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<https://doi.org/10.1057/s41599-023-01874-w>

OPEN

A flexible and efficient hybrid agricultural subsidy design for promoting food security and safety

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The quantity and quality of edible agricultural products are critical for food security (quantity) and safety (quality). Supplying consumers with enough safe food is the key responsibility of food production firms. Still, this aim is not always guaranteed because of input capacity constraints and other limitations in the agricultural sector. A hybrid subsidy, a mix of quantity and quality subsidy, could help achieve food security and safety in a country its flexibility. However, the advantages of the hybrid have not been fully investigated. Thus, this paper designs a hybrid subsidy for edible agricultural products by considering cost uncertainties and input resource constraints. All conclusions are obtained by theoretical mathematical analysis. (1) equilibrium solutions under different conditions—cost uncertainties and input constraints—are obtained, and comparative analyses is offered. (2) the results show that the hybrid subsidy is convenient in the trade-off between food quantity and quality, which means a hybrid subsidy policy design is flexible and efficient for food security and safety. (3) cost uncertainties and input resource constraints have significant impacts on the efficiency of the hybrid subsidy. Findings show that the hybrid subsidy is ideal for supporting edible agricultural products. Additionally, we argue that cost uncertainties and input constraints should be considered when making policy efficiency evaluations. This study has a novel contribution to agricultural support policy design.

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Introduction

A subsidy is widely used for environmental protection (Erickson et al., 2020; Chen et al., 2017), innovation stimulation (McRae, 2015; Rotemberg, 2019), industrial development and agricultural production (Pe'er et al., 2019; Chen et al., 2020). The economic foundation character of agriculture makes it the key sector subsidized by the government. The latest data from the Organization for Economic Cooperation and Development (OECD) show that the agriculture sector received billions of dollars from the government in developed or developing countries. For example, the total support estimate (TSE) for agriculture in China, EU28 and the United States are 243, 123, and 99 billion US Dollars, respectively, in 2019.

Green agriculture development needs a more efficient and green-oriented subsidy system (Pe'er et al., 2019). In increasing agricultural output, governments worldwide have enacted policies in the agricultural sector that encourage farmers to use excessive and highly efficient inputs, such as high polluting fertilizers and pesticides. Output-oriented agriculture caused serious pollution problems, depleted soil fertility, and damaged the ecological environment, especially in developing countries, including China. The current subsidy system exacerbates the problem (Chen et al., 2020; Scholz and Geissler, 2018). Since 2017, green and high-quality development has been the goal of Chinese agriculture (Shen et al., 2020). Just as chairman Xi said, "Clear waters and green mountains are as good as mountains of gold and silver."

Effective subsidy policies are quite helpful in green agricultural development. Most agricultural subsidy programs aim to increasing output quantity (Fan et al., 2023), but edible agricultural product defined as food plants, livestock, fishery products and primary processed products, quality safety is a major issue for green agriculture and high-quality development and residents' health (Li et al., 2015; Matyjaszczyka and Śmiechowska, 2019). Thus, both quantity and quality should be taken into consideration for the governments to implement agricultural support policy. Other issues that have significant impact on agricultural output are uncertainty and input constraints. Additionally, both uncertainty and input constraints significantly impact the efficiency of agricultural subsidy policies (Chen et al., 2017; Chen et al., 2020). To the best of our knowledge, several types of subsidy policies have been employed in the agricultural sector, such as outputs subsidy, input subsidy, and price support (Chavas et al., 2022; Deaton and Lawley, 2022), but hybrid subsidy is rarely mentioned.

Hybrid subsidy, a mix of quantity subsidy and quality subsidy, is a more effective and reasonable agricultural support policy for that it can make a trade-off between food quantity and quality conveniently. In 2016, the Ministry of Agriculture and Rural Affairs of the People's Republic of China (MARA) merged direct subsidy for grain farmers, subsidy for improved crop varieties and comprehensive subsidy for agricultural materials into agricultural support and protection subsidy (ASPS). The ASPS policy can be seen as a hybrid subsidy because direct subsidy for grain farmers is output-oriented, while subsidy for improved crop varieties and comprehensive subsidy are input-oriented. For more details about the ASPS reform, please see the website of the Ministry of Agriculture and Rural Affairs of the People's Republic of China (<http://english.moa.gov.cn/>). The purpose of ASPA is to promote green agricultural development, that is, to ensure food security while improving the quality of agricultural development. However, only a few studies assessed the feasibility of a hybrid subsidy (Fan et al., 2023; Yu et al., 2022; Chen et al., 2021). For example, Chen et al. (2021) investigated the effects of hybrid subsidy on renewable energy promotion and declared that hybrid subsidy is flexible, while Fan et al. (2023) shown that a hybrid agricultural subsidy, combined planting and harvesting

has the advantage to achieve the target with the least amount of government budget.

The hybrid subsidy is a mixture of quantity and quality subsidies that policymakers can enact for food security (quantity of food) and food safety (quality of food). Therefore, the objective of this study is to design and assess the feasibility of hybrid subsidy. In addition, we also present analyses of a hybrid subsidy in the presence of cost uncertainties and input constraints. We argue that hybrid subsidy is a more flexible and efficient agricultural policy for green agriculture and high-quality food item development. Note that quality is not equal to safety because food quality consists of different dimensions and not all dimensions influence food safety. Therefore, quality in this study only includes dimensions that have a direct impact on food safety.

