in the subsidy coefficient and the balance returns are best under the ENL model.

Figure (14) shows the trend of supply chain member returns with $s1$ for the three models. From the figure, it can be seen that when $s_1>0$, the producer adopts the loss-reducing technology, according to ② in Appendix B-2 and ④ in Appendix B-3, the producer's earnings at this time will increase with the increase of the subsidy factor for the adoption of the loss-reducing technology, and the government's returns will not have a negative effect due to the subsidy to the producer after it adopts the loss-reducing technology. And the loss reduction subsidy factor for the producer's adoption of the loss reduction technology will only have an impact on the producer's returns.

IV. Discussion

To highlight the main contributions of this paper, we compare our study with other research and policies on subsidies to reduce food loss investment in the food supply chain [44]-[46]. Several scholars have made significant efforts in this area[40][41][43]. Building on existing research, we analyzed our findings and explained the reasons for the differences between our results and those of others. However, this study differs in the following ways. The issue of post-harvest food loss requires attention to both quantity and quality loss, and at the same time, the government should introduce corresponding incentive policies to encourage supply chain members to participate in food loss reduction.

1) In order to understand the relationship between food post-harvest loss (FPHL) and government subsidies, we classified FPHL into two categories: quantitative loss and qualitative loss, based on existing studies [47]-[50]. To define the loss reduction efforts of supply chain members and considering the accessibility of realistic data, we proposed quality and quantity loss reduction levels, which reflect the FPHL reduction efforts in terms of both quality and quantity. Given the difficulty in obtaining data on food loss reduction costs, we proposed using food quality loss reduction costs and quantity loss reduction costs to represent food loss reduction inputs. Due to the lack of government subsidies, producers and retailers have insufficient incentives to reduce food losses, leading to ineffective food loss reduction. Our study suggests that increasing government subsidies would enhance the benefits for supply chain members, thus incentivizing them to reduce losses and making post-harvest loss reduction more effective.

2) Additionally, we modified the market demand function based on the discount coefficient of unit quantity loss and the improvement coefficient of unit quality loss. In contrast to existing studies[43][47] , which often assume market imbalances, we acknowledged that Chinese food supply and demand have been in a tight balance for a long time. We proposed that production equals demand, making our research hypothesis more consistent with reality. On this basis, we adjusted the market demand function to account for the impact of loss reduction efforts by supply chain members on the decline in food quality.

Compared to existing studies, our findings differ in the following ways. This paper introduces a government subsidy strategy for food supply chains adopting post-harvest loss reduction techniques, similar to the findings of scholars such as Yang Qin[23] and Andrea Cattaneo[38], who also concluded that government subsidies are essential for reducing post-harvest food loss. However, in this study, the government subsidy strategy is linked to the unit quantity loss discount factor and the unit quality loss improvement factor. We argue that the discount coefficient of unit quantity loss and the improvement coefficient of unit quality loss are positively correlated with the revenue of both the government and retailers.

V. Results

FPHL threatens national food security. To promote sustainable agricultural development and ensure food security, the Chinese government has introduced a series of policies aimed at reducing FPHL. However, profit-driven supply chain members have shown limited enthusiasm, and efforts to reduce FPHL remain insufficient. Therefore, it is crucial to formulate appropriate policies that motivate supply chain members to actively participate in loss reduction. Addressing this issue lies at the heart of the subsidies and investment rules for supply chain stakeholders.

In response to this challenge, we propose the concept and functional expressions for the discount factor of unit quantity loss and the improvement factor of unit quality loss, considering FPHL, and modify the grain demand function accordingly. We then introduce three FPHL-related investment and subsidy models: NEL, ENL, and ELB. Based on these models, we construct and analyze the investment and subsidy rules for supply chain members under different scenarios. This research enriches the investment decision-making theory and subsidy theory related to FPHL loss reduction technologies. Moreover, under various conditions, we derive investment and subsidy rules that can guide producers and retailers in making appropriate investment decisions. With government subsidies, both producers and retailers should actively invest in loss-reduction technologies to reduce FPHL. For the government, subsidies should be directed towards production, and appropriate subsidy strategies should be formulated to ensure the sustainable development of agriculture.

As a result of the analysis, the following conclusions were drawn:

1) After the adoption of loss reduction technologies, the returns of supply chain members is positively correlated with the government's production subsidy coefficient. Adopting different production subsidy factors can have an impact on the benefits of supply chain members, and after adoption loss reduction technologies, when the government subsidized, profits for producers and retailers are bound to rise.

