AN ECONOMIC ANALYSIS OF NANOFOOD LABELING

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ABSTRACT

The paper examines the economic effects of labeling of food nanotechnology products using an analytical framework of heterogeneous consumers and imperfectly competitive suppliers. Labeling results in increased costs for nanofood producers that in turn increase nanofood prices and reduce their market demand; the cost effect of the labeling policy. Labeling also affects consumer preferences, the preference effect, by reducing uncertainty regarding the nature of the food product (certainty effect), and by potentially being perceived as a warning signal (stigma effect). The market and welfare impacts of nanofood labeling depend on which of the above effects dominate. If consumer aversion towards food nanotechnology increases due to labeling, nanofood suppliers incur losses to the benefit of suppliers of conventional and organic food substitutes and welfare decreases for most of consumers. Consumers who experience greater losses are those with relatively high aversion to interventions in the production process. On the other hand, if the labeling regime results in consumers becoming less averse to food nanotechnology and the preference effect dominates the cost effect, then nanofood suppliers see their profits increase. The economic impacts of nanofood labeling are intensified when consumers have low awareness of food nanotechnology prior to the implementation of the labeling policy and/or when competition among food suppliers is more intense.

JEL classification: L13, Q13, Q18.

Keywords: food nanotechnology; consumer heterogeneity; consumer and producer welfare; food labeling.

I. Introduction

The application of nanotechnology[1] in the food sector has the potential to transform food production by increasing food supply and enhancing food quality and safety.[2] While the potential benefits of food nanotechnology can be immense, its potential risks, including possible toxicity of nanoparticles which could be harmful to humans and the environment, are not well understood. An inventory report by the Project on Emerging Nanotechnologies shows that, as of

[1] Nanotechnology is a science that involves ‘the design and application of structures, devices and systems on a nanoscale; that is billionth of a meter’ (National Nanotechnology Initiative).
[2] Food nanotechnology applications include: nanosensors for monitoring crop growth and pest control; additives and ingredients that enable changes in food texture, taste, processability and quality; packaging material that release preservatives to extend food life and improve food safety by signaling whether food is contaminated or spoiled (Sekhon 2010).

January 2014, there are 199 manufacturer-identified nanofood products (PEN 2013).[3] None of these products, however, is labeled as a nanofood. Major impediments to mandatory labeling have been the disagreement on the definition of nanofoods and lack of appropriate risk assessment due to "difficulties in characterizing, detecting and measuring nanomaterials and insufficient information on toxicology data" (Cushen 2012, p.40; Gruere 2011). Some caution that, given the lack of appropriate risk assessments, the role of mandatory labeling is limited to informing consumers of the nature of the products rather than providing a necessary precautionary measure (Gruere 2011).

Currently, with the exception of the EU where mandatory labeling of nanotechnology is underway and will take effect in December of 2014,[4] mandatory labeling of food nanotechnology is not required in any country. Taiwan is the first country to carry out a certification system, the Nano-Mark, for nanoproducts that meet specific standards as a means of a voluntary labeling system that promotes safe and high quality nanoproducts (Chau et al. 2007). In the US, there are currently no plans to implement mandatory labeling of the use of nanotechnology despite being the country with the largest number of commercialized consumer products (Chau et al. 2007).[5] The Food and Drug Administration (FDA) maintains its position on regulating products, and states that "food (except food or color additives) is not subject to mandatory premarket review" (FDA 2012).

The lack of nanofood labeling could explain, at least in part, why approximately eighty percent of participants in recent EU and US surveys reported to know "nothing" or "a little"

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[3] Examples include Hershey's chocolate, Kraft Mayo, M&M's chocolate, Nestlé Coffee Mate, Albertsons cheese and Philadelphia cream cheese. See http://www.nanotechproject.org/cpi/about/background/ for information about how food products are registered as nanofoods.
[4] The word "nano" must be placed on the product's label next to the man-made nanomaterials or nano-ingredients used in food production (NanoTrust Dossier 2012).
[5] Currently in the US the Environmental Protection Agency (EPA) is developing a Significant New Use Rule (SNUR) to ensure that nanoscale material receive appropriate review while the FDA outlines that "the paradigm for regulation of these products is based on the concepts of 'risk management', i.e. risk identification, risk analysis, and risk control" (FDA, 2011). A draft guidance for nanofoods is circulated for comments but not for implementation.

