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Research Article

The Pricing Strategy of Oligopolistic Competition Food Firms with the Asymmetric Information and Scientific Uncertainty

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The arguments for and against genetically modified (GM) food focus on the characteristics of the scientific uncertainty and asymmetric information for the GM food. How do these two factors affect the competition and pricing strategy of food firms that separate GM food and conventional food conforming to consumer's right to know? We explore the issue of pricing strategies between two firms producing horizontally and vertically differentiated foods in the context of asymmetric information and scientific uncertainty. The theoretical results show that there are two separating perfect Bayesian equilibria in which the prices of the conventional food and GM food are strategic complements and the profits of two types of firms are both increasing in the price of GM food. The numerical example shows that a decrease of the expected potential net damage as the most sensitive parameter leads to an increase of the profits of the two firms. Additionally, an increase in product differentiation helps to increase the two firms' profits. Finally, the decrease in risk aversion as the second sensitive parameter helps to increase both products' prices and quantities and both firms' profits. This paper contributes by combining food safety regulation with market mechanisms and competition.

1. Introduction

How does asymmetric information and scientific uncertainty impact the pricing strategy of food firms and ultimately consumer understanding of the newer foods on the market? Food quality and safety are of great concern to governments, food enterprises, and, certainly, consumers [1, 2]. With the continuing development of economies, horizontally and vertically differentiated foods have been produced to meet consumers' needs regarding food quantity and variety [3]. However, because of the asymmetric information between consumers and food enterprises, consumers cannot identify the real quality until purchasing and consuming the experience goods, and they do not know the quality or variety even after consuming credence goods such as genetically modified (GM) food [4]. The application of transgenic technology can help to reduce food shortages and production costs [5], but GM food is also characterized by significant asymmetric information and scientific uncertainty, raising concerns for consumers and governments [6].

In order to satisfy the consumer's right to know, governments have taken measures with respect to food safety regulation [7, 8]. Apart from the government regulation to separate foods with differentiated qualities through labelling, the power of market mechanisms should not be ignored [9–11]. In this paper, we examine the effect of the asymmetric information and scientific uncertainty on the pricing strategies of food firms and try to combine the market mechanism with government regulation to separate GM food and conventional food, consistent with the consumer's right to know.

The competition among firms in the marketplace would be reflected in many ways, not just in price [12, 13]. A firm seeks to choose a combination of strategic variables such as price and product type (e.g., low or high; GM or conventional) that they expect would maximize profits [14–16]. However, some strategic variables are the firm's private information, which leads to information asymmetry between the firm and its consumers as well as between the firm and its rivals. The firm's choice of price may signal its type to consumers, for example.

In this article, we explore pricing strategies used by two firms that produce horizontally and vertically differentiated foods in the context of imperfect oligopolistic competition, incomplete information, and scientific uncertainty. We find that there are two separating perfect Bayesian equilibriums in which the price of the conventional food is significantly higher than that of GM food and the two prices are strategic complements.

There is a fairly extensive literature on the use price to signal product quality. From the perspective of a monopoly market structure, Bagwell and Riordan [17] examined a two-type model and showed that, compared to the price under full information, the low-quality firm charged the same price under incomplete information while the high-type firm charged a higher price in the context of asymmetric information. Daughety and Reinganum [18] extended the model developed by Bagwell and Riordan [17] by utilizing a continuum of types representing product safety. They showed that whether the higher price in fact signalled safer products depended on the allocation of the associated loss between the firm and the consumer and concluded that lower prices signalled safer products if the firm bore a sufficiently high percentage of the loss, while higher prices signal safer products if the consumer bore a sufficiently high percentage of the loss. Under monopolistic conditions, Mirman et al. [19] also studied the informational role of prices under the asymmetric information and noisy signalling.

For example, from the perspective of an oligopoly market structure, Janssen and Roy [20] developed a symmetric Bertrand oligopoly model and studied the competitive strategy between the high-quality and the low-quality firms. They found that there existed Bayesian separating equilibria in which the low-quality firms chose random pricing strategy and the high-quality firms charged high prices. Different from Janssen and Roy [20], Daher et al. [21] assumed that the quality was common knowledge to all the firms since firms sold a homogeneous good, but consumers owned incomplete information on product quality. They found the price under the (signalling) Cournot equilibrium was higher than that under the full-information Cournot equilibrium and the profits under a signalling Cournot were equal to the profits of a cartel with full information. Based on Janssen and Roy [20], Dubovik and Janssen [12] set up an oligopoly model where consumers had heterogeneous information. They showed that when there was a sufficiently high portion of uninformed consumers, there existed a unique equilibrium where high price was associated with high quality. However, this equilibrium was Pareto-inefficient since firms had incentives to distort quality downwards. Following Janssen and Roy [20], Adriani and Deidda [22] also assumed all firms produce the same good whose quality is known to all firms but unknown to uninformed buyers. Adriani and Deidda [22] explored the impact of the strength of competition among sellers on the ability of high-quality sellers to inform consumers about the quality of their goods through the pricing strategy when there were a large number of price-setting sellers and a large number of consumers. They showed that high-quality sellers could use price to signal their high quality in the context of weak competition among sellers. On the contrary, high-quality sellers failed to signal and then were driven out of the market if the competition among sellers were strong. Daughety and Reinganum [23] described the role of quality signalling via price and quality disclosure through a credible direct claim played in the market competition. In the context of sufficiently high disclosure costs, the firm would always use price to signal the quality of its product. In the unique separating equilibrium, consumers inferred the quality of the product through its price and then made their purchasing decisions. In contrast, if the disclosure costs were zero, then all types of firms would disclosure their qualities and charge the full-information prices according to their own types. In this situation, consumers made decisions according to prices and qualities of the products. Furthermore, Janssen and Roy [24] explained why it was hard for firms to voluntarily disclose quality in a symmetric duopoly. In the context of the relatively low-quality premiums, the unique symmetric equilibrium was to not disclose product quality (for both firms), even if the disclosure costs were zero. In the context of the relatively high-quality premium and the increasing cost in quality, there were two equilibriums: full disclosure and nondisclosure.

As such, our study differs from the previous studies in several ways. First, we construct a representative consumer's model in an oligopolistic market with the scientific uncertainty. Though GM food is generally considered as safe, there are still some unknowns compared to conventional food, particularly with respect to human health [25, 26]. We treat the scientific uncertainty as a kind of risk with a distribution that has known expected potential net damage and variance. Additionally, we consider the consumers' heterogeneous degree of risk aversion and study the effects of various degrees of risk aversion on the prices, quantities, and profits in the separating equilibrium. Finally, the products in our model are horizontally and vertically differentiated.

In addition, the paper's numerical simulation and sensitivity analysis both suggest important policy implications. First, the expected potential net damage is the most sensitive parameter regarding the price of GM food, the quantities of the conventional food and GM food, and the profits of the two types of firms, making government information particularly important for consumers. Although some recent studies show GM food may have potential damage to human health [26], many studies also show GM food is as safe as the conventional food [27]. Thus, due to the scientific uncertainty of GM food's impact on human health, the expectation of the potential risk is there, though it has gotten lower as more study is undertaken. Moreover, the two kinds of foods' price and quantities and two firms' profits increase as the product differentiation increases. Government has a role in encouraging the innovation of food to increase the product differentiation. Finally, the degree of risk aversion is very sensitive to the price of GM food and the profits of the firm producing the conventional food. Governments should consider the heterogeneity of consumers when developing policies.

The paper is organized as follows. The next section describes models of the representative consumer and two firms and Section 3 discusses the theoretical separating equilibrium. Section 4 further analyses the prices, quantities, and profits in the separating equilibrium using numerical examples. Additionally an extension is conducted to study how the changes in the parameters affect prices, quantities, and profits. The final section presents general conclusions from the results with policy recommendations.

2. Model Setup

Our theoretic model includes a representative consumer and two firms. The representative consumer has a certain degree of risk aversion on the potential damage from GM food. Each firm produces its product with constant marginal costs depending on the type of its product. Additionally, the products in our model are horizontally and vertically differentiated. Horizontal differentiation means there exists difference between two firms' products' qualities. Vertical differentiation means there are two versions including conventional food and GM food for each product. In our model, first, nature independently decides the types of the two firms from a common distribution and each firm can observe its own type. Second, two firms simultaneously choose product prices based on their own types, and finally the representative consumer determines quantities of the products based on the observed price. In the model with asymmetric information, one firm does not observe the type of food produced by the other firm, and the representative consumer does not observe the two firms' food types. In the model with full information, firms and consumers observe all the food types.