The basic model employed in this is quite general and can be applied in other sectors. Still, it has the highest application efficiency in agriculture, especially in the edible agricultural product sector for food (crop) safety (security) is the fundamental safety strategy for a responsible government. And no industry can get as much government support as agriculture, no matter in developed countries or developing countries (see Fig. 1). Therefore, this study focuses on the application of food security and safety for edible agricultural products.

The novel contributions of this paper are threefold. First, we design a hybrid subsidy policy, subsidies are paid based on both quantity and quality of food outputs for edible agricultural products support. Both quantity security and quality safety are critical for consumers, and hybrid subsidy is flexible and efficient for the trade-off between security and safety. Second, we consider the impacts of cost uncertainty and input constraints on the efficiency of hybrid subsidy. Cost uncertainty is isolated into quantity of product uncertainty and quality investment uncertainty. Both uncertainties have significant influences on the equilibrium output and subsidy efficiency. Finally, this study captures the effects of input constraints on the efficiency of the hybrid subsidy. Input resource constraint is another key factor that impacts a firm's output decision. Furthermore, there are three different choices for the firm under input constraints: equal priority between quantity and quality, quantity priority, and quality priority. More importantly, the results of this study can be taken as important theoretical support for the ASPA policy reform of China.

The remainder of this paper is organized as follows. The following section presents the literature review. Next is the basic model and analyses section. And then the expansion analysis section is presented. The final section presents discussions and conclusions. The additional calculation process is shown in the supplementary information.

Literature review

Agricultural subsidy is a quite controversial government policy. On the one hand, a farming subsidy is essential for securing food and rural development (Huang et al., 2013; Jordan et al., 2007). On the other hand, it causes market distortions (Anderson and Swinnen, 2010; Anderson et al., 2013). An agricultural subsidy is employed by most of the counties. See Fig. 1 for total support for agriculture in the form of subsidies that is spent around the world. Countries worldwide have been reforming their agricultural production system and constantly exploring agricultural subsidy policies that are suitable food security and agricultural development (Graddy-Lovelace and Diamond, 2017; Garrone et al., 2019). To improve the national food self-sufficiency and rural household incomes, China began to provide subsidies to farm households in 2004, and subsidies became a major support

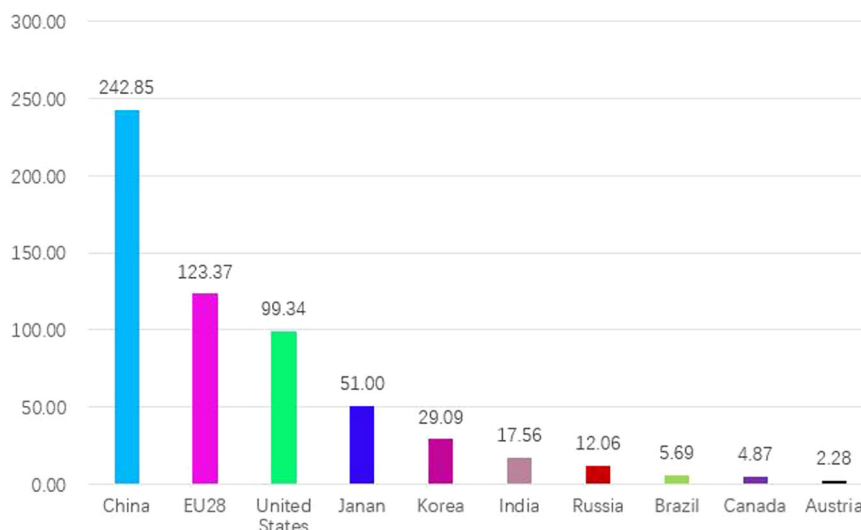


Fig. 1 Total support estimate (TSE) for agriculture (billion US Dollar). Top 10 highest TSE for agriculture in 2019. Both developed countries such as the United States and developing countries such as China support huge subsidies to agriculture. Notes: The figure is based on the data of OECD. Stat 2019 (<https://stats.oecd.org/>).

policy for agriculture (Huang et al., 2013). Different types of agricultural subsidies, such as input subsidy, output subsidy, and price support, are used by other countries (Scholz and Geissler, 2018; Bojnec and Latruffe, 2013). Recently, consistent with the WTO rules, the decoupled subsidy is more prevalent among countries in the WTO (Gibson and Luckstead, 2017).

Most government subsidies, whether for agriculture or other sectors, are quantity and price-oriented. However, only a few studies have investigated the effects of the subsidy on quality. For example, based on the monopolist concept, Nauleau et al. (2015) studied the differences in the energy efficiency of different types of subsidies. The authors concluded that hybrid subsidy policy to be superior. They also argued that single-instrument subsidy can only achieve second-best outcomes. More importantly, their study showed that the subsidy of the high-end goods induces the monopolist to reduce the quality of the low-end good. In other words, subsidy impacted the quality of output quality. In another study, Shin and Kim (2010) investigated the effect of the subsidy on product quality. The authors employed three different subsidy policies under monopoly: constant subsidy, quality matching subsidy, and time-limited subsidy. They concluded that all subsidy policies guarantee quality product development. They show that the matching fund style subsidy is more efficient than the constant subsidy.