about (food) nanotechnology (IFIC 2012; European Commission 2010; Food Safety News 2010; Kahan 2009; Cobb and Macoubrie 2004). The rising number of nanofood products on the market and the low public awareness towards food nanotechnology have given rise to a policy debate as to whether labeling should be imposed. Proponents of labeling point to the need of protecting the right of consumers to be informed and warn that lack of transparency may create a backlash for the food nanotechnology sector if the public perceives the withholding of information to imply that the technology has undesirable or harmful consequences. Brown and Kuzma (2013) find that US consumers were willing to pay for nanofood labeling as a means of avoiding risk, even when the risk was perceived to be minimal. In contrast, skeptics of the labeling regulation are concerned that the designation of "nano" on food labels might hinder the acceptability of nanotechnology by consumers who might perceive it as a warning that nano-ingredients or nano-materials are intrinsically harmful, even when such risks are not scientifically validated (Gruere 2011; Siegrist 2008). Siegrist and Keller (2011) support this argument in a study showing that nanotechnology labels resulted in an increase of perceived risks and a reduction of perceived benefits compared to no labeling. An adverse consumer response to nanofood labeling might hinder the adoption of food nanotechnology by producers and/or processors under a mandatory labeling regime and might even deter voluntary labeling when labeling is not mandated. Despite the significant (and rising) interest in the ramifications of a nanofood labeling regime, there has been, to our knowledge, no systematic analysis of its market and welfare impacts.

This paper addresses this issue and develops a framework of heterogeneous consumers and imperfectly competitive suppliers to examine the effects of the introduction of nanofood labeling on (a) equilibrium prices and quantities of existing products, and (b) the welfare of the interest groups involved (i.e., consumers and suppliers of nanofoods and their conventional and organic counterparts). Different scenarios on the consumer attitudes towards nanofoods and the potential impact of labeling on these attitudes are considered within this framework. Specifically, the paper examines the market and welfare implications of nanofood labeling under the following cases: (1) under no labeling consumers are more averse to food nanotechnology than conventional food technology and their aversion increases under the labeling regime; (2) under no labeling consumers are less averse to food nanotechnology than conventional food technology and their aversion for nanofoods either increases or decreases under the labeling regime; (3) under no labeling consumers are unaware of the presence of food nanotechnology and their preference is formed under the labeling regime.

II. Market and welfare effects under a no labeling regime

Consider a food product that is produced using one of the following production methods: nanotechnology, conventional, or organic production method. Let $\alpha \in [0,1]$ be the consumer differentiating characteristic which captures consumer aversion to interventions in the production process; the more intrusive is a technology perceived to be, the greater is the value of α. Assume consumers are uniformly distributed with respect to α, each consumes one unit of their preferred product, and this consumption accounts for a small share of their budget. Under no labeling for food nanotechnology products, the consumer utility associated with the consumption of a unit of the nanofood, conventional, and organic food substitute is given by:[6]

$$
\begin{aligned}
U_c^{nl} &= U - P_c^{nl} - c\alpha && \text{if the conventional food product is consumed} \\
U_n^{nl} &= U + V - P_n^{nl} - n^{nl}\alpha && \text{if the nanofood product is consumed} \\
U_h^{nl} &= U - P_h^{nl} + h\alpha && \text{if the organic food product is consumed}
\end{aligned}
\tag{1}
$$

Here U denotes a base level of utility obtained from consuming a unit of the food product produced by any of the above production methods, and is common for all consumers. V captures

[6] See Tran, Yiannaka, and Giannakas (2014) for specifics on the framework.

consumer valuations of the enhanced attributes enabled by food nanotechnology and it is non-negative. P_c^{nl}, P_n^{nl}, and P_h^{nl} are market prices for the conventional food, nanofood, and organic food in the absence of nanofood labels, respectively (the superscripts *'nl'* and *'l'* are used to denote the no labeling and labeling regimes, henceforth). $c, h,$ and n^{nl} are utility discount or enhancement factors associated with consuming a unit of the conventional, organic, and nanofood product, respectively, capturing the intensity of consumer preferences for the production technologies used to produce the above products with $c > 0$ and $h > 0$.[7] Note that although the value of α, the characteristic which differentiates consumers based on their preferences/aversion towards the level of interventions in the production process, remains constant after the nanofood labeling policy is implemented, n^{nl} may change reflecting the effects of labeling on consumer preferences for the nanofood (e.g., certainty effect or stigma effect, which shall be discussed at length in the labeling section). Given the above, $n^{nl}\alpha$, for example, can be interpreted as consumer utility discount or enhancement for the use of food nanotechnology in the absence of nanofood labeling for the consumer of the differentiating characteristic α. In most cases, organic production methods are perceived as less intrusive than conventional production methods (e.g., minimal interventions with respect to the use of pesticides, chemicals, or hormones in food production). However, whether it is the conventional or the nanotechnology production methods that are perceived as more intrusive depends on how consumers evaluate risks and benefits of nanotechnology and/or which types of nanofood applications are being considered.[8] To capture all plausible cases regarding consumer attitudes

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[7] It follows that consumer willingness-to-pay for a unit of conventional food, nanofood, and organic food is given by $U - c\alpha$, $U + V - n^{nl}\alpha$, and $U + h\alpha$, respectively.