Based on backward induction, we firstly solve consumer's problem and then firms' problems.

2.1. Consumer's Problem. We consider a representative consumer with risk aversion, who consumes some of each product. Products 1 and 2 are differentiated goods and the two products are substitutes. The third is a numeraire good. Products 1 and 2 can be either conventional or GM food (signified by T or G, resp.).

Horizontal differentiation is captured by a consumer-specific incremental value of one kind of product. Some consumers are willing to pay P for one unit of Product 1 and $P+\varepsilon$ for one unit of Product 2 while, all else equal, another part of consumers are willing to pay P for one unit of Product 1 and $P-\varepsilon$ for one unit of Product 2. The consumer-specific incremental net value will be indicated by horizontal differentiation.

As for the vertical differentiation, the two products are vertically differentiated in regard to the quality. All consumers will prefer safer product to one with a lower level of safety. Any consumers prefer the product without scientific uncertainty to one with scientific uncertainty if both products are sold at the same price.

Assumption 1 ($(\theta_G,\theta_T) = (0,1)$). θ_i denotes an indicator function which takes on 0 when product i is GM food and takes on 1 when product i is the conventional food. And hence $(\theta_G,\theta_T) = (0,1)$.

The consumer chooses the food variety and quantity to maximize the utility. According to Daughety and Reinganum [23, 28] we set up an initial quadratic utility function. Considering the scientific uncertainty of GM food, we view the scientific uncertainty as a risk with a certain expectation and variation and deal with the risk by introducing the mean and variation into the initial quadratic utility function based on the method of Johnstone and Lindley [29]. The utility function is shown in the following assumption.

Assumption 2. The consumer's utility function is quadratic in the two differentiated products with the parameters $\alpha > 0$, $\beta > \gamma > 0$, $\tau > 0$, and $\delta \sim N(E(\delta), \operatorname{var}(\delta))$.

$$U(q_1,q_2) = \sum_{i=1}^{2} q_i\left[\alpha - (1-\theta_i)E(\delta)\right] - \frac{1}{2}\left(\sum_{i=1}^{2}\beta q_i^2 + \sum_{i}\sum_{j\neq i}\gamma q_i q_j\right) - \frac{1}{2}\sum_{i=1}^{2}\left[\tau(1-\theta_i)^2 \operatorname{var}(\delta)\right]q_i^2, \quad (1)$$

where γ is the degree of product substitution between the two goods produced by Firms 1 and 2.

As γ decreases, the two kinds of products are more differentiated and consumer's utility goes up. We assume that γ lies in the interval $(0,\beta)$. The coefficient α means the basic utility of consuming one unit of the conventional food. The parameter $\delta \sim N(E(\delta), \operatorname{var}(\delta))$ means scientific uncertainty from GM food. GM food may or may not be as safe as the conventional food to human health. Meanwhile, genetic modification necessarily improves some traits of plants such as resistance to pests and tolerance to bad conditions. $E(\delta)$ means the expected potential damage minus the utility increase from the improved traits and $\operatorname{var}(\delta)$ is the volatility of risk. τ is the degree of risk aversion. A consumer's utility of consuming one unit of GM food goes down as τ increases.

The consumer chooses quantities (q_1 and q_2) to maximize his/her utility with income I; that is, $\max_{q_1,q_2} U(q_1,q_2) + I - \sum_{i=1}^{2} p_i q_i$, where $I - \sum_{i=1}^{2} p_i q_i$ means the consumption of the numeraire good.

First-order conditions show the inverse demand function for product i is

$$p_i(q_i, q_{-i}) = \alpha - (1-\theta_i)E(\delta) - \left[\beta + \tau(1-\theta_i)^2 \operatorname{var}(\delta)\right]q_i - \gamma q_{-i}. \quad (2)$$

Obviously $p_i < \alpha$ always holds.

Since we focus on firms' pricing strategy to signal their product quality, here we further need the following ordinary demand function:

$$q_i(p_i, p_{-i}) = \frac{[\alpha - (1-\theta_i)E(\delta)]\left[\beta + \tau(1-\theta_{-i})^2 \operatorname{var}(\delta)\right] - \gamma[\alpha - (1-\theta_{-i})E(\delta)]}{\left[\beta + \tau(1-\theta_i)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau(1-\theta_{-i})^2 \operatorname{var}(\delta)\right] - \gamma^2} + \frac{\gamma p_{-i} - \left[\beta + \tau(1-\theta_{-i})^2 \operatorname{var}(\delta)\right] p_i}{\left[\beta + \tau(1-\theta_i)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau(1-\theta_{-i})^2 \operatorname{var}(\delta)\right] - \gamma^2}. \quad (3)$$

The equation above represents the consumer's demand in the context of full information. However, when information asymmetry exists, the representative consumer could not observe products' qualities but only have perceptions of products' qualities, denoted by $\widetilde{\theta}_i$, $(i = 1, 2)$. And hence substituting $\widetilde{\theta}_i$ for θ_i of the above equation yields demand functions under the condition of asymmetric information.

2.2. The Firm's Problem. It is known that the application of transgenic technology can reduce agricultural production costs [5, 30]. For simplicity, we assume the marginal cost of GM food is normalized to zero and that of conventional food is $k > 0$. Additionally, we maintain the following assumption throughout this paper.

Assumption 3 $(E(\delta_i) > k > 0)$. $E(\delta_i) > k$ means the consumer would be willing to pay k to buy the conventional food to avoid the expected loss $E(\delta_i)$ from purchasing and consuming one unit of GM food.

Given the rival's price and perceived product type, one firm's profits can be expressed as a function of its price, cost, true product type, and perceived product type. In the context of full information, the perceived type is consistent with the true product type. However, under the condition of asymmetric information, the perceived type may be different from the true product type. And hence firm i's profits can be written as

$$\pi_i\left(p_i, \theta_i, \widetilde{\theta}_i \mid p_{-i}, \widetilde{\theta}_{-i}\right) = (p_i - k\theta_i)\left\{\frac{\left[\alpha - \left(1-\widetilde{\theta}_i\right)E(\delta)\right]\left[\beta + \tau\left(1-\widetilde{\theta}_{-i}\right)^2 \operatorname{var}(\delta)\right] - \gamma\left[\alpha - \left(1-\widetilde{\theta}_{-i}\right)E(\delta)\right]}{\left[\beta + \tau\left(1-\widetilde{\theta}_i\right)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau\left(1-\widetilde{\theta}_{-i}\right)^2 \operatorname{var}(\delta)\right] - \gamma^2} + \frac{\gamma p_{-i} - \left[\beta + \tau\left(1-\widetilde{\theta}_{-i}\right)^2 \operatorname{var}(\delta)\right] p_i}{\left[\beta + \tau\left(1-\widetilde{\theta}_i\right)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau\left(1-\widetilde{\theta}_{-i}\right)^2 \operatorname{var}(\delta)\right] - \gamma^2}\right\}. \quad (4)$$

A firm has the full information about its own marginal cost and hence we do not use $k\widetilde{\theta}_i$ but $k\theta_i$ to mean firm i' marginal cost in its profits function. The second term above is the consumer's demand based on the prices and his perceived types of two firms' products.