Meanwhile, the authors argued that time-limited subsidy improves the quality of products much faster than other subsidy delivery methods. Interestingly, Li and Li (2018) captured the effect of cross-subsidy on utility service quality under the condition that the government may not fully cover the firm's deficit from subsidizing poor households. The authors also found that the firm will reduce quality for subsidized consumers if the government transfers cannot cover the firm's loss. McRae (2015) concluded the subsidy deter quality infrastructure investment, referred to as the "subsidy trap". Wang and Yan (2017) argued that the government should offer both quantity and quality subsidies to guarantee food security and safety.

Concerning the efficiency of agricultural subsidy, studies argue that uncertainty and input constraints have critical impacts on the efficiency of agricultural subsidy. For instance, Cohen et al. (2016) investigated the effect of demand uncertainty on consumer subsidy. They found that an increase in demand uncertainty increased output quantities and lowered prices, resulting in lower

profits. Of course, agricultural support policy itself is uncertain, and a lack of complete information on subsidy policies may lead to inefficiency (Lagerkvist, 2005). For example, Sckokai and Moro (2006) studied the impact of price uncertainty on the decision-making of crop producers in the European Union. The authors concluded that the European Union (EU) should implement subsidy partially decoupled. The authors argue that the EU should eliminate crop-specific payment and replace it with a single farm payment.

Similarly, input resource constraints will lead to different results on the quantity and quality of output (see Esó et al., 2010; Chen et al., 2018a, 2018b). For example, Dervillé and Allaire (2014) investigated the impact of input resource constraints on the quality and quantity of milk supply. The authors concluded that dairy farmers could increase the quality and quantity of milk supply through investment in input capacity expansion. Another research on the milk industry shows that due to input constraints, the high-quality amount of input resources, and the rapid growth of demand will likely cause production limits. Such actions could lead to adulteration and fraud in milk processing companies and result in food safety incidents (Chen et al., 2014; Chen et al., 2023).

The studies mentioned above have focused on agricultural subsidy. Still, none of the studies in the literature have investigated the impact of subsidies on quality, not to mention the quality-oriented subsidy policy. Further, some studies implied that uncertainty and input resource constraints affect firm's decision and the efficiency of subsidy. This study tries to fill the gaps and captures the effects of hybrid subsidy by taking both cost uncertainties and input resource constraints. Finally, a total of eight different conditions are considered, compared, and emphasized in this study.

Basic model

Assumption. Quantity and quality are two major elements that consumers are concerned about when purchasing food items (Dai & Wu, 2023; Tyagi, 2023). Quality and quantity output decision are depended on each other. Unfortunately, most quality studies ignored the quantity issue. There is no sense of analyzing quality without the concern of quantity. Besides, quality issue will only be considered when residents are able to obtain sufficient quantities

of food. The governors should consider the effects of food safety governance policies on both quality and quantity. So, different from other studies, this paper employs a hybrid subsidy policy on food safety governance and quantity and quality are the two major output variables for the firm.

The supply and demand theorem knows that food prices decrease with quantity but increase with quality. So, the food equilibrium price is influenced both by quantity and quality. Similar to (Chen et al., 2018a; Chen et al., 2018b), this study employed the following inverse demand function to capture the impacts of food quantity and quality on equilibrium:

$$p = \alpha + \beta q - x. \tag{1}$$

In Eq. (1), p , x , and q represent price, quantity, and quality, respectively. Additionally, α represents the market capacity or highest market price. Notice that β is the marginal price contribution of food quality. Easy know $\partial p/\partial x < 0$ and $\partial p/\partial q > 0$. Furthermore, it assumes that $\alpha \gg 0$ which means market capacity should be large enough, or firm will exit the market.

As both consumers and the government are concerned about food safety issues, including quantity security and quality safety, this study supposes that the government will support food production firms with quantity subsidies, quality subsidies, or both. Quantity subsidy is common in many industries, such as the new energy vehicle industry. For example, to reduce greenhouse gas emissions, the Chinese government will offer the consumer a subsidy to encourage new energy vehicle purchases. However, a quality subsidy is not common, for that quality is difficult to observe. But if defining $q = Ai$ and i representing quality improves innovation, then quality subsidy in this study can be taken as an innovation subsidy, usually employed by the government to stimulate innovation. A monopoly market is not typical for the agricultural sector in many countries, but the effects of competition on the conclusions found in this paper are weak. So, this paper employs a monopoly structure similar to Lim and Yurukoglu (2018) and Nava and Schiraldi (2019). Therefore, a food products firm is subjected to the following function:

$$\pi = (\alpha + \beta q - x)x - c(x, q) + \gamma sx + (1 - \gamma)sq \tag{2}$$

Here, π represents the firm's profits; s is the subsidy intensity, while γ is quantity-oriented subsidy ratio and $1 - \gamma$ indicates quality-oriented subsidy ratio. This paper has $0 < s < 1$ and $0 < \gamma < 1$. An extreme subsidy intensity $s > 1$ is possible especially for quality, but excessive subsidy intensity may lead to rent-seeking behavior or cultivate inefficient producers just like high welfare will cultivate lazy people (Cooley et al., 2021). So, in economics field, the subsidy intensity is always assumed to be $0 < s < 1$ (Casey, 2023; Yang & Nie, 2022). $0 < \gamma < 1$ means hybrid subsidy; $\gamma = 0$ represents pure quality subsidy and $\gamma = 1$ means pure quantity subsidy. γ is an exogenous variable for the firm because is determined by the regulator and dependent on the regulation purposes. However, subsidy ratio in hybrid policy can also be taken as an endogenous variable if one wants to capture the optimal behavior of the regulator, while that is not concern in this study.