2) After adopting the loss reduction technique, the discount coefficient of unit quantity loss is positively correlated with the government's income, the improvement coefficient of unit quality loss is positively correlated with the retailer's income. According to the subsidy analysis chart, it can be concluded that after adopting the loss reduction technology, the government's revenue increases with the increase of the unit quantity loss discount coefficient, and the retailer's revenue increases with the increase of the unit quality loss improvement coefficient.

3) In the ENL model, the equilibrium profit of supply chain members is maximized, and the effect of government subsidies is optimized. According to Figures 14 and 15 in the subsidy analyses, it could be concluded that under the ENL model. When only the producer adopted the loss reduction technology and the government subsidizes it, the benefits of the supply chain members were optimized as shown in the graph.

4) The government enhances its returns through subsidy policies that improve supply chain efficiency, with no negative impact from the subsidies. With the adoption of FPHL reduction technologies, government production subsidies will incentivize producers and retailers to reduce the food post-harvest loss, returns of the producer and the retailer would increase due to the FPHL reduction, and the social benefits to the government and its tax benefits would increase, but it needs to subsidize the producer and the retailer, which was an expenditure item, and therefore shown a negative trend. Only the total government revenues showed an increasing trend, subsidies were only viable.

To analyze the robustness of our findings, we will extend the three subsidy models proposed in this paper (models of PRC, PRR and PRCR). These three modes belong to the variable subsidy

There were some limitations to this study. Although we considered both the unit quantity loss and the unit quality loss of food, we do not discuss the coupling between output subsidies and other subsidies. In the next study, we focus on the coupling between output subsidies and loss-reduction subsidies. We also propose that in order to stimulate food the producer and the retailer to reduce FPHL more effectively, the government should subsidize the effort degree made by food firms to reduce FPHL. However, we have not conducted an in-depth study of the subsidy mechanism, and we can do so in the future as well.

APPENDIX

Appendix A

In the subsequent expressions make the following shown:

$$\frac{a}{4}+\frac{\beta}{4}-\frac{c}{4}+\frac{j}{4}+\frac{5\alpha_1 j}{4}-\frac{\alpha_2 j}{4}+\frac{j\alpha_1\alpha_2}{4}=E$$

Appendix A-1:

Proof: By assumption (5), we know that in the NEL model $D=a-p_i+e(1-\alpha_1)(1-\alpha_2)q_0$,and placing it in equation (2), Solving for the first partial derivative of π_r^{NEL} with respect to p^{NEL} and letting it equal zero, we can obtain $p^{NEL}(w^{NEL})$ .Then, putting $p^{NEL}(w^{NEL})$ into equation (1) and solving for the first partial derivative of π_p^{NEL} with respect to w^{NEL} so that it equals zero, we get w^{NEL*} .From w^{NEL*} and $p^{NEL}(w^{NEL})$, we ge p^{NEL*}.From w^{NEL*} and p^{NEL*}, we get π_r^{NEL*} , π_p^{NEL*} and π_g^{NEL*}.

Appendix A-2:

Proof: According to assumption (5), we know that in the ENL model $D=a-p_i+e(\beta_1)(1-\alpha_1)(1-\alpha_2)q_0$,and putting it into equation (7), Solving for the first partial derivative of π_r^{ENL} with respect to p^{ENL} and letting it equal zero, we can obtain $p^{ENL}(w^{ENL})$ .Then, putting $p^{ENL}(w^{ENL})$ into equation (6) and solving for the first partial derivative of π_p^{ENL} with respect to w^{ENL} so that it equals zero, we get w^{ENL*} .Based on w^{ENL*} and $p^{ENL}(w^{ENL})$, we get p^{ENL*}.Based on w^{ENL*} and p^{ENL*}, we get π_r^{ENL*} , π_p^{ENL*} and π_g^{ENL*} .

Appendix A-3:

Proof: According to assumption (5), we know that in the ELB model $D=a-p_i+e(\beta_1)(\beta_2)(1-\alpha_1)(1-\alpha_2)q_0$,and putting it into equation (17),Solving for the first partial derivative of π_r^{ELB} with respect to p^{ELB} and letting it equal zero, we can obtain $p^{ELB}(w^{ELB})$ .Then, putting $p^{ELB}(w^{ELB})$ into equation (16) and solving for the first partial derivative of π_p^{ELB} with respect to w^{ELB} so that it equals zero, we get w^{ELB*} .Based on w^{ELB*} and $p^{ELB}(w^{ELB})$, we get p^{ELB*} .Based on w^{ELB*} and p^{ELB*}, we get π_r^{ELB*} , π_p^{ELB*} and π_g^{ELB*} .