For the game with asymmetric information, we characterize a symmetric separating perfect Bayesian equilibrium. Firm i does not know the product type of its rival and predicts that its rival uses the pricing strategy $p^*(\theta)$ by charging the price $p^*(1)$ with probability λ and the price $p^*(0)$ with probability $1-\lambda$. Thus, firm i's expected profits with respect to θ_{-i} can be written as

$$E_{-i}\left[\pi_i\left(p_i, \theta_i, \widetilde{\theta}_i \mid p_{-i}, \widetilde{\theta}_{-i}\right)\right] = (p_i - k\theta_i) E_{-i}\left\{\frac{\left[\alpha - \left(1-\widetilde{\theta}_i\right)E(\delta)\right]\left[\beta + \tau\left(1-\widetilde{\theta}_{-i}\right)^2 \operatorname{var}(\delta)\right] - \gamma\left[\alpha - \left(1-\widetilde{\theta}_{-i}\right)E(\delta)\right]}{\left[\beta + \tau\left(1-\widetilde{\theta}_i\right)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau\left(1-\widetilde{\theta}_{-i}\right)^2 \operatorname{var}(\delta)\right] - \gamma^2} + \frac{\gamma p_{-i} - \left[\beta + \tau\left(1-\widetilde{\theta}_{-i}\right)^2 \operatorname{var}(\delta)\right] p_i}{\left[\beta + \tau\left(1-\widetilde{\theta}_i\right)^2 \operatorname{var}(\delta)\right]\left[\beta + \tau\left(1-\widetilde{\theta}_{-i}\right)^2 \operatorname{var}(\delta)\right] - \gamma^2}\right\}. \quad (5)$$

Simplifying the second term yields firm i's expected profits:

$$\Pi_i\left(p_i,\theta_i,\widetilde{\theta}_i \mid E\left(p^*\right)\right) = \left(p_i - k\theta_i\right)\left\{\frac{\left[\alpha-\left(1-\widetilde{\theta}_i\right)E(\delta)\right]\left[\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)\right]-\gamma\left[\alpha-(1-\lambda)E(\delta)\right]}{\left[\beta+\tau\left(1-\widetilde{\theta}_i\right)^2\operatorname{var}(\delta)\right]\left[\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)\right]-\gamma^2} + \frac{\gamma E\left(p^*\right)-\left[\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)\right]p_i}{\left[\beta+\tau\left(1-\widetilde{\theta}_i\right)^2\operatorname{var}(\delta)\right]\left[\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)\right]-\gamma^2}\right\}, \quad (6)$$

where $E(p^*) = \lambda p^*(1) + (1-\lambda)p^*(0)$.

Moreover, the second term above is linear in the rival's price but nonlinear in the rival's product types. Irrespective of true product type, it is always more profitable to be perceived as type T when prices are given since $\partial\Pi_i(p_i,\theta_i,\widetilde{\theta}_i \mid E(p^*))/\partial\widetilde{\theta}_i > 0$ always holds. Let $B(p)$ denote the consumer's belief function. The consumer infers firm i to be of type $B(p_i)$ based only on the price p_i charged by firm i. When the representative consumer's belief function and the rival's pricing strategy are given, two firms manage to maximize their own expected profits in equilibrium. Specifically, the separating perfect Bayesian equilibrium would be formalized as follows.

Definition 4. The separating perfect Bayesian equilibrium consists of a pair of prices $(p^*(0), p^*(1)) = (P_G, P_T)$ and beliefs $B^*(p)$ such that, for $i = 1, 2$,

(i) $\Pi_i(P_G, 0, 0 \mid E(p^*)) \geq \max_p \Pi_i(p, 0, B^*(p) \mid E(p^*))$,

(ii) $\Pi_i(P_T, 1, 1 \mid E(p^*)) \geq \max_p \Pi_i(p, 1, B^*(p) \mid E(p^*))$.

Parts (i) and (ii) show that the consumer's beliefs are consistent with the fact in equilibrium. When one firm charges P_G, the consumer believes the firm produces GM food. When one firm charges P_T, the consumer believes the firm produces conventional food. Moreover, in the context of the given pricing strategy of the rival and the consumer's belief function, part (i) says the firm producing GM food prefers to charge P_G, while part (ii) says the firm producing conventional food prefers to charge P_T in the separating perfect Bayesian equilibrium.

3. Theoretical Analyses

In this section, we solve for a separating perfect Bayesian equilibrium; that is, we solve for the pricing strategy (P_G, P_T), the associated quantities (Q_G, Q_T), and the associated profits (Π_G, Π_T).

Each firm has full information on his own product type and cost, and let $c_u = k\theta_u$, where $u = G, T$. Based on Assumption 1 ($\theta_G = 0, \theta_T = 1$), we have $(c_G, c_T) = (0, k)$ which is consistent with the previous assumption on marginal costs.

The firm's demand based on its perceived product type is $(d_v - p)h_v$, where $v = G, T$, $d_v \equiv [\alpha - (1-\widetilde{\theta}_v)E(\delta)] - e\gamma[\alpha - (1-\lambda)E(\delta) - E(p^*)]$, $h_v \equiv f_v/e$, $e \equiv 1/(\beta + \tau(1-\lambda)^2\operatorname{var}(\delta))$, and $f_v \equiv 1/([\beta + \tau(1-\widetilde{\theta}_v)^2\operatorname{var}(\delta)][\beta + \tau(1-\lambda)^2\operatorname{var}(\delta)] - \gamma^2)$. And hence the firm's profits can be rewritten as $\Pi_{uv} = (p - c_u)h_v(d_v - p)$, where the true type $u = G, T$ and the perceived type $v = G, T$.

To guarantee that a firm always has positive profits, regardless of the perceived product type and the rival firm's pricing strategy, we need $d_v > c_u$ for all u, v. Its tightest constraint is $\min(d_v) > \max(c_u)$; that is,

$$\alpha - \left(1-\widetilde{\theta}_i\right)E(\delta) - e\gamma\left[\alpha - (1-\lambda)E(\delta) - E\left(p^*\right)\right] = d_G > c_T = k. \quad (7)$$

Considering that λ may be arbitrarily close to 1, $E(p^*)$ may be arbitrarily close to 0, and k (though smaller) may be arbitrarily close to $E(\delta)$, we employ the following sufficient condition.

Assumption 5 ($\alpha > 2E(\delta)\beta/(\beta-\gamma)$). Notice that Assumption 5 is a strong sufficient condition for $d_G > c_T$, not a necessary condition. Obviously d_G is not less than $\alpha(1-\gamma/\beta) - E(\delta)$ and Assumption 5 yields $\alpha(1-\gamma/\beta) - E(\delta) > E(\delta)$. And hence $d_G > E(\delta)$. Based on the fact $c_T = k$ and Assumption 3, we obtain $d_G > c_T$.

Proposition 6. *The prices $p_{uv} = (c_u + d_v)/2$ to maximize one firm's profits given pricing strategy of the rival are ordered as follows: $p_{TT} > p_{GT} > p_{TG} > p_{GG}$, where u means the true product type and v means the perceived product type, and $u = G, T$, $v = G, T$.*

Obviously, profits Π_{uv} would be maximized when $p_{uv} = (c_u + d_v)/2$. Since the production cost is an increasing function of the true type of products and d_v is an increasing function of the perceived product type, the price p_{GT} or p_{TG} will fall in between p_{TT} and p_{GG}.

According to the fact $E(\delta_i) = d_T - d_G$ and Assumption 3, we can obtain that p_{GT} is higher than p_{TG}. The price charged by the T-type firm which is perceived as the G-type firm is higher than the price charged by the G-type firm which is perceived as the T-type firm if the consumer is willing to pay k to buy the conventional food to avoid the expected loss from GM food. The incorrect perception of consumers will negatively affect the production enthusiasm of the T-type firm. It reflects the importance of consumer's perception and the exact quality signalling by price.

Lemma 7. *Given $E(p^*)$, in the separating equilibrium, T-type firm's best response is $p_T(E(p^*)) = 0.5(d_T + \sqrt{d_T^2 - (h_G/h_T)d_G^2})$, while G-type firm's best response is $p_G(E(p^*)) = d_G/2$. Additionally, the own-price and the expected rival's price are strategic complements.*

As introduced before, we have the maximum profits $\max(\Pi_{uv}) = h_v(d_v - c_u)^2/4$. If a firm of type G is perceived as being of type G, its best response is p_{GG}. If the T-type firm is perceived as such, its best response is p_{TT}. However, we need to judge whether p_{TT} meets the need of the separating perfect Bayesian equilibrium.

The proof of Lemma 7 is presented in Appendix.

According to Lemma 7, we know two firms' best responses $p_T(E(p^*))$ and $p_G(E(p^*))$ are both the function of $E(p^*)$ since both d_T and d_G contain the term of $E(p^*)$. After we derive the solution to $E(p^*)$, we can obtain the best responses of the two types.

We can see that the pricing strategy between the G-type firm and the T-type firm are complementary. In the situation of information asymmetry, the behavior of the T-type firm will be affected by the pricing strategy of the G-type firm. The consistent pricing strategy is advantageous to itself and its opponent. In the face of raising price of GM food, the T-type firm will be afraid that its conventional food may be viewed as GM food if it does not put up the price of the conventional food.