[8] Food nanotechnology could be perceived as *less* intrusive than conventional technology if consumers place more weight on applications of food nanotechnology such as reducing pesticide and chemical use in food production or its potential to address non-point source pollution problems or *mor*e intrusive if consumers care more about the potential risks of releasing nanoparticles into the environment. In addition, nano-based applications on the

towards food nanotechnology, the utility maximization problem in equation (1) will be considered under three scenarios: Scenario A where consumers (of the differentiating characteristic α) perceive food nanotechnology as more intrusive than conventional production methods (i.e., $n^{nl} > c$), Scenario B when consumers perceive food nanotechnology as less intrusive than conventional production methods (i.e., $n^{nl} < c$), and Scenario C where consumers are unaware of food nanotechnology or indifferent between food nanotechnology and conventional production methods (i.e., $n^{nl} = c$).

Consider scenario A where consumers are more averse towards the use of food nanotechnology than conventional technology under a no labeling regime. Let $\alpha_n^{nl} : U_n^{nl}(\alpha_n) = U_c^{nl}(\alpha_n) => \alpha_n^{nl} = \dfrac{P_c^{nl} - P_n^{nl} + V}{n^{nl} - c}$ the consumer who obtains the same utility from the consumptions of the nanofood and the conventional food in the no labeling regime and is, thus, indifferent between the two options. The consumer with the differentiating characteristic $\alpha_c^{nl} : U_c^{nl}(\alpha_c) = U_h^{nl}(\alpha_c) => \alpha_c^{nl} = \dfrac{P_h^{nl} - P_c^{nl}}{h + c}$ is indifferent between the conventional food and the organic food substitute. Given the above, the consumer with the differentiating characteristic α such that $\alpha \in [0, \alpha_n^{nl}], \alpha \in (\alpha_n^{nl}, \alpha_c^{nl}],$ and $\alpha \in (\alpha_c^{nl}, 1]$ consumes the nanofood, conventional, and organic food substitute, respectively (see Figure 1). Since consumers are uniformly distributed along α, the market demand for the three food products under coexistence of the three product forms is determined by:

$$X_n^{nl} = \alpha_n^{nl} = \frac{P_c^{nl} - P_n^{nl} + V}{n^{nl} - c},\; X_h^{nl} = 1 - \alpha_c^{nl} = \frac{h + c - P_h^{nl} + P_c^{nl}}{h + c},$$
$$X_c^{nl} = \alpha_c^{nl} - \alpha_n^{nl} = \frac{(n^{nl} - c)(P_h^{nl} - P_c^{nl}) - (h + c)(P_c^{nl} - P_n^{nl} + V)}{(h + c)(n^{nl} - c)}.$$

packaging such as sensors which signal the freshness or ripeness of the food product inside could be perceived to be less intrusive than applications where nanoparticles are part of the product.

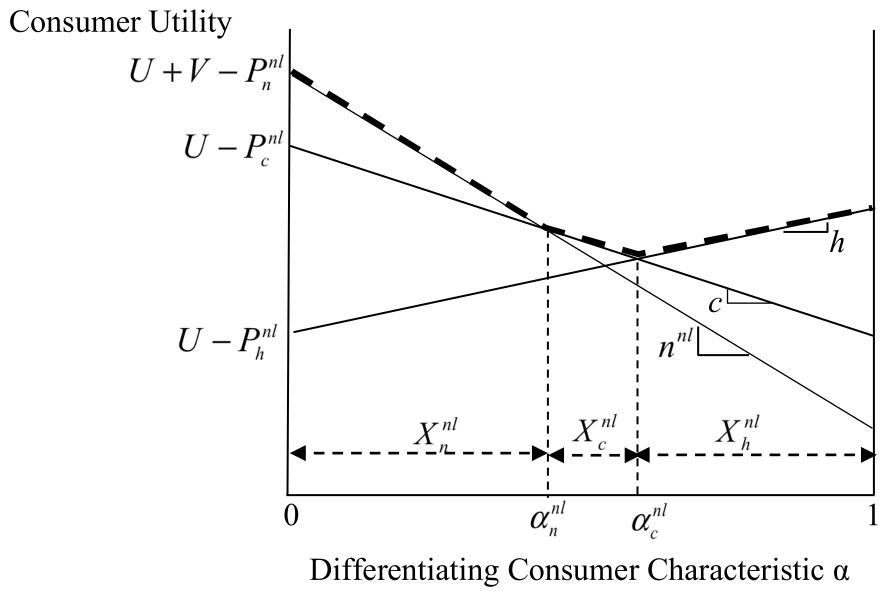

Figure 1: Consumer decisions and market shares under no labeling under scenario A ($n^{nl} > c$).