Appendix B

Appendix B-1:

Proof: By Proposition 1, we have that

$$① \frac{\partial p^{NEL*}}{\partial\beta}<0,\frac{\partial w^{NEL*}}{\partial\beta}<0,\frac{\partial\pi_r^{NEL*}}{\partial\beta}>0,\frac{\partial\pi_p^{NEL*}}{\partial\beta}>0,\frac{\partial\pi_g^{NEL*}}{\partial\beta}>0$$

Appendix B-2:

Proof: By Proposition 2, we have that

Inference 2:

$$① \frac{\partial p^{ENL*}}{\partial\beta}<0,\frac{\partial w^{ENL*}}{\partial\beta}<0,\frac{\partial\pi_r^{ENL*}}{\partial\beta}>0,\frac{\partial\pi_p^{ENL*}}{\partial\beta}>0,\frac{\partial\pi_g^{ENL*}}{\partial\beta}>0$$

$$② \frac{\partial p^{ENL*}}{\partial s_1}=0\ ,\frac{\partial w^{ENL*}}{\partial s_1}=0\ ,\frac{\partial\pi_r^{ENL*}}{\partial s_1}=0\ ,\ \frac{\partial\pi_p^{ENL*}}{\partial s_1}>0\ ,\frac{\partial\pi_g^{ENL*}}{\partial s_1}=0\ ;$$

$$③ \frac{\partial p^{ENL*}}{\partial\beta_1}>0,\frac{\partial w^{ENL*}}{\partial\beta_1}>0,\frac{\partial\pi_r^{ENL*}}{\partial\beta_1}<0,\frac{\partial\pi_p^{ENL*}}{\partial\beta_1}>0,\frac{\partial\pi_g^{ENL*}}{\partial\beta_1}>0$$

$$④ \frac{\partial p^{ENL*}}{\partial\delta_1}=0,\frac{\partial w^{ENL*}}{\partial\delta_1}=0,\frac{\partial\pi_r^{ENL*}}{\partial\delta_1}=0,\frac{\partial\pi_p^{ENL*}}{\partial\delta_1}>0,\frac{\partial\pi_g^{ENL*}}{\partial\delta_1}>0$$

Inference 2 can therefore be drawn from the proof of ①②③④.

Appendix B-3:

Proof: By Proposition 3, we have that

$$①\ \frac{\partial p^{ELB*}}{\partial \beta}=0, \frac{\partial w^{EL*}}{\partial \beta}=0, \frac{\partial \pi_r^{EL*}}{\partial \beta}>0, \frac{\partial \pi_p^{EL*}}{\partial \beta}>0, \frac{\partial \pi_g^{EL*}}{\partial \beta}>0$$

$$②\ \frac{\partial p^{EL*}}{\partial s_1}=0\ , \frac{\partial w^{EL*}}{\partial s_1}=0\ , \frac{\partial \pi_r^{EL*}}{\partial s_1}=0\ , \frac{\partial \pi_p^{EL*}}{\partial s_1}>0\ , \frac{\partial \pi_g^{EL*}}{\partial s_1}=0$$

$$③\ \frac{\partial p^{EL*}}{\partial \beta_1}>0, \frac{\partial w^{EL*}}{\partial \beta_1}>0, \frac{\partial \pi_r^{EL*}}{\partial \beta_1}>0, \frac{\partial \pi_p^{EL*}}{\partial \beta_1}>0, \frac{\partial \pi_g^{EL*}}{\partial \beta_1}>0$$

$$④\ \frac{\partial p^{EL*}}{\partial \delta_1}=0, \frac{\partial w^{EL*}}{\partial \delta_1}=0, \frac{\partial \pi_r^{EL*}}{\partial \delta_1}>0, \frac{\partial \pi_p^{EL*}}{\partial \delta_1}<0, \frac{\partial \pi_g^{EL*}}{\partial \delta_1}>0$$

$$⑤\ \frac{\partial p^{ELB*}}{\partial s_2}=0\ , \frac{\partial w^{ELB*}}{\partial s_2}=0\ , \frac{\partial \pi_r^{ELB*}}{\partial s_2}>0\ , \frac{\partial \pi_p^{ELB*}}{\partial s_2}=0\ , \frac{\partial \pi_g^{ELB*}}{\partial s_2}=0$$

$$⑥\ \frac{\partial p^{ELB*}}{\partial \delta_2}=0, \frac{\partial w^{ELB*}}{\partial \delta_2}=0, \frac{\partial \pi_r^{ELB*}}{\partial \delta_2}=0, \frac{\partial \pi_p^{ELB*}}{\partial \delta_2}>0, \frac{\partial \pi_g^{ELB*}}{\partial \delta_2}>0$$

$$⑦\ \frac{\partial p^{ELB*}}{\partial \beta_2}>0, \frac{\partial w^{ELB*}}{\partial \beta_2}>0, \frac{\partial \pi_r^{ELB*}}{\partial \beta_2}>0, \frac{\partial \pi_p^{ELB*}}{\partial \beta_2}>0, \frac{\partial \pi_g^{ELB*}}{\partial \beta_2}>0$$