Proposition 8. *There are two separating perfect Bayesian equilibriums consisting of a pair of prices (P_G, P_T) with $P_G < P_T$, and supporting beliefs $B(p^*)$, with $B(p^*) = 1$ when $p \geq P_T$, and $B(p^*) = 0$ when $p < P_T$.*

The proof of Proposition 6 is presented in Appendix.

In both Bayesian equilibriums, the price is a good signal of the type of foods. The food with the higher price of P_T is perceived as the conventional food. Otherwise, the food would be viewed as GM food. The price of conventional food is significantly higher than that of GM food in terms of separating equilibrium, and additionally the price gap between the conventional food and GM food is positively correlated to the expected net potential damage $E(\delta)$ because of the positive correlation between ω^* and $E(\delta)$.

Proposition 9. *In the separating perfect Bayesian equilibrium, $Q_T < Q_G$ holds if $(p_T - p_G - E(\delta))/p_G > 1 - h_G/h_T$; $Q_T > Q_G$ holds if $(p_T - p_G - E(\delta))/p_G < 1 - h_G/h_T$, where $h_G = (\beta + \tau(1-\lambda)^2\mathrm{var}(\delta))/([\beta + \tau\mathrm{var}(\delta)][\beta + \tau(1-\lambda)^2\mathrm{var}(\delta)] - \gamma^2)$ and $h_T = (\beta + \tau(1-\lambda)^2\mathrm{var}(\delta))/(\beta[\beta + \tau(1-\lambda)^2\mathrm{var}(\delta)] - \gamma^2)$.*

In the separating perfect Bayesian equilibrium, two firms' quantities are $Q_G = h_G Y^*$ and $Q_T = h_T(d_T - p_T) = h_T(Y^* + E(\delta)/2 - \omega^*)$, respectively. We know the equilibrium prices of GM food and conventional food are $p_G = Y^*$ and $p_T = Y^* + \omega^* + E(\delta)/2$, respectively. It means that, in the separating perfect Bayesian equilibrium, the demand of the conventional food is smaller than that of GM food if the expected net potential damage of GM food is small enough or the gap between the price of conventional food and GM food is big enough; otherwise the demand of GM food is smaller than that of the conventional food.

This reflects the distortion in prices due to signalling product type when the expected net potential damage of GM food is small enough or the gap between the prices of conventional food and GM food is big enough. In this situation, the price from the T-type firm is so much higher than the price charged by the G-type firm that it is not worth avoiding the risk from the scientific uncertainty by paying a high price for the convention food and that consumers are redistributed toward the G-type firm.

Proposition 10. *The profits of the G-type firm and the T-type firm are both monotonically increasing in the price of GM food.*

It can be proved that the profit of the G-type firm is increasing with the price of the GM food. In addition, we can also get that, with the increase of GM food price, the profits of T-type firm will rise since the pricing strategy between the G-type firm and the T-type firm is complementary.

In the situation of information asymmetry, the optimal pricing strategy of the T-type firm will be affected by the behavior of the G-type firm. The consistent pricing strategy is beneficial to itself and its opponent. When the G-type firm enhances the price of GM food, the optimal strategy for the T-type firm is to put up the price of the conventional food in case the conventional food is viewed as GM food and further enlarges its profit.

Proposition 11. *The separating perfect Bayesian equilibrium consisting of a pair of larger prices (P_G^*, P_T^*) is the first-best solution if $P_G^* < P_T^* < \alpha$; smaller prices (P_G^*, P_T^*) are the first-best solution if $P_T^* \geq P_G^* \geq \alpha$.*

Although (A.8) in the part of proof of Proposition 8 has two positive roots, which one is the optimal solution? The answer depends on the profits and the basic utility α. Proposition 10 shows the profits functions of the G-type firm and the T-type firm both monotonically increase as the price of GM food. Therefore, in terms of the principle of maximizing profits, the bigger Y^* is the more optimal the solution is.

In this equilibrium, P_T^* is the lowest price that the T-type firm can distinguish from a G-type firm and receive the maximum profit. The higher price than P_T^* also signals the conventional food but is less profitable for the T-type firm. On the contrary, the lower price than P_T^* charged by the T-type firm will provide a profitable deviation for a G-type firm if consumers infer that the G-type firm charging that price is a T-type firm.

In short, the separating perfect Bayesian equilibrium consisting of the higher price combination is the first-best solution when the price of the conventional food is low enough (i.e., lower than the basic utility α). In contrast, the lower price combination is the optimal solution when the price of GM food is high enough (i.e., higher than the basic utility α).

4. Numerical Simulation

In this section, we further analyze the separating perfect Bayesian equilibrium under the asymmetric information using numerical examples. Based on Assumptions 1–5, consider $\alpha = 10$; $\beta = 2$; $\gamma = 0.5$; $\tau = 0.5$; $\lambda = 0.5$; $k = 2.5$; $E(\delta) = 3$; $\mathrm{var}(\delta) = 1.5$.

We begin by solving for (q_1, q_2). To do so we solve $\max_{q_1,q_2} U(q_1, q_2) + I - \sum_{i=1}^{2} p_i q_i$ and obtain the following ordinary demand function:

$$q_i(p_i, p_{-i}) = \frac{[10-3(1-\theta_i)]\left[2+0.5(1-\theta_{-i})^2\times 1.5\right] - 0.5[\alpha-(1-\theta_{-i})E(\delta)] + \gamma p_{-i} - \left[2+0.5(1-\theta_{-i})^2\times 1.5\right]p_i}{\left[2+0.5(1-\theta_i)^2\times 1.5\right]\left[2+0.5(1-\theta_{-i})^2\times 1.5\right]-0.5^2}. \quad (8)$$

And hence firm i's profits are as follows:

$$\pi_i\left(p_i,\theta_i,\tilde{\theta}_{-i} \mid p_{-i},\tilde{\theta}_{-i}\right) = (p_i - 2.5\theta_i)\left\{\frac{\left[10-3\left(1-\tilde{\theta}_i\right)\right]\left[2+0.5\left(1-\tilde{\theta}_{-i}\right)^2\times 1.5\right]-0.5\left[10-3\left(1-\tilde{\theta}_{-i}\right)\right]}{\left[2+0.5\left(1-\tilde{\theta}_i\right)^2\times 1.5\right]\left[2+0.5\left(1-\tilde{\theta}_{-i}\right)^2\times 1.5\right]-0.5^2}\right.$$
$$\left. + \frac{0.5p_{-i}-\left[2+0.5\left(1-\tilde{\theta}_{-i}\right)^2\times 1.5\right]p_i}{\left[2+0.5\left(1-\tilde{\theta}_{-i}\right)^2\times 1.5\right]\left[2+0.5\left(1-\tilde{\theta}_{-i}\right)^2\times 1.5\right]-0.5^2}\right\}, \quad (9)$$

and firm i's expected profits are

$$\Pi_i\left(p_i,\theta_i,\tilde{\theta}_i \mid E(p^*)\right) = (p_i - 2.5\theta_i)\left\{\frac{\left[10-3\left(1-\tilde{\theta}_i\right)\right]\left[2+0.5(1-\lambda)^2\times 1.5\right]-0.5[10-3(1-\lambda)]}{\left[2+0.5\left(1-\tilde{\theta}_i\right)^2\times 1.5\right]\left[2+0.5(1-\lambda)^2\times 1.5\right]-0.5^2}\right.$$
$$\left. + \frac{0.5E(p^*)-\left[2+0.5(1-\lambda)^2\times 1.5\right]p_i}{\left[2+0.5\left(1-\tilde{\theta}_i\right)^2\times 1.5\right]\left[2+0.5(1-\lambda)^2\times 1.5\right]-0.5^2}\right\}, \quad (10)$$

where $E(p^*) = 0.5p^*(1) + 0.5p^*(0)$.

Thus, based on Proposition 10, in the separating perfect Bayesian equilibrium, the prices of GM food and conventional food are $p_G = 1.53$ and $p_T = 5.77$, respectively. The corresponding quantities are $Q_G = 0.58$ and, $Q_T = 0.15$, respectively. $Q_T < Q_G$ since $(\omega^* - 0.5E(\delta))/Y^* > 1 - h_G/h_T$ holds in this example. Two firms' profits are $\Pi_T = 0.89$ and $\Pi_G = 0.50$, respectively.