Assume $c(x, q)$ the cost function of the firm. Quadratic cost function is common in economics research for the convenience of analysis (see Darai et al., 2010; Sacco & Schmutzler, 2011). Generally, if both quantity and quality are endogenous variables, then there is an interactive effect between them on costs. It is more difficult to raise quality as quantity increase and vice versa. However, consider this interaction will make the model more complex, while the focus of this study is subsidies. So, we ignore the interaction between quantity and quality in cost function and further assume that quantity and quality are symmetric in the cost function. Therefore, the only concern for cost function is its

convexity. Similar to Chen et al. (2018a), Chen et al. (2018b), this study employs $c(x, q) = \frac{1}{2}x^2 + \frac{1}{2}q^2$ as the cost function for the firm. The cost function in this study is a special case of $c(x, q) = \frac{1}{m}x^m + \frac{1}{n}q^n$ and the values of m and n impact the results. We don't want to spend too much attention in discussing the cost function and for the university of quadratic structure, this paper only focused on $c(x, q) = \frac{1}{2}x^2 + \frac{1}{2}q^2$. This convex cost function guarantees the existence of optimal solutions based on cost minimization for quantity and quality. Other parameters are the same as Eq. (1).

The cost function implies a further assumption about the marginal effect of quality on price, $1 < \beta < 2$. On the one hand, $\partial \pi / \partial q = \beta x - q$ should be not too small, otherwise firm will have no stimulation to quality innovation. Thus, to make thing simple, we add the assumption $\beta > 1$, on the other hand, it should also not too large, or price in equilibrium will too high to perchance and quality subsidy will make no sense. So, we further assume $\beta > 2$ based on the reality that organic production's price is near twice as the price of the general food, while the marginal effect of organic food can be taken as the upper bound. The basic model set above will be solved under three different cases: hybrid subsidy, pure quality subsidy, and pure quantity subsidy.

Hybrid subsidy. Hybrid subsidy means $0 < \gamma < 1$ and the government subsidizes the food product firm with quantity and quality subsidies. Then the quantity, quality, and price in equilibrium for function (2) are:

$$\begin{cases} x^H = \frac{\alpha + [(1-\gamma)\beta + \gamma]s}{3 - \beta^2}, \\ q^H = \frac{\alpha\beta + [3(1-\gamma) + \gamma]\beta s}{3 - \beta^2}, \\ p^H = \frac{2\alpha + [2(1-\gamma)\beta - (1-\beta^2)]\gamma s}{3 - \beta^2}. \end{cases} \tag{3}$$

Quality subsidy. Quality subsidy means the government only supports the food product firm with quality subsidy. In this case, it has $\gamma = 0$, and function (2) indicates the following equilibrium solutions:

$$\begin{cases} x^0 = \frac{\alpha + \beta s}{3 - \beta^2}, \\ q^0 = \frac{\alpha\beta + 3s}{3 - \beta^2}, \\ p^0 = \frac{2\alpha + 2\beta s}{3 - \beta^2}. \end{cases} \tag{4}$$

Quantity subsidy. Correspondingly, if the government employs quantity subsidies for the food product industry, then it knows that $\gamma = 1$. And resolve function (2), it obtains the following solutions:

$$\begin{cases} x^1 = \frac{\alpha + s}{3 - \beta^2}, \\ q^1 = \frac{(\alpha + s)\beta}{3 - \beta^2}, \\ p^1 = \frac{2\alpha - (1 - \beta^2)s}{3 - \beta^2}. \end{cases} \tag{5}$$

Equations (3)–(5) achieve the following proposition about the relationships for equilibrium solutions under the three cases.

Proposition 1 $x^0 \leq x^H \leq x^1$, $q^1 \leq q^H \leq q^0$ and $p^1 \leq p^H \leq p^0$.

Conclusions in proposition 1 show that subsidy has stimulation effects, which are consistent with the reality. If the government cares more about food security, it will implement quantity subsidy policy; if the supervisor concerns more about food safety, it will enforce quality subsidy. However, both security and safety are important for the residents, so a hybrid subsidy policy is most suitable for food product industry regulation. Unlike car,

cellphone and other general commodities, food is a special good which has the minimum consumption quantity and quality for residents. Both high quality with low quantity and low quality with high quantity are detrimental to residents. There is no sense to discuss quality without quantity, or quantity without quality. So, the governors should stimulate firms to enhance food quality based on a certain quantity output. On the one hand, quality subsidy leads to a higher quality as well as a higher price. Notice that most consumers are food price-sensitive, it should be prudent for quality subsidy. On the other hand, food quality (safety) is a quasi-public good need government regulation to guarantee the optimal or minimum effective quality. Please see the proof of proposition 1 in the supplementary information.