It follows that the inverse demands under scenario A are:

$$
\begin{aligned}
P_n^{nl}(X_n^{nl}) &= P_c^{nl} + V - (n^{nl} - c)X_n^{nl} \\
P_c^{nl}(X_c^{nl}) &= \frac{(n^{nl} - c)P_h^{nl} + (h+c)(P_n^{nl} - V) - (h+c)(n^{nl} - c)X_c^{nl}}{h + n^{nl}} \\
P_h^{nl}(X_h^{nl}) &= P_c^{nl} + h + c - (h+c)X_h^{nl}
\end{aligned}
\qquad (2)
$$

Similarly, the inverse demands under scenario B where consumers under no labeling perceive food nanotechnology as more intrusive than conventional food technology can be derived as:

$$
\begin{aligned}
P_c^{nl}(X_c^{nl}) &= P_n^{nl} - V - (c - n^{nl})X_c^{nl} \\
P_n^{nl}(X_n^{nl}) &= \frac{(c - n^{nl})P_h^{nl} + (h + n^{nl})P_c^{nl} - (h+c)P_n^{nl} + (h+c)V}{(c - n^{nl})(h + n^{nl})} \\
P_h^{nl}(X_h^{nl}) &= P_n^{nl} + h + n^{nl} - V - (h + n^{nl})X_h^{nl}
\end{aligned}
\qquad (3)
$$

Under scenario C where consumers are, under the no labeling regime, unaware of food nanotechnology or indifferent between nanotechnology and conventional food production method, the inverse demand functions are given in equation (4).

$$P_c^{nl}\left(X_c^{nl}\right)=P_h^{nl}-2\left(h+c\right)X_c^{nl}$$
$$P_n^{nl}\left(X_n^{nl}\right)=P_h^{nl}+V-2\left(h+c\right)X_n^{nl} \tag{4}$$
$$P_h^{nl}\left(X_h^{nl}\right)=P_c^{nl}+h+c-\left(h+c\right)X_h^{nl}$$

Having derived the demand functions, we next find the market quantities and prices for the conventional, nanofood, and organic food by solving the profit maximization problem as shown in equation (5).

$$\underset{x_i}{Max}\ \pi_c^{nl}=(P_c^{nl}(X_c^{nl})-C_c)x_i,\quad s.t.\ P_c^{nl}(X_c^{nl})=g_1(P_h^{nl},P_n^{nl})$$
$$\underset{x_k}{Max}\ \pi_n^{nl}=(P_n^{nl}(X_n^{nl})-C_n^{nl})x_k,\quad s.t.\ P_n^{nl}(X_n^{nl})=g_2(P_h^{nl},P_c^{nl}) \tag{5}$$
$$\underset{x_j}{Max}\ \pi_h^{nl}=(P_h^{nl}(X_h^{nl})-C_h)x_j,\quad s.t.\ P_h^{nl}(X_h^{nl})=g_3(P_c^{nl},P_n^{nl})$$

where *g(.)* is given by equation (2) under scenario A, equation (3) under scenario B, and equation (4) under scenario C; x_i, x_k, and x_j are the quantities supplied by firms *i, k* and *j* in the conventional food, nanofood, and organic food supply sector, respectively; and C_c, C_n^{nl}, and C_h are unit costs of producing the conventional, nanofood, and organic food product in the absence of nanofood labeling, respectively. For example, under scenario A $(n^{nl}>c)$, the profit maximization problem when the three products coexist[9] in the market is given by:

$$\underset{x_i}{Max}\ \pi_c^{nl}=(P_c^{nl}(X_c^{nl})-C_c)x_i,\quad s.t.\ P_c^{nl}(X_c^{nl})=\frac{(n^{nl}-c)P_h^{nl}+(h+c)(P_n^{nl}-V)-(h+c)(n^{nl}-c)X_c^{nl}}{h+n^{nl}}$$
$$\underset{x_k}{Max}\ \pi_n^{nl}=(P_n^{nl}(X_n^{nl})-C_n^{nl})x_k,\quad s.t.\ P_n^{nl}(X_n^{nl})=P_c^{nl}+V-(n^{nl}-c)X_n^{nl}$$
$$\underset{x_j}{Max}\ \pi_h^{nl}=(P_h^{nl}(X_h^{nl})-C_h)x_j,\quad s.t.\ P_h^{nl}(X_h^{nl})=P_c^{nl}+h+c-(h+c)X_h^{nl}$$

[9] See Appendix A1 for the conditions a nanotechnology innovation has to satisfy to coexist with the conventional and organic food products, drive the conventional food out of the market, or be driven out of the market.