In this section, we will investigate how the change in the model parameters affect the pricing strategy (P_G, P_T), the associated quantities (Q_G, Q_T), and the associated profits (Π_G, Π_T) in the separating perfect Bayesian equilibrium. We focus on the following four categories of parameters: (i) parameters on the scientific uncertainty: $E(\delta)$ and $\mathrm{var}(\delta)$; (ii) parameters on the asymmetric information: λ; (iii) parameters on the degree of product substitution γ; (iv) parameters on the degree of risk aversion τ.

Table 1 illustrates the effects of changing four categories of parameters on the price of GM food P_G. It shows that increases of the expected net potential damage $E(\delta)$, the perceived proportion of T-type firm λ, the degree of product substitution γ, and the degree of risk aversion τ all lead to decreases of the price of GM food; an increase of the volatility of potential risk $\mathrm{var}(\delta)$ leads to an increase of the price of GM food. From the perspective of the average volatility, P_G is more sensitive to the expected net potential damage $E(\delta)$ compared to another four parameters.

Table 2 reveals the effects of changing four categories of parameters on the price of the conventional food P_T. From Table 2 we can see that increases of the expected net potential damage $E(\delta)$ and the volatility of potential risk $\mathrm{var}(\delta)$ both lead to increases of the price of the conventional food; increases of the perceived proportion of T-type firm λ,

Table 1: Effects of changing four categories of parameters on P_G.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	1.6773	1.6405	1.6036	1.5668	1.5299	1.4930	1.4561	1.4192	1.3823
$\mathrm{var}(\delta)$	1.5267	1.5275	1.5283	1.5291	1.5299	1.5307	1.5315	1.5323	1.5331
γ	1.5695	1.5594	1.5494	1.5395	1.5299	1.5205	1.5114	1.5024	1.4938
τ	1.5828	1.5641	1.5498	1.5387	1.5299	1.5230	1.5175	1.5130	1.5095
λ	1.5484	1.5439	1.5393	1.5346	1.5299	1.5252	1.5204	1.5156	1.5107

Table 2: Effects of changing four categories of parameters on P_T.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	5.3805	5.4796	5.5774	5.6741	5.7696	5.8641	5.9576	6.0502	6.1419
$\mathrm{var}(\delta)$	5.7457	5.7519	5.7580	5.7639	5.7696	5.7752	5.7807	5.7861	5.7914
γ	5.8352	5.8183	5.8018	5.7855	5.7696	5.7541	5.7390	5.7243	5.7102
τ	5.8402	5.8138	5.7944	5.7801	5.7696	5.7620	5.7566	5.7529	5.7507
λ	5.8009	5.7932	5.7855	5.7776	5.7696	5.7616	5.7534	5.7452	5.7370

Table 3: Effects of changing four categories of parameters on Q_G.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	0.6364	0.6224	0.6084	0.5944	0.5805	0.5665	0.5525	0.5385	0.5244
$\mathrm{var}(\delta)$	0.6147	0.6057	0.5971	0.5886	0.5805	0.5725	0.5648	0.5573	0.5500
γ	0.5863	0.5846	0.5830	0.5817	0.5805	0.5795	0.5787	0.5781	0.5778
τ	0.6373	0.6203	0.6055	0.5923	0.5805	0.5696	0.5596	0.5503	0.5415
λ	0.5865	0.5851	0.5836	0.5820	0.5805	0.5789	0.5773	0.5756	0.5740

the degree of product substitution γ, and the degree of risk aversion τ all lead to decrease of the price of the conventional food. Moreover, P_G is more sensitive to the expected net potential damage $E(\delta)$ compared to the volatility of potential risk $\mathrm{var}(\delta)$, the degree of product substitution γ, the perceived proportion of T-type firm λ, and the degree of risk aversion τ.

Tables 3–6 show the effects of changing four categories of parameters on the quantity of GM food, the quantity of the conventional food, the profits of G-type firm, and the profits of T-type firm. We see that the quantity of GM food, the quantity of the conventional food, the profits of G-type firm, and the profits of T-type firm all decrease as the expected net potential damage $E(\delta)$, and the volatility of potential risk $\mathrm{var}(\delta)$, the perceived proportion of T-type firm λ, the degree of product substitution γ, or the degree of risk aversion τ increases. Moreover, the quantity of GM food Q_G, the quantity of the conventional food Q_T, and the profits of G-type firm Π_G and T-type firm Π_T are all most sensitive to the expected net potential damage $E(\delta)$. It is essential to officially enhance the popularization of science on GM food to get the consumers' expected potential net damage stable or even lower. Finally, the degree of risk aversion τ is the second sensitive parameter to the profits of T-type firm Π_T. It should be noted that governments should not overlook the heterogeneity of consumers in their degree of risk aversion when making policy-decisions.

5. Conclusion

In this article, we combine the consumer's utility maximization model and the firm's profits maximization model. In doing so, we constructed a representative consumer's model in an oligopolistic market with information asymmetry and scientific uncertainty and horizontally and vertically differentiated and substitute goods. This paper treats the scientific uncertainty as a risk with a known distribution, the expected potential net damage, and the volatility of risk. We employ a signalling model in which the type of a firm's product is not public information, but private information; the firm's choice of price may signal its product type to consumers. In the separating perfect Bayesian equilibrium, there exists the lowest price for the T-type firm to distinguish itself from the G-type firm and maximize profits.

Deriving from these two models, we have been able to generate a variety of results. First, to maximize one firm's profits given pricing strategy of the rival, the firm charges the highest price if the T-type firm is perceived as such; the firm charges the second highest price if the G-type firm is perceived as the T-type firm; the firm charges the

Table 4: Effects of changing four categories of parameters on Q_T.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	0.1984	0.1863	0.1749	0.1641	0.1539	0.1442	0.1350	0.1263	0.1180
$\text{var}(\delta)$	0.1633	0.1609	0.1585	0.1562	0.1539	0.1517	0.1496	0.1476	0.1456
γ	0.1577	0.1567	0.1557	0.1548	0.1539	0.1531	0.1524	0.1517	0.1512
τ	0.1727	0.1669	0.1619	0.1577	0.1539	0.1506	0.1475	0.1447	0.1421
λ	0.1566	0.1559	0.1553	0.1546	0.1539	0.1532	0.1525	0.1518	0.1511

Table 5: Effects of changing four categories of parameters on Π_G.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	1.0674	1.0210	0.9757	0.9314	0.8881	0.8458	0.8045	0.7642	0.7249
$\text{var}(\delta)$	0.9384	0.9253	0.9125	0.9001	0.8881	0.8764	0.8650	0.8539	0.8431
γ	0.9203	0.9116	0.9033	0.8955	0.8881	0.8811	0.8746	0.8686	0.8631
τ	1.0087	0.9701	0.9383	0.9114	0.8881	0.8675	0.8492	0.8326	0.8174
λ	0.9082	0.9033	0.8983	0.8932	0.8881	0.8829	0.8777	0.8724	0.8671

Table 6: Effects of changing four categories of parameters on Π_T.

Variation in parameter	% change value in parameter								
	−20	−15	−10	−5	0	5	10	15	20
$E(\delta)$	0.5714	0.5552	0.5384	0.5210	0.5033	0.4852	0.4669	0.4484	0.4298
$\text{var}(\delta)$	0.5301	0.5231	0.5163	0.5097	0.5033	0.4970	0.4909	0.4850	0.4792
γ	0.5260	0.5199	0.5141	0.5085	0.5033	0.4983	0.4936	0.4892	0.4852
τ	0.5769	0.5530	0.5335	0.5172	0.5033	0.4911	0.4804	0.4708	0.4620
λ	0.5168	0.5135	0.5101	0.5067	0.5033	0.4998	0.4963	0.4928	0.4892

second lowest price if the T-type firm is perceived as the G-type firm; the firm charges the lowest price if the G-type firm is perceived as such. The interesting result is the price charged by the T-type firm which is perceived as the G-type firm is higher than the price charged by the G-type firm which is perceived as the T-type firm, if the consumer is willing to pay k to buy the conventional food to avoid the expected loss from GM food. Second, there are two separating perfect Bayesian equilibriums in which the price of the conventional food is significantly higher than that of GM food and the own-price and the expected rival's price are strategic complements, and additionally the price gap between the conventional food and GM food enlarges as the expected net potential damage increases. The separating perfect Bayesian equilibrium consisting of the higher price combination is the first-best solution when the price of the conventional food is low enough (i.e., lower than the basic utility α). In contrast, the lower price combination is the optimal solution when the price of GM food is high enough (i.e., higher than the basic utility α). Actually, the price of GM food is larger than the basic utility when the difference between the conventional food and GM food is large enough. In the separating perfect Bayesian equilibriums, there exists the corresponding lowest price for the firm producing the conventional food to distinguish it from the other types of firms. Third, in the separating perfect Bayesian equilibrium, it is ambiguous whether the quantity of the conventional food is smaller than the quantity of GM food. Finally, the profits of the G-type firm and the T-type firm are both monotonically increasing in the price of GM food.