Equation (3) also implies the following proposition.

Proposition 2 $\frac{dx}{dy} > 0, \frac{dq}{dy} < 0, \frac{dp}{dy} < 0; \frac{dx}{d\beta} > 0, \frac{dq}{d\beta} > 0, \frac{dp}{d\beta} > 0; \frac{dx}{ds} > 0, \frac{dq}{ds} > 0, \frac{dp}{ds} > 0$ if $0 \leq \gamma \leq \bar{\gamma}$ and $\frac{dp}{ds} < 0$ if $\bar{\gamma} < \gamma \leq 1$.

Both quantity and quality subsidy are double-edged swords. Quantity subsidy increases the output quantity of food product firms and reduces the equilibrium price, but it also reduces food quality at the same time. And the effects of quality subsidy on equilibrium quantity, quality and price are just opposite to quantity subsidy because the subsidy ratios of are substitution (or $d(\cdot)/d(1-\gamma) = -d(\cdot)/d\gamma$). On the one hand, there is a trade-off between quantity (food security) and quality (food safety) for the government to implement a quantity or quality subsidy. On the other hand, regulators can offset each other's negative impacts by implementing both quantity and quality subsidies simultaneously. Those conclusions imply hybrid subsidy is suitable for food industry regulation. Notice that the improvement of marginal price contribution of quality will stimulate the firm to increase output quantity and quality.

The policy implication for this is that the government should help food product firms improve their reputation because reputation will enhance marginal price contribution of quality. Similar to the effects of marginal price contribution of quality, subsidy intensity increases both quantity and quality, which means the government should increase support to food products. Different from other industries, food product industry has more influence on residents' health. Interestingly, there is an inverse-U shape between subsidy intensity and food price, which is deepened on the ratio of quantity subsidy. If the quantity subsidy ratio is low, then food price will increase with subsidy intensity and vice versa. Please see the proof of proposition 2 in the supplementary information.

Welfare analysis. The effects of the subsidy on social welfare, including consumer surplus (CS), producer surplus (PS), government budget (TS) and total social welfare (SW), are addressed here. Definitions: $CS = \int p(x, q)dx - px$, $PS = \pi$, $TS = \gamma sx + (1-\gamma)sq$ and $SW = CS + PS - TS$. Then the following proposition is achieved.

Proposition 3 $\frac{dCS}{dy} > 0, \frac{dPS}{dy} > 0, \frac{dTS}{dy} > 0, \frac{dSW}{dy} > 0; \frac{dCS}{d\beta} > 0, \frac{dPS}{d\beta} > 0, \frac{dTS}{d\beta} > 0, \frac{dSW}{d\beta} > 0; \frac{dCS}{ds} > 0, \frac{dPS}{ds} > 0, \frac{dTS}{ds} > 0, \frac{dSW}{ds} > 0$.

Proposition 3 captures the influences of the three key parameters, quantity subsidy ratio, marginal price contribution of quality and subsidy intensity, on the major welfare measures, including CS, PS, TS and SW. The conclusions of Proposition 3 show that all welfare variables increase with quantity subsidy ratio, marginal price contribution of quality and subsidy intensity. Although increasing food product subsidies increase government budget costs, it improves CS, PS, and SW. Compared with the free competitive market, the subsidy would decrease welfare because of deadweight losses resulting in price distortion. But subsidy here has no direct impact on price. And the positive effects of the subsidy on CS and PS are higher than on TS, so we conclude that

the subsidy increase SW. So, under financial budget constraints, the government should increase food product subsidies. However, growing subsidies increase the financial budget, leading to a constraint on the government for its revenue limitation. Proposition 3 implies that pure quantity subsidy leads to the highest welfare because increasing the quantity subsidy ratio improves CS, PS and SW. Please see the proof of proposition 3 in the supplementary information.

Expansion analysis

Scarcity, such as input resource constraints and uncertainty, are two typical features of edible agricultural product firm operations. This paper will consider input constraints and uncertainty to model the firm's decision.

Input constraints. Input constraints mean food product firms cannot obtain enough input resources to make quantity and quality decisions based on first-order optimal conditions. Under input constraints, the firm must make a trade-off between output quantity and quality. Furthermore, input constraints can be isolated into three different types: equal priority (EC), quantity priority (XC), and quality priority (QC). EC means food firm takes quantity and quality equality under input constraints, and XC implies that firm priority satisfies quantity needs. QC represents firm priority and satisfies quality needs when it makes output decisions.

(1) **Equal priority.** Suppose the total input resources that the firm can use for food products is $R (R < \alpha)$, which is less than that under optimal conditions. Generally, a firm needs more than one type of input resource to produce, but those different inputs are standardized to R (or R can be taken as an input portfolio). Then it has $x + kq = R$ under input constraint. k represents resource conversion efficiency of quality and, larger k means lower conversion efficiency. To simplify the study, we standard the resource conversion efficiency of quantity to 1. Furthermore, this study assumes $1 \leq k \leq 2$ that one-unit quality needs more resources than one quantity or quality is higher in resource depletion. Under equal priority case, function (2) is rewritten as:

$$\pi = (\alpha + \beta q - x)x - \frac{1}{2}x^2 - \frac{1}{2}q^2 + \gamma sx + (1 - \gamma)sq, \tag{6}$$

s.t. $x + kq = R$.