Appendix C

Appendix C-1:

Proof:

$$①\ \frac{\partial p^{NEL*}}{\partial \beta}<0\ , \frac{\partial w^{NEL*}}{\partial \beta}<0\ , \frac{\partial \pi_r^{NEL*}}{\partial \beta}=0, \beta=c-a+eq_0(\alpha_1-1)(1-\alpha_2)=S\ ,$$

when $\beta>S, \frac{\partial \pi_r^{NEL*}}{\partial \beta}>0,$

$$\frac{\partial \pi_p^{NEL*}}{\partial \beta}=0, \beta=c-a+eq_0(1-\alpha_1)(\frac{1}{2}+\alpha_2)=F\ ,$$

when $\beta>F, \frac{\partial \pi_p^{NEL*}}{\partial \beta}>0$, $\frac{\partial \pi_g^{NEL*}}{\partial \beta}=0,$

$$\beta=\frac{\begin{array}{l}3(a-c)-(3\lambda_1+\lambda_2)(2a+2c)-3m(2\alpha_1-\alpha_2-2)\\ -m(2\lambda_2-3f)+2n(a-c)+2m\alpha_1\lambda_2\\ +2m(3\lambda_1+\lambda_2)(\alpha_1-f)-2mn(\alpha_1+\alpha_2+f-1)\end{array}}{6\lambda_1+2\lambda_2-2n+1}=K$$

In this case, F>S, and K>F are obtained.

Appendix D

TABLE II
SUMMARY OF CHINA'S POLICIES TO REDUCE POST-HARVEST LOSS OF FOOD

Date	POLICY TITLE	POLICY CONTENT
2015	Construction Plan for Grain Collection, Storage and Supply Security Project (2015-2020)	The issue of serious post-harvest loss and waste of grain has been raised. In order to effectively safeguard national food security and implement the "national food security strategy based on us, domestic production capacity, moderate imports, and scientific and technological support", it is necessary to urgently promote the construction of the "Food Security Project" and comprehensively enhance the capacity of food collection, storage, and supply security.
2017	Opinions of the General Office of the Central Committee of the Communist Party of China and the General Office of the State Council on the Strict Exercise of Economy and Opposition to Food Waste	It is required to strengthen the management of food drying, storage, and processing to effectively reduce post-harvest loss and ensure food security and effective supply.
2018	Opinions of the State Council of the Central Committee of the Communist Party of China on the Implementation of the Rural Revitalization Strategy and Opinions of the General Office of the State Council on Further Promoting the Development of the Agricultural Products Processing Industry	To further promote the transformation and upgrading of China's agricultural products processing industry, to promote the high-quality development of the agricultural and rural economy, and to provide new momentum for the revitalization of the countryside, the construction of food drying and storage centers and fruit and vegetable processing centers is mentioned in the coordinated development to encourage the reduction of post-harvest loss and to enhance the level of commercialization.
2021	The Jinan Initiative of the International Conference on Food Loss Reduction	Initiatives to upgrade agricultural infrastructure and strengthen comprehensive food production capacity. Reducing food loss and waste requires a holistic and whole-chain approach.
2021	Food Conservation Action Program	Targeted initiatives were proposed in all aspects of production, storage, transportation, processing and consumption around the outstanding problems of food loss and waste.

Data source: http://www.moa.gov.cn/ and http://www.lswz.gov.cn/.

TABLE III
SUMMARY OF RELEVANT FOOD SUBSIDY POLICIES IN CHINA

Date	POLICY TITLE	POLICY CONTENT
2002	Subsidies for good seeds	Subsidies to farmers through the promotion of good seeds, as well as the popularization of good seeds and supporting technologies
2004	Agricultural machinery subsidies	Agricultural producers who purchase agricultural machinery can receive subsidies to increase the level of agricultural mechanization. A percentage of the subsidy is usually provided based on the value of the agricultural machinery.
2004	Direct subsidies to food	Subsidies will be provided to food producers to encourage them to grow more food. The subsidies are provided based on the area planted.
2006	Comprehensive Subsidy	This subsidy is primarily intended to compensate for the rising cost of the means of production.
2016	"Four subsidies"	Such subsidies include subsidies for quality seeds, subsidies for the purchase of agricultural machinery, direct food subsidies,and comprehensive subsidies.

Data source: http://www.moa.gov.cn/ and http://www.lswz.gov.cn/

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