Our numerical example and sensitivity analysis also show that increases of the expected net potential damage, the perceived proportion of T-type firm, the degree of product substitution, and the degree of risk aversion all lead to decreases of the price of GM food; and an increase of the volatility of potential risk leads to an increase of the price of GM food. From the perspective of the average volatility, the price of GM food is most sensitive to the expected net potential damage.

Additionally, increases of the expected net potential damage and the volatility of potential risk both lead to increases of the price of the conventional food; increases of the perceived proportion of T-type firm, the degree of product substitution, and the degree of risk aversion all lead to decreases of the price of the conventional food. Moreover, the price of the conventional food is most sensitive to the expected net potential damage.

Finally, the quantity of GM food, the quantity of the conventional food, the profits of G-type firm, and the profits of T-type firm all decrease as the expected net potential damage, and the volatility of potential risk, the perceived proportion of T-type firm, the degree of product substitution, or the degree of risk aversion increases. Moreover, the quantities of GM food and the conventional food and the profits of G-type firm and T-type firm are all most sensitive to the expected net potential damage. Finally, the degree of risk aversion is the second sensitive parameter to the profits of T-type firm.

Several important policy implications emerge based on the results from our theory deduction and sensitivity analysis. First, the improved traits via genetically modified technology should be encouraged to be developed and presented to decrease the expected potential net damage and hence to increase the profits of both types of firms. Second, our simulation results show that the expected potential net damage is the most sensitive parameter to the prices of GM food and the conventional food, the quantities of the conventional food and GM food, and also the profits of two types of firms. Thus, government should help consumers to know more about GM food, particularly its generally regarded as safe nature. Although some recent studies show certain GM foods may negatively impact human health [26], numerous studies also show GM food to be as safe as the conventional food [27]. Labelling is not required for GM plant food since the Food & Drug Administration (FDA) in United States thinks GM food is bioequivalent to conventional plant food. The risk rankings of Costa-Font et al. [31] also indicate that GM food is perceived as less risky than irradiation, artificial growth hormones in food, or pesticides used in the production process. Thus, given these potential upsides, it is essential to officially enhance the popularization of the science on GM food to help reduce the consumers' expected potential fears. Third, governments should encourage the innovation of food products to increase the product differentiation, which helps increase the food's price, quantities, and firm profitability. Finally, our results show that the profit of the firm producing the conventional food is very sensitive to the degree of risk aversion, while the decrease in the degree of risk aversion helps increase the food's price, quantity, and the firm's profits. Different consumers have different degrees of risk aversion [32]. Government should consider the heterogeneity of consumers in their degree of risk aversion when making policy-decisions, particularly with wide-ranging public health concerns.

Appendix

Proof of Lemma 7. Based on Definition 4, in order to separate from G-type firm, the best response for the type T firm would be a member of the following set:

$$\left\{ p \mid (p - c_G) h_T (d_T - p) \leq \frac{h_G (d_G - c_G)^2}{4},\ (p - c_T) h_T (d_T - p) \geq \frac{h_G (d_G - c_T)^2}{4} \right\}, \tag{A.1}$$

where $c_G = 0$ and $c_T = k$.

The first inequality says that G-type firm prefers to charge price p_{GG} rather than price p to be perceived as T-type, which means G-type firm has no incentive to act as T-type in this situation. The second inequality says that T-type firm prefers to charge price p to be perceived as T-type rather than p_{TG}, which means it is worthwhile for the T-type firm to use this price to avoid being perceived as a type G firm.

Based on Assumption 3 ($E(\delta_i) > k > 0$) and the fact $d_T - d_G\sqrt{h_G/h_T} > d_T - d_G = E(\delta_i)$, we obtain the following inequality:

$$0.5\left\{d_T + c_G + \sqrt{(d_T - c_G)^2 - \frac{h_G}{h_T}(d_G - c_G)^2}\right\} > 0.5\left\{d_T + c_T - \sqrt{(d_T - c_T)^2 - \frac{h_G}{h_T}(d_G - c_T)^2}\right\}. \tag{A.2}$$

And hence T-type firm's best response belongs to the following interval:

$$\left[0.5\left\{d_T + c_G + \sqrt{(d_T - c_G)^2 - \frac{h_G}{h_T}(d_G - c_G)^2}\right\},\ 0.5\left\{d_T + c_T + \sqrt{(d_T - c_T)^2 - \frac{h_G}{h_T}(d_G - c_T)^2}\right\}\right]. \tag{A.3}$$

The key question is whether $(c_T + d_T)/2$ belongs to the interval above. If yes, then T-type firm's best response is $(c_T + d_T)/2$ because it leads to maximized profits. However, if $(c_T + d_T)/2$ does not belong to the interval above, then T-type firm's best response turns to be the floor price of the interval above, that is, $0.5\{d_T + c_G + \sqrt{(d_T - c_G)^2 - (h_G/h_T)(d_G - c_G)^2}\}$.

The fact is $p_{TT} = (c_T + d_T)/2 < 0.5\{d_T + c_G + \sqrt{(d_T - c_G)^2 - (h_G/h_T)(d_G - c_G)^2}\}$ because of Assumption 3, which means p_{TT} is not high enough to distinguish the T-type firm from the G-type firm.

Thus, given $E(p^*)$, in the separating equilibrium, T-type firm's best response is $p_T(E(p^*)) = 0.5(d_T + \sqrt{d_T^2 - (h_G/h_T)d_G^2})$, while G-type firm's best response is $p_G(E(p^*)) = d_G/2$. The definition of d_v yields $E(\delta) = d_T - d_G$. Therefore $p_T(E(p^*)) - p_G(E(p^*)) = 0.5(E(\delta) + \sqrt{d_T^2 - (h_G/h_T)d_G^2}) > 0$, which means the own-price and the expected rival's price are strategic complements. □

Proof of Proposition 6. Profits Π_{uv} would be maximized when $p_{uv} = (c_u + d_v)/2$ and accordingly the maximum profits $\max(\Pi_{uv}) = h_v(d_v - c_u)^2/4$. Since c_u is an increasing function of the true product type and d_v is an increasing function of the perceived product type, the prices p_{uv} have the following relationship: $p_{TT} > p_{GT} > p_{GG}$, and $p_{TT} > p_{TG} > p_{GG}$.

Based on the fact $E(\delta_i) = d_T - d_G$ and Assumption 3, we obtain $d_T - d_G > c_T - c_G = k$ and $p_{GT} > p_{TG}$. Therefore the prices p_{uv} are ordered as follows: $p_{TT} > p_{GT} > p_{TG} > p_{GG}$. □

Proof of Proposition 8. Each firm plays its best response according to its own type, given the rival's pricing strategy. Then based on the definition of $E(p^*)$ and Lemma 7, we know the expected price $E(p^*)$ in the separating equilibrium is a solution to the following equation:

$$X = \lambda p_T(X) + (1-\lambda) p_G(X) = \frac{\lambda d_T}{2} + \left(\frac{\lambda}{2}\right)\sqrt{\left(d_T + \sqrt{\frac{h_G}{h_T}} d_G\right)\left(d_T - \sqrt{\frac{h_G}{h_T}} d_G\right)} + \frac{(1-\lambda) d_G}{2}. \quad (A.4)$$

Substituting d_T and d_G into the equation above, we obtain

$$X = \frac{S+\eta X}{2} + \frac{\lambda}{2} E(\delta) + \lambda \left\{ \left[\left(1+\sqrt{\frac{h_G}{h_T}}\right)\frac{S+\eta X}{2} + \frac{E(\delta)}{2}\right] \cdot \left[\left(1-\sqrt{\frac{h_G}{h_T}}\right)\frac{S+\eta X}{2} + \frac{E(\delta)}{2}\right]\right\}^{1/2}, \quad (A.5)$$

where $S \equiv \alpha - E(\delta) - \gamma[\alpha - (1-\lambda)E(\delta)]/(\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta))$, and $\eta \equiv \gamma/(\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta))$.