Solve function (6) has the following solutions in equilibrium:

$$\begin{cases} x^{EC} = \frac{(1+\beta k)R+k^2\alpha+[ky-(1-\gamma)]ks}{1+3k^2+2\beta k}, \\ q^{EC} = \frac{(3k+\beta)R-k\alpha-[(1+k)\gamma-1]s}{1+3k^2+2\beta k}, \\ p^{EC} = \frac{(1+2k^2+k\beta)\alpha+(2\beta k+\beta^2-1)R+(k+\beta)(1-\gamma)ks}{1+3k^2+2\beta k}. \end{cases} \tag{7}$$

(2) **Quantity priority.** Under quantity priority case, the restriction for food product firms is $kq = R - x$. Resolve function (2) has:

$$\begin{cases} x^{XC} = \frac{\beta R+k\alpha+k\gamma s}{3k+\beta}, \\ q^{XC} = \frac{3R-\alpha-\gamma s}{3k+\beta}, \\ p^{XC} = \frac{(2\alpha-s\gamma)k+2\beta R-\beta\gamma s}{3k+\beta}. \end{cases} \tag{8}$$

(3) **Quality priority.** Quality priority implies $x = R - kq$. It has the following equations by solving function (2):

$$\begin{cases} x^{QC} = \frac{R-(1-\gamma)ks}{1+\beta k}, \\ q^{QC} = \frac{\beta R-(1-\gamma)s}{1+\beta k}, \\ p^{QC} = \frac{(1+\beta k)\alpha-(1-\beta^2)R+(1-\gamma)(k+\beta)s}{1+\beta k}. \end{cases} \tag{9}$$

Comparing the equilibrium solutions under three different cases have the following proposition.

Proposition 4 $x^{QC} < x^{EC} < x^{XC}$, $q^{XC} < q^{EC} < q^{QC}$ and $p^{XC} < p^{EC} < p^{QC}$.

The equilibrium quantity, quality, and price relationships under different cases are outlined in Proposition 4. We learn from Proposition 4 that the food quantity in equilibrium is the highest under the quantity priority case, while the quality and price are the lowest. All the quantity, quality, and price are at the medium level for equal priority. Thus, the supervisor should convince the food product firm to take quantity and quality equally under input resource constraints to balance food security and food safety. Furthermore, combining the conclusions in Proposition 1 and 4, we learn that to keep a balanced food regulation policy, the government should offer quantity priority preference firms with quality investment to offset the negative effect of input constraints on food quality, and vice versa. More critically, food safety risks can result in input capacity constraints besides information asymmetry. The corresponding policy implication is that the regulator should expand the punitive regulations to an incentive approach because information asymmetry and input capacity constraints negatively impact quality. Another study shows that a penalty can only relieve the effects of information asymmetry, while a reward has the advantage of handling the negative effects of input constraints (Chen et al., 2023). The equilibrium quantity and quality under six different conditions above are outlined in Fig. 2.

For the social welfare of different conditions, it has the following proposition.

Proposition 5 (i) $CS^{QC} < CS^{EC} < CS^{XC}$, $PS^{QC} < PS^{EC} < PS^{XC}$, $SW^{QC} < SW^{EC} < SW^{XC}$, and (ii) define $\bar{\gamma} = \frac{1}{1+k}$, then $TS^{XC} < TS^{EC} < TS^{QC}$, if $\gamma \leq \bar{\gamma}$; $TS^{QC} < TS^{EC} < TS^{XC}$, if $\gamma > \bar{\gamma}$.

All the CS, PS and SW are the highest under quantity priority input constraints condition, while they are the lowest under quality priority case. And interestingly, equal priority results in an intermediate welfare level. Noting that quality priority results in the lowest consumer surplus, the regulator should not always just be concerned about the quality but make a balance between quantity and quality from the social welfare maximization perspective. From the definitions and measurement of consumer utility and surplus, we know that although improved food quality increases consumer utility, consumer surplus is independent of quality. But the relationships between total subsidies are uncertain, which depends on the quantity subsidy ratio. Proposition 5 also shows that the resource conversion efficiency impacts the total subsidy costs of the government because the threshold value for the relationships among total subsidies

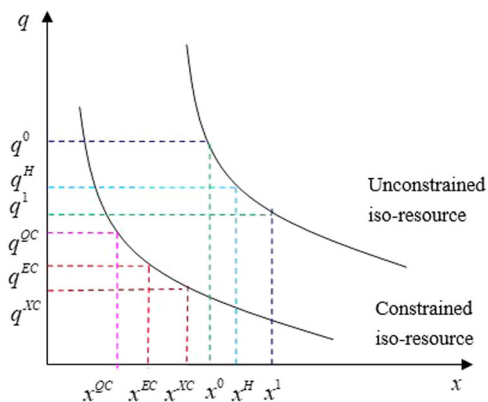


Fig. 2 Iso-resource curve and equilibrium quantity and quality of different conditions. The horizontal axis represents quantity, and the vertical axis represents quality. Input constraints is a major factor quality decrease as well as food fraud. Quantity priority firm confronted with input resource constraints will have the lowest output quality.

depends on the resource conversion efficiency. Please see the proof of proposition 5 in the supplementary information.