Let θ_c, θ_n, and θ_h be the conjectural variation elasticities which capture market power in the conventional, nanofood, and organic food product sectors.[10] The first order conditions are derived as:

$$
\begin{aligned}
MR_c^{nl} = C_c: \quad & \frac{(n^{nl}-c)P_h^{nl} + (h+c)(P_n^{nl}-V) - (1+\theta_c)(h+c)(n^{nl}-c)X_c^{nl}}{h+n^{nl}} = C_c \\
& \Rightarrow X_c^{nl} = \frac{(n^{nl}-c)P_h^{nl} + (h+c)(P_n^{nl}-V) - (n^{nl}+h)C_c}{(1+\theta_c)(h+c)(n^{nl}-c)} \\
& \Rightarrow P_c^{nl} = \frac{\theta_c[(n^{nl}-c)P_h + (h+c)(P_n^{nl}-V)] + (n^{nl}+h)C_c}{(1+\theta_c)(h+n^{nl})}
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
MR_n^{nl} = C_n^{nl}: \quad & P_c^{nl} + V - (1+\theta_n)(n^{nl}-c)X_n^{nl} = C_n^{nl} \\
& \Rightarrow X_n^{nl} = \frac{P_c^{nl} + V - C_n^{nl}}{(1+\theta_n)(n^{nl}-c)} \\
& \Rightarrow P_n^{nl} = \frac{(P_c^{nl}+V)\theta_n + C_n^{nl}}{1+\theta_n}
\end{aligned} \tag{7}
$$

$$
\begin{aligned}
MR_h^{nl} = C_h: \quad & P_c^{nl} + h + c - (1+\theta_h)(h+c)X_h^{nl} = C_h \\
& \Rightarrow X_h^{nl} = \frac{P_c^{nl} + h + c - C_h}{(1+\theta_h)(h+c)} \\
& \Rightarrow P_h^{nl} = \frac{(P_c^{nl}+h+c)\theta_h + C_h}{1+\theta_h}
\end{aligned} \tag{8}
$$

Under the special case where only the nanofood and the organic substitute coexists under a no labeling regime, i.e., the introduction of nanofoods drives conventional foods out of market, the quantities and prices of the nanofood and the organic food are determined by:

$$
\begin{aligned}
X_n^{nl} &= \frac{P_h^{nl} + V - C_n^{nl}}{(1+\theta_n)(h+n^{nl})} \Rightarrow P_n^{nl} = \frac{\theta_n(P_h^{nl}+V) + C_n^{nl}}{1+\theta_n} \\
X_h^{nl} &= \frac{P_n^{nl} + h + n^{nl} - V - C_h}{(1+\theta_h)(h+n^{nl})} \Rightarrow P_h^{nl} = \frac{\theta_h(P_n^{nl}+h+n^{nl}-V) + C_h}{1+\theta_h}
\end{aligned} \tag{9}
$$

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[10] $\theta_c = \frac{1}{N_c}\sum_{i=1}^{N_c}\frac{dX_c^{nl}}{dx_i}\frac{x_i}{X_c^{nl}}$, $\theta_n = \frac{1}{N_n}\sum_{k=1}^{N_n}\frac{dX_n^{nl}}{dx_k}\frac{x_k}{X_n^{nl}}$, and $\theta_h = \frac{1}{N_h}\sum_{j=1}^{N_h}\frac{dX_h^{nl}}{dx_j}\frac{x_j}{X_h^{nl}}$.

Simultaneously solving the FOCs gives the market equilibrium quantities and prices for the coexisting food products under scenario A (also scenarios B and C) in Appendix A2. Welfare for consumers and profits for suppliers of the nanofood, conventional, and organic food products can be obtained as follows:

$$
\begin{aligned}
CW_n^{nl} &= \int_0^{\alpha_n^{nl}} U_n^{nl}(\alpha)\,d(\alpha) = \int_0^{X_n^{nl*}} (U + V - P_n^{nl*} - n^{nl}\alpha)\,d(\alpha); \quad \Pi_n^{nl} = (P_n^{nl*} - C_n^{nl})X_n^{nl*} \\
CW_c^{nl} &= \int_{\alpha_n^{nl}}^{\alpha_c^{nl}} U_c^{nl}(\alpha)\,d(\alpha) = \int_{X_n^{nl*}}^{X_n^{nl*}+X_c^{nl*}} (U - P_c^{nl*} - c\alpha)\,d(\alpha); \quad \Pi_c^{nl} = (P_c^{nl*} - C_c)X_c^{nl*} \\
CW_h^{nl} &= \int_{\alpha_c^{nl}}^{1} U_h^{nl}(\alpha)\,d(\alpha) = \int_{X_n^{nl*}+X_c^{nl*}}^{1} (U - P_h^{nl*} + h\alpha)\,d(\alpha); \quad \Pi_h^{nl} = (P_h^{nl*} - C_h)X_h^{nl*}
\end{aligned}
\tag{10}
$$

The market equilibrium and welfare under scenarios B and C can be obtained in a similar manner (see Appendix A.2a).