Let $Y \equiv (S+\eta X)/2$, then $X = (2Y - S)/\eta$, and (A.5) can be rewritten as

$$Y\left(\frac{2}{\eta} - 1\right) - \frac{S}{\eta} - \frac{\lambda}{2} E(\delta) = \lambda \left\{\left[\left(1+\sqrt{\frac{h_G}{h_T}}\right) Y + \frac{E(\delta)}{2}\right] \cdot \left[\left(1-\sqrt{\frac{h_G}{h_T}}\right) Y + \frac{E(\delta)}{2}\right]\right\}^{1/2}. \quad (A.6)$$

Note that $p_G(E(p^*)) = d_G/2 = Y$.

Let

$$\omega \equiv \left\{\left[\left(1+\sqrt{\frac{h_G}{h_T}}\right) Y + \frac{E(\delta)}{2}\right] \cdot \left[\left(1-\sqrt{\frac{h_G}{h_T}}\right) Y + \frac{E(\delta)}{2}\right]\right\}^{1/2} = \sqrt{\left(1-\frac{h_G}{h_T}\right) Y^2 + E(\delta) Y + \frac{E^2(\delta)}{4}}, \quad (A.7)$$

and then $p_T(E(p^*)) = d_T/2 + \omega$ and $p_T(E(p^*)) - p_G(E(p^*)) = \omega + E(\delta)/2 > 0$.

Equation (A.6) can be written as

$$\xi_1 Y^2 + \xi_2 Y + \xi_3 = 0, \quad (A.8)$$

where $\xi_1 = (2/\eta - 1)^2 - \lambda^2(1 - h_G/h_T)$, $\xi_2 = -(4/\eta - 2)(S/\eta) - \lambda(2/\eta - 1)E(\delta) - \lambda^2 E(\delta)$, and $\xi_3 = (S/\eta)\lambda E(\delta) + (S/\eta)^2$.

Obviously the coefficient ξ_2 is negative while ξ_3 is positive. Next we infer the sign of the coefficient ξ_1.

$$\xi_1 = \left(\frac{2}{\eta} - 1\right)^2 - \lambda^2\left(1 - \frac{h_G}{h_T}\right), \quad (A.9)$$

where $S \equiv \alpha - E(\delta) - \gamma[\alpha - (1-\lambda)E(\delta)]/(\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta))$, $\eta \equiv \gamma/(\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta))$,

$$h_G = \frac{\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta)}{[\beta + \tau \mathrm{var}(\delta)]\left[\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta)\right] - \gamma^2}, \quad h_T = \frac{\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta)}{\beta\left[\beta + \tau(1-\lambda)^2 \mathrm{var}(\delta)\right] - \gamma^2}. \quad (A.10)$$

Obviously ξ_1 is the decreasing function of λ under the assumption of $\beta > \gamma$.

$$\min \xi_1 = \xi_1 \mid (\lambda = 0) = \left(\frac{2}{\eta} - 1\right)^2 > 0,$$
$$\max \xi_1 = \xi_1 \mid (\lambda = 1) = \frac{4\beta(\beta+\gamma)(\beta-\gamma)^2 + \gamma^2(\beta+\gamma)(\beta-\gamma) + 4\beta^2\tau \mathrm{var}(\delta)(\beta-\gamma)}{\gamma^2\{\beta[\beta + \tau \mathrm{var}(\delta)] - \gamma^2\}} > 0, \quad (A.11)$$

and hence $\xi_1 > 0$. According to $\xi_1 > 0$, $\xi_2 < 0$, and $\xi_3 > 0$, we infer that (A.8) has two positive roots.

$$Y^* = \frac{(4/\eta - 2)(S/\eta) + \lambda(2/\eta - 1)E(\delta) + \lambda^2 E(\delta)}{2\left[(2/\eta - 1)^2 - \lambda^2(1 - h_G/h_T)\right]}$$

$$\pm \frac{\sqrt{\left[(4/\eta-2)(S/\eta)+\lambda(2/\eta-1)E(\delta)+\lambda^2E(\delta)\right]^2-4\left[(2/\eta-1)^2-\lambda^2(1-h_G/h_T)\right]\left[(S/\eta)\lambda E(\delta)+(S/\eta)^2\right]}}{2\left[(2/\eta-1)^2-\lambda^2(1-h_G/h_T)\right]}, \tag{A.12}$$

where

$$S \equiv \alpha - E(\delta) - \frac{\gamma\left[\alpha-(1-\lambda)E(\delta)\right]}{\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)},$$
$$\eta \equiv \frac{\gamma}{\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)},$$
$$1-\frac{h_G}{h_T} = \frac{\tau\operatorname{var}(\delta)\left[\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)\right]}{\left[\beta+\tau\operatorname{var}(\delta)\right]\left[\beta+\tau(1-\lambda)^2\operatorname{var}(\delta)\right]-\gamma^2}. \tag{A.13}$$

We can derive ω according to the fact $\omega = \sqrt{(1-h_G/h_T)Y^2+E(\delta)Y+E^2(\delta)/4}$. We noted above that $p_G(E(p^*)) = d_G/2 = Y$ and $p_T(E(p^*)) = d_T/2+\omega = Y+\omega+E(\delta)/2$. And hence the equilibrium prices of GM food and conventional food are $p_G = Y^*$ and $p_T = Y^*+\omega^*+E(\delta)/2$, respectively. The price of conventional food is significantly higher than that of GM food in terms of separating equilibrium, and additionally the price gap between the traditional food and GM food is positively correlated to the expected net potential damage $E(\delta)$ because of the positive correlation between ω^* and $E(\delta)$.

Therefore there exist two different separating perfect Bayesian equilibriums consisting of a pair of prices (P_G, P_T) with $P_G < P_T$ and supporting beliefs $B(p^*)$, with $B(p^*) = 1$ if $p \ge P_T$, and $B(p^*) = 0$ if $p < P_T$. □

Proof of Proposition 9. In the separating perfect Bayesian equilibrium, two firms' quantities are $Q_G = h_GY^*$ and $Q_T = h_T(d_T-p_T) = h_T(Y^*+E(\delta)/2-\omega^*)$, respectively. $Q_T/Q_G = (h_T(Y^*+E(\delta)/2-\omega^*)/h_GY^*)(E(\delta)/2)-\omega^* < 0$, $h_G/h_T < 1$, and hence the sign of (Q_T/Q_G-1) depends on $(\omega^*-0.5E(\delta))/Y^*$ and $(1-h_G/h_T)$. $Q_T < Q_G$ holds if $(\omega^*-0.5E(\delta))/Y^* > 1-h_G/h_T$; $Q_T > Q_G$ holds if $(\omega^*-0.5E(\delta))/Y^* < 1-h_G/h_T$. According to the proof of Proposition 8, we know the equilibrium prices of GM food and conventional food are $p_G = Y^*$ and $p_T = Y^*+\omega^*+E(\delta)/2$, respectively. It means that, in the separating perfect Bayesian equilibrium, $Q_T < Q_G$ holds if $(p_T-p_G-E(\delta))/p_G > 1-h_G/h_T$; $Q_T > Q_G$ holds if $(p_T-p_G-E(\delta))/p_G < 1-h_G/h_T$. □

Proof of Proposition 10. In the equilibrium, two firms' profits are $\Pi_T = (Y^*+E(\delta)/2+\omega^*-k)h_T(Y^*+E(\delta)/2-\omega^*)$ and $\Pi_G = h_G(Y^*)^2$, respectively.