Cost uncertainty. Our real world is full of uncertainty and risk. Uncertainty is not necessarily bad for a firm. Still, it significantly influences the firm’s decisions and profit, while cost uncertainty is one of the major uncertainties a firm faces. So, this section is focused on cost uncertainty. This study separates cost uncertainty into quantity and quality cost uncertainty for the representative firm to simultaneously make quantity and quality decisions. It defines θ the uncertainty variable, which obeys the uniform distribution of $[\underline{\theta}, \bar{\theta}]$ with density function $f(\theta)$. This paper further assumes that $E(\theta) = 1$, $f(\theta) \geq 0$ and $\int_{\underline{\theta}}^{\bar{\theta}} f(\theta) d\theta = 1$. $\theta < 1$ means the good condition and $\theta > 1$ represents a bad situation. To simplify the calculation, this paper considers $\theta \in [\frac{1}{2}, \frac{3}{2}]$ the likes of Chen et al. (2020).

(1) **Quantity cost uncertainty.** Under quantity cost uncertainty, the cost function of the firm is $c(x, q, \theta) = \frac{\theta}{2}x^2 + \frac{1}{2}q^2$, and function (2) is rewritten as:

$$\pi = (\alpha + \beta q - x)x - \frac{\theta}{2}x^2 - \frac{1}{2}q^2 + \gamma sx + (1 - \gamma)sq. \tag{10}$$

Then the equilibrium solutions for function (10) are outlined as follows:

$$\begin{cases} x^{XU} = \frac{\alpha + [(1-\gamma)\beta + \gamma]s}{2 + \theta - \beta^2}, \\ q^{XU} = \frac{\alpha\beta + [(1-\gamma)(2-\theta) + \gamma]\beta s}{2 + \theta - \beta^2}, \\ p^{XU} = \frac{(1+\theta)[\alpha + (1-\gamma)\beta s] - (1-\beta^2)\gamma s}{2 + \theta - \beta^2}. \end{cases} \tag{11}$$

And the corresponding expected values are:

$$\begin{cases} E(x^{XU}) = \alpha + [\gamma + (1-\gamma)\beta]s[\text{Log}(7-2\beta^2) - \text{Log}(5-2\beta^2)], \\ E(q^{XU}) = (1-\gamma)s + \{\alpha + [(1-\gamma)\beta + \gamma]s\}[\text{Log}(7-2\beta^2) - \text{Log}(5-2\beta^2)], \\ E(p^{XU}) = \alpha + (1+\gamma)\beta s - (1-\beta^2)\{\alpha + [(1-\gamma)\beta + \gamma]s\}[\text{Log}(7-2\beta^2) - \text{Log}(5-2\beta^2)]. \end{cases} \tag{12}$$

(2) **Quality cost uncertainty.** Like quantity cost uncertainty, the cost function under quality cost uncertainty is $c(x, q, \theta) = \frac{1}{2}x^2 + \frac{\theta}{2}q^2$. Then, it has the equilibrium solutions under quality cost uncertainty as:

$$\begin{cases} x^{QU} = \frac{(\alpha + \gamma s)\theta + (1-\gamma)\beta s}{3\theta - \beta^2}, \\ q^{QU} = \frac{\alpha\beta + [3(1-\gamma) + \gamma]\beta s}{3\theta - \beta^2}, \\ p^{QU} = \frac{(2\alpha - \gamma s)\theta + [2(1-\gamma)\beta s + \beta^2 \gamma s]}{3\theta - \beta^2}. \end{cases} \tag{13}$$

And the corresponding expected values are:

$$\begin{cases} E(x^{QU}) = \frac{[(\alpha + \gamma s)(3 + \beta^2) + 3(1-\gamma)s\beta][\text{Log}(9-2\beta^2) - \text{Log}(3-2\beta^2)]}{9}, \\ E(q^{QU}) = \frac{[\alpha\beta + 3(1-\gamma)s + \gamma\beta s][\text{Log}(9-2\beta^2) - \text{Log}(3-2\beta^2)]}{3}, \\ E(p^{QU}) = \frac{[2(3 + \beta^2)\alpha] + [6(1-\gamma)\beta - 3(3-2\beta^2)\gamma]s[\text{Log}(9-2\beta^2) - \text{Log}(3-2\beta^2)]}{9}. \end{cases} \tag{14}$$

Equations (11) and (13) imply the following proposition.

Proposition 6 $\frac{dx^i}{d\theta} < 0$, $\frac{dq^i}{d\theta} < 0$, $\frac{dp^i}{d\theta} < 0$, $i = XU, QU$; $\frac{dP^{XU}}{d\theta} > 0$, while $\frac{dP^{QU}}{d\theta} < 0$.