III. Market equilibrium and welfare under a labeling regime

Nanofood labels, if imposed, may have two major effects: a cost effect and a preference effect. The cost effect refers to the changes in the nanofood consumption, consumer welfare, and supplier profits due to the labeling cost of the nanofood product. In particular, an increase in the production costs due to labeling would induce an increase in the nanofood price and have a negative impact on nanofood consumption since fewer consumers will be willing to buy the product when the nanofood price increases. Profits for nanofood suppliers decrease accordingly. Suppliers of the conventional and organic food substitutes, in contrast, are better off due to the cost effect as the demands and prices for their products increase. Finally consumers experience welfare losses due to the higher prices of all food products. It should be noted that, for simplicity, we assume that the labeling regulation for nanofoods affects the cost structure of the nanofood sector only.[11] Moreover, related administrative costs of the regulation are assumed to be fixed and borne by nanofood producers.

In addition to the cost effect, the introduction of nanofood labels may change consumer preferences for the use of food nanotechnology (from n^{nl} to n^{l}). On the one hand, the presence of nanofood labels informs consumers of the true nature of the nanofood and, thus, eliminate the uncertainty consumers face under no labeling- this is the certainty effect of nanofood labeling.[12] On the other hand, nanofood labels may also have a stigma effect on the nanofood consumption because consumers may view labeling as a warning that the product is hazardous, and, thus, become more averse to food nanotechnology under labeling than under no labeling. Mathematically, n^{l} can be expressed as $n^{l} = n + \varepsilon$ where n^{l} represents the preference effect, n the certainty effect of labeling, and ε ($\varepsilon \geq 0$) the stigma effect. Under the certainty effect, consumer aversion (preference) for the nanofood increases. The stigma effect (if any) exacerbates consumer aversion and mitigates consumer preference for the nanofoods.

By and large, when the preference effect works in the same direction as the cost effect, more consumers will switch their consumption from the nanofood to its substitutes. As a result, the market demand for the nanofood would drop further while there is a greater increase in the consumption of the conventional and organic food products. By contrast, when the two effects work in the opposite direction (e.g., when consumers become less averse than before the labels

[11] For the time being, there is no scientific consensus on the environmental impacts of food nanotechnology. Hence, whether the production of nanofoods contaminates the surroundings and therefore whether the conventional and/or organic substitute incurs the segregation or identity preservation (SIP) costs is uncertain. Also, as far as we know, there has been no discussion on SIP costs regarding nanofoods, thus, assuming no spillover effects is plausible at this point.

[12] Here, for simplicity, we assume that consumers completely trust the authenticity of the labels and therefore their uncertainty is fully eliminated by the presence of labels and their utility discount/enhancement factor for the nanofood is exactly n. However, note that relaxing this assumption does not change the analytical results because the important point is that, under the labeling regime, the probability consumers assign to nanofoods being a nanofood would be greater than before and, thus, their utility discount/enhancement factor for the nanofood is closer to n.

are introduced), then the market demand for the nanofood would increase if the preference effect dominates the cost effect, and vice versa.

Consumer attitudes towards the use of nanotechnology after the introduction of labeling determine the nature and magnitude of the effects of the labeling regulation and are, thus, critical in determining the effects of labeling on the market equilibrium of all food products, consumer welfare, and supplier profits. In what follows, we examine the effects of labeling on the market equilibrium and welfare in the following cases: Case I - Under no labeling consumers are more averse to food nanotechnology than conventional food technology (i.e., Scenario A) and their aversion increases under the labeling regime $(n^l > n^{nl})$, Case II - Under no labeling consumers are less averse to food nanotechnology than conventional food technology (Scenario B) and their preference for nanofoods either increases or decreases under the labeling regime, and Case III - Under no labeling consumers are unaware of the existence of nanotechnology (Scenario C) and their preference is formed (either more averse or less averse towards the use of food nanotechnology than conventional technology) under the labeling regime.

Under case I, equation (7) gives the differences in the market quantities and prices of nanofoods due to the labeling regulation as:

$$\Delta X_n^l = X_n^l - X_n^{nl} = \frac{1}{1+\theta_n}\left(\frac{P_c^l + V - C_n^l}{n^l - c} - \frac{P_c^{nl} + V - C_n^{nl}}{n^{nl} - c}\right) \tag{11}$$

$$\Delta P_n^l = P_n^l - P_n^{nl} = \frac{\theta_n (P_c^l + V) + C_n^l}{1+\theta_n} - \frac{\theta_n (P_c^{nl} + V) + C_n^{nl}}{1+\theta_n} = \frac{\theta_n (P_c^l - P_c^{nl}) + C_n^l - C_n^{nl}}{1+\theta_n} \tag{12}$$

Let $\Delta C_n^l = C_n^l - C_n^{nl}$ be the labeling cost incurred by a nanofood supplier $(\Delta C_n^l > 0)$ and $\Delta P_c^l = P_c^l - P_c^{nl}$ be the change in the conventional food price due to the labeling policy. We have $\Delta C_n^l \geq \Delta P_c^l$ since the change in the conventional food price is indirectly caused by the increase in the production cost of the nanofood. It follows that,

$$\Delta X_n^l < \frac{(P_c^l + V - C_n^l) - (P_c^{nl} + V - C_n^{nl})}{(1+\theta_n)(n^{nl} - c)} = \frac{\Delta P_c^l - \Delta C_n^l}{(1+\theta_n)(n^{nl} - c)} \le 0 \text{ and } \Delta P_n^l = \frac{\Delta C_n^l + \theta_n \Delta P_c^l}{1+\theta_n} \ge 0,$$

indicating the decrease in the market demand for the nanofood and the increase in its price under the cost and preference effects of labeling. Moreover, since $\frac{\delta\left|\Delta X_n^l\right|}{\delta C_n^l} > 0$, $\frac{\delta\left|\Delta X_n^l\right|}{\delta \theta_n} < 0$, $\frac{\delta \Delta P_n^l}{\delta C_n^l} > 0$, and $\frac{\delta \Delta P_n^l}{\delta \theta_n} \le 0$, the greater is the increase in the production cost and the less concentrated is the nanofood sector, the greater is the reduction in the market demand for the nanofood and the increase in the nanofood price. The price of the nanofood is unaffected by the change in consumer attitudes towards nanofoods ($\frac{\delta \Delta P_n^l}{\delta n^l} = 0$) while the more averse consumers are to the use of food nanotechnology, the lower is the consumption of the nanofood ($\frac{\delta\left|\Delta X_n^l\right|}{\delta n^l} > 0$).

Figure 2 demonstrates the direct impact of the labeling regulation on the nanofood. With the imposition of nanofood labels, the nanofood sector incurs an increase in the production cost which is passed on to consumers through higher prices (going up from P_n^{nl*} to P^l) (see Figure 2, panel (i)). We observe a decrease in the quantity of the nanofood (from X_n^{nl*} to X_1) due to consumers' negative response to the increase in its price. Meanwhile, consumers' increased aversion towards nanofoods after labeling results in the increase in the magnitude of the slope of the demand curve from $n^{nl} - c$ to $n^l - c$, where $n^l > n^{nl}$, which also causes a reduction in the quantity of the nanofood, leaving, however, the price of the nanofood unchanged (Figure 2, panel (ii)).[13] The combined direct effect of labeling on the nanofood sector - cost and preference effects is illustrated in Figure 2, panel (iii).

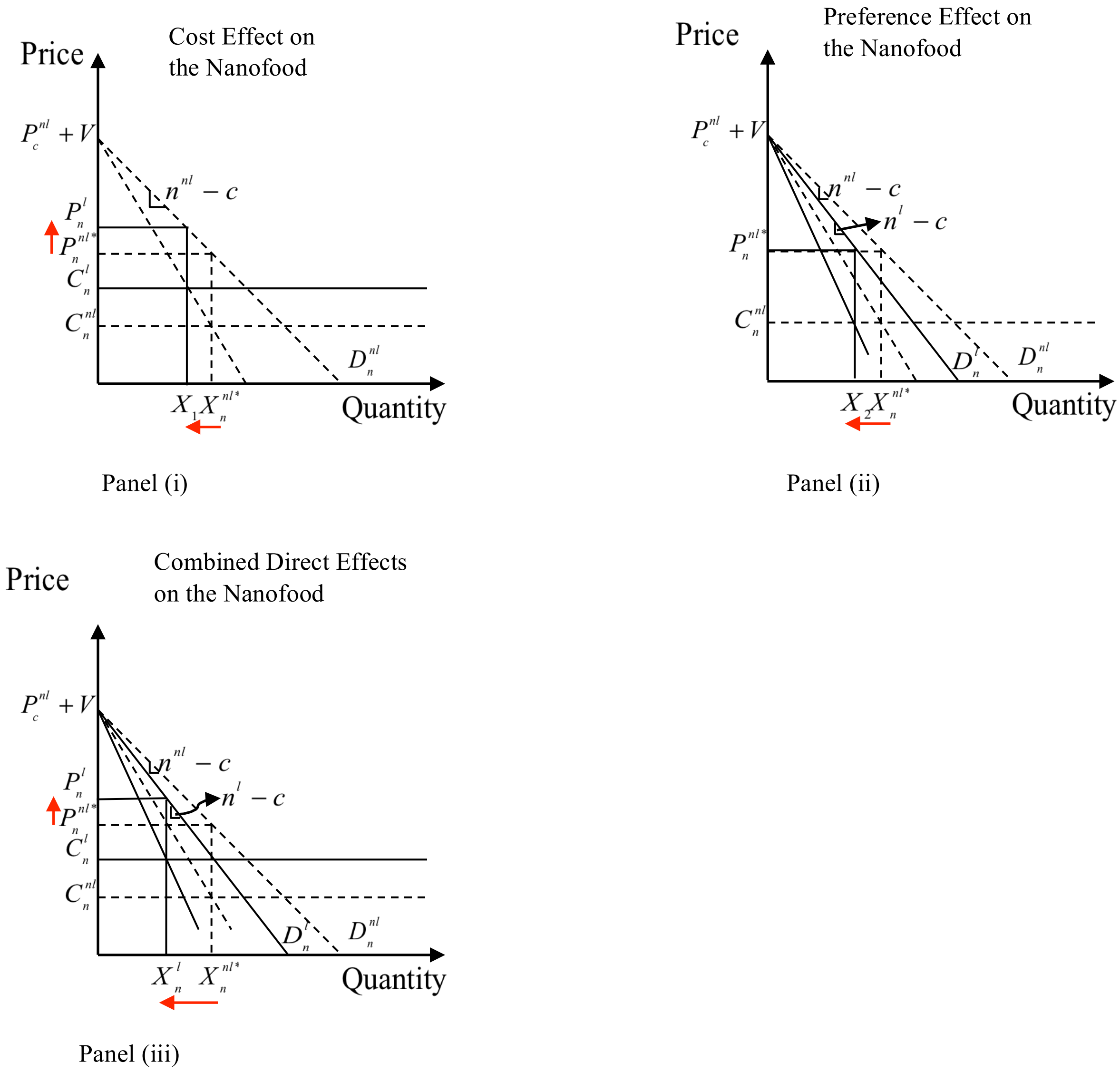


Figure 2: Combined direct effects of the labeling regime on the nanofood sector under case I *(i.e., from* $n^{nl} > c$ *to* $n^{l} > n^{nl}$*).*

[13] Note that given the constant marginal cost and the linear demand curve, the change in the slope of the demand curve does not influence the price if the intercept of the demand curve remains the same.

Figure 3 depicts the effects of nanofood labeling in all food markets under Case I. The increase in the nanofood price, which is shown earlier, triggers a rightward shift in the demand curve of the conventional food, resulting in an increase in the demand and price of the conventional food product (Figure 3, panel (i)).[14] The increase in the price of the conventional food, in turn, causes a right shift in the market demand for both the organic food and the nanofood; therefore, the market demand and price for the organic and nanofood product increase. Note that such increase in the quantity of the nanofood due to the increase in the conventional food (or the indirect effect of the nanofood labeling regulation) is not sufficient to offset the initial direct effects of labeling, resulting in an overall decrease in the nanofood quantity. Since the prices and quantities of the conventional food and organic food products increase, suppliers of these products gain profits when nanofood labeling is imposed (Figure 3, panel (i), (ii)). On the contrary, nanofood suppliers incur losses due to smaller quantities demanded (Figure 3, panel (iii)).[15] On the consumer side, the increase in the prices of all food products and the increased aversion towards food nanotechnology reduce consumer utility from the consumption of these products (Figure 3, panel (iv)). Consumers who switch their consumption from the nanofood to the conventional food are those with moderate aversion towards interventions in the production process, $\alpha \in (\alpha_n^l, \alpha_n^{nl})$. Among those who continue to consume the nanofood, those more averse to interventions in the production process experience greater welfare losses. In addition, the greater is the labeling cost and the higher is aversion towards nanotechnology under a labeling system, the greater is the decrease in consumer welfare, nanofood supplier profits, and the increase in the conventional and organic supplier profits.

[14] We also can see these interactions through the FOCs given in equations (6) and (8).
[15] See Appendix A3 for simulation results on the effects of labeling on the profits of nanofood suppliers.