As for the G-type firm, obviously its profit (Π_G) is an increasing function of Y^* or the price of GM food since $Y^* > 0$ and $\partial\Pi_G/\partial Y^* > 0$ always holds. As for the T-type firm, substitution of ω^* in terms of Y^* and simplification yield the following form in Y^*:

$$\begin{aligned}\Pi_T &= \left(Y^*+\frac{E(\delta)}{2}+\omega^*-k\right)h_T\left(Y^*+\frac{E(\delta)}{2}-\omega^*\right)\\ &= \left(1-\frac{h_G}{h_T}\right)^2Y^{*4}+2E(\delta)\left(1-\frac{h_G}{h_T}\right)Y^{*3}\\ &\quad+\left[1+E^2(\delta)+\left(\frac{E^2(\delta)}{2}-k\right)\left(1-\frac{h_G}{h_T}\right)\right]Y^{*2}\\ &\quad+\left[E(\delta)-k+\left(\frac{E^2(\delta)}{2}-k\right)E(\delta)\right]Y^*\\ &\quad+\left(\frac{E^2(\delta)}{4}-\frac{E(\delta)}{2}\right)\left(\frac{E^2(\delta)}{4}+\frac{E(\delta)}{2}-k\right).\end{aligned} \tag{A.14}$$

Based on Assumption 1, we know Π_T increases as Y^* since $Y^* > 0$ and $\partial\Pi_T/\partial Y^* > 0$ always holds. Hence, the profits of the G-type firm and the T-type firm are both monotonically increasing in the price of GM food. □

Proof of Proposition 11. Although (A.8) has two positive roots, which one is the optimal solution? The answer depends on the profits and the basic utility α.

Proposition 10 shows the profits functions of the G-type firm and the T-type firm both monotonically increase as the price of GM food. Therefore, in terms of the principle of maximizing profits, the bigger Y^* is the optimal solution; that is,

$$\begin{aligned}Y^* &= \frac{(4/\eta-2)(S/\eta)+\lambda(2/\eta-1)E(\delta)+\lambda^2E(\delta)}{2\left[(2/\eta-1)^2-\lambda^2(1-h_G/h_T)\right]}\\ &\quad+\frac{\sqrt{\left[(4/\eta-2)(S/\eta)+\lambda(2/\eta-1)E(\delta)+\lambda^2E(\delta)\right]^2-4\left[(2/\eta-1)^2-\lambda^2(1-h_G/h_T)\right]\left[(S/\eta)\lambda E(\delta)+(S/\eta)^2\right]}}{2\left[(2/\eta-1)^2-\lambda^2(1-h_G/h_T)\right]}.\end{aligned} \tag{A.15}$$

And hence the separating perfect Bayesian equilibrium consisting of a pair of the larger prices (P_G^*, P_T^*) is the first-best solution if $P_G^* < P_T^* < \alpha$, while the smaller prices (P_G^*, P_T^*) are the first-best solution if $P_T^* \ge P_G^* \ge \alpha$. □

Next we prove the larger $P_G^* \geq \alpha$ holds if γ is small enough. Obviously the smaller P_G^* is smaller than $((4/\eta - 2)(S/\eta) + \lambda(2/\eta - 1)E(\delta) + \lambda^2 E(\delta))/2[(2/\eta - 1)^2 - \lambda^2(1 - h_G/h_T)]$, while the larger P_G^* is larger than $((4/\eta - 2)(S/\eta) + \lambda(2/\eta - 1)E(\delta) + \lambda^2 E(\delta))/2[(2/\eta - 1)^2 - \lambda^2(1 - h_G/h_T)]$.

Since S can be rewritten as $\alpha - E(\delta) - \eta[\alpha - (1-\lambda)E(\delta)]$ and $1 - h_G/h_T$ can be expressed as $\tau\,\mathrm{var}(\delta)/([\beta + \tau\,\mathrm{var}(\delta)] - \eta\gamma)$, $(4/\eta - 2)(S/\eta) + \lambda(2/\eta - 1)E(\delta) + \lambda^2 E(\delta)/2[(2/\eta - 1)^2 - \lambda^2(1 - h_G/h_T)]$ will be equal to $((2 - 3\eta + \eta^2)\alpha + [3\eta - \lambda\eta - 2 - \eta^2(1 + \lambda/2 + \lambda^2/2)]E(\delta))/\eta^2[(2/\eta - 1)^2 - \lambda^2(\tau\,\mathrm{var}(\delta)/((\beta + \tau\,\mathrm{var}(\delta)) - \eta\gamma))] \equiv \Psi$. When the degree of product substitution γ is small enough (i.e., the difference between the conventional food and GM food is large enough), we can obtain $\eta \rightarrow 0$ and hence the numerator of Ψ converges to $2(\alpha - E(\delta))$ and the denominator converges to 0. Therefore $\Psi \rightarrow \infty$. Therefore the larger $P_G^* > \Psi > \alpha$ holds when the difference between the conventional food and GM food is large enough.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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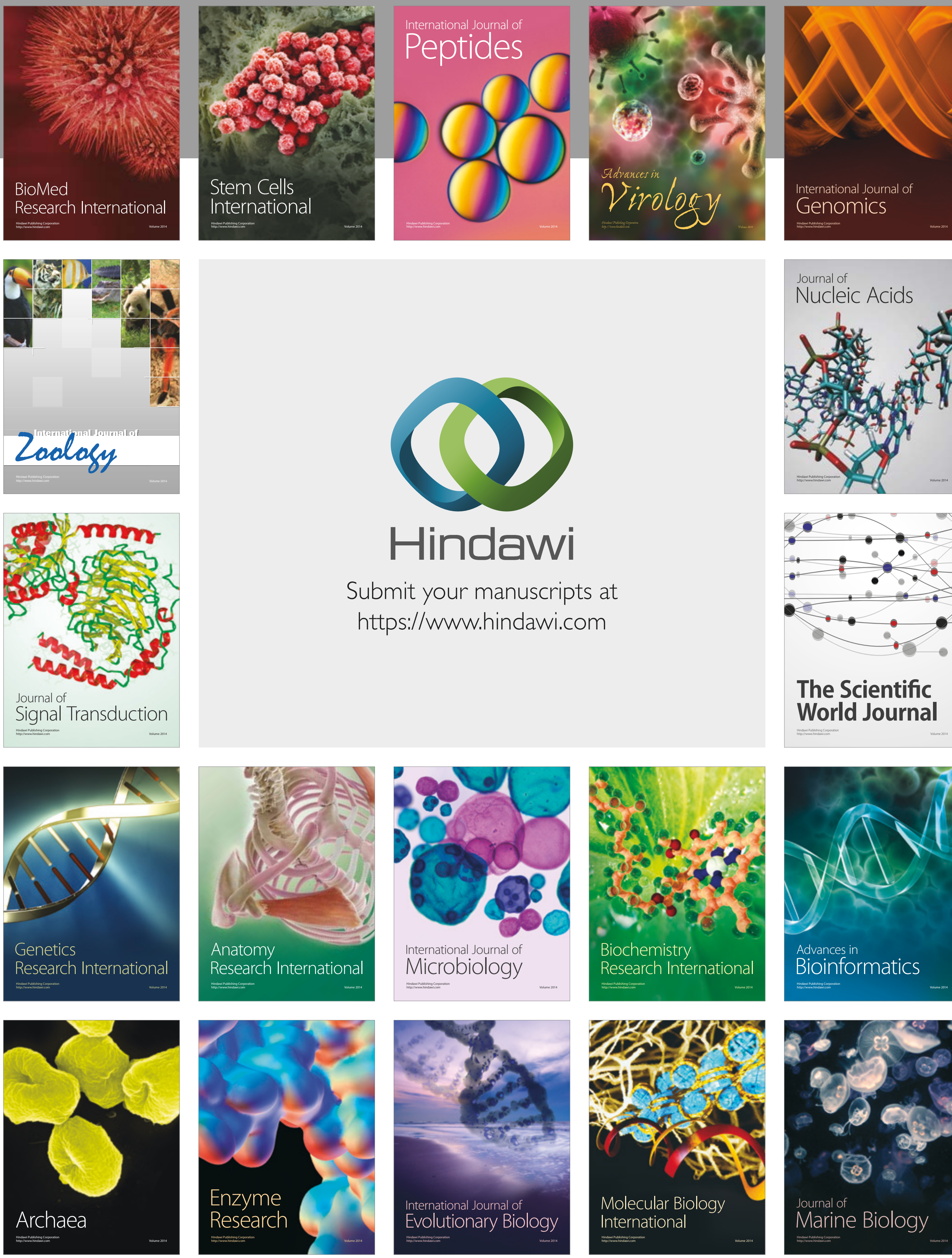
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