Cost uncertainty, regardless of quantity cost uncertainty or quality cost uncertainty, reduces equilibrium quantity, quality and profits. This is reasonable because the increase in uncertainty means higher costs for the firm. Interestingly, quantity cost uncertainty increases the price, while quality cost uncertainty decreases it. The increases in cost uncertainty reduce both equilibrium quantity and quality. From the inverse demand function, we know that quantity (quality) decreases (increases) the equilibrium price. So, quantity cost uncertainty reduces

quantity more than quality cost. In contrast, quality cost uncertainty reduces quality more than quantity cost uncertainty. The conclusions in Proposition 6 imply that quantity has a more negative impact on firm operation than quality cost uncertainty, so producers and regulators should care more about quantity cost uncertainty. The regulator can stimulate the producer to control its cost uncertainty to stabilize social welfare. Please see the proof of proposition 6 in the supplementary information.

Proposition 7 (i) $E(q^{XU}) < E(q^{QU})$ and $E(p^{XU}) < E(p^{QU})$; (ii) Sign of $E(x^{XU}) - E(x^{QU})$, $E(\pi^{XU}) - E(\pi^{QU})$ and $Var(\pi^{XU}) - Var(\pi^{QU})$ are uncertainty.

The first part of Proposition 7 shows that quality cost uncertainty results in higher expected quality and price than quantity cost uncertainty in equilibrium. So, from a food safety perspective, quality cost uncertainty is better than quantity cost uncertainty. The relationships of expected quantity, expected profits and risk of profits between the two types of cost uncertainty are uncertain. The marginal price contribution of food quality, subsidy intensity, and hybrid subsidy ratio synthetically influences those relationships. Generally, the marginal price contribution of food quality and subsidy intensity increases the gap between the two types of uncertainty, while quantity subsidy ration decreases it. Furthermore, expected values, including quantity, quality and profits under quality cost uncertainty, are higher than those under the quantity cost uncertainty. In contrast, the risk of profits under quantity cost uncertainty is higher. Again, the conclusions in Proposition 7 imply that quantity cost uncertainty is worse than quality cost uncertainty conditions for food security or safety. So, the regulator should encourage food products to reduce quantity cost uncertainty. Fortunately, quality cost uncertainty is more common than cost uncertainty. Please see the proof of Proposition 7 in the supplementary information.

Discussions and conclusions

A subsidy, especially an innovation subsidy, is usually employed by the government to support the development of firms and industries. But few studies investigated hybrid subsidy between quantity and quality innovation. Both food quantity security and quality safety are critical. So, this paper captures the effect of the subsidy on food product firms' output decisions by employing a hybrid subsidy policy. More importantly, input resource constraints and cost uncertainties are considered in this paper. Under different circumstances, all the equilibrium solutions and welfare variables, including consumer surplus, producer surplus, and social welfare, are concerned. Mathematical calculations and numerical simulations obtain the results of this study.

This study shows that hybrid subsidy is flexible and efficient in edible agricultural product support. A hybrid subsidy makes it convenient to trade between food quantity security and quality safety. High-quality development of edible product production is vertical to green agricultural development. Furthermore, this paper shows that both cost uncertainties and input resource constraints considerably impact the efficiency of farming subsidies. So, the government should consider those factors for agricultural subsidy policy implementation. For example, suppose the producer is concerned more about the quantity under input resource constraints. In that case, the regulator should increase the hybrid subsidy policy's quality subsidy ratio to offset the input constraints' negative impacts. This will guarantee food quality and safety and, vice versa. Besides, uncertainty will make things more complex. The regulator (or the regulator) should thoroughly evaluate the producer operation uncertainty before implementing a subsidy policy for the edible agricultural product sector. More

importantly, the results of this study can be taken as important theoretical support for the ASPA policy of China.

The limitation of this paper is that it ignores the effects of competition and fails to verify the theoretical conclusions by empirical data. The agriculture and food sector are industries with numerous small firms, especially in developing countries like China. Hence, a competitive market deserves further study and empirical research makes sense. Thus, this study can be used for other market structures and quantitative analyses. Another limitation of this paper is that the subsidy ratio and intensity are exogenous. Since the results show that input capacity constraints and uncertainties affect subsidy effectiveness, endogenous subsidy intensity is meaningful. Some interesting conclusions will be obtained if we let subsidy be endogenous and then an optimal subsidy intensity from social welfare maximization will be further obtained. Besides, the cost function of this study is special and there is no interaction effect between quantity and quality on cost. However, some assumptions about the basic model can be relaxed in further research and a feasible expansion direction is to consider the interaction between quality and quantity on cost. After all, improving quality will become more difficult as the quantity increases. Further, agriculture is a major non-point source of pollution sources and agriculture contributes nearly one-third of greenhouse gases. So, negative effects of emission/pollution could be considered in edible agricultural products' quality and price investigation. For example, the price of organic agricultural products is usually twice or higher than non-organic products.

Data availability

The data set generated during and analyzed during the current study is submitted as supplementary file and can also be obtained from the corresponding author upon reasonable request.

Received: 3 April 2023; Accepted: 16 June 2023;

Published online: 03 July 2023

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Acknowledgements

This work was supported by the Key Program of the National Social Science Foundation of China (20&ZD17), the National Natural Science Foundation of China (72273045), and the Natural Science Foundation of Guangdong (2021A1515011960).

Author contributions

YHC: substantial contributions to the conception or design of the work. YHC and ZZ provided oversight and contributed to writing the manuscript. AKM: final approval of the version to be published. All authors contributed meaningfully to this study.

Competing interests

The author(s) declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1057/s41599-023-01874-w>.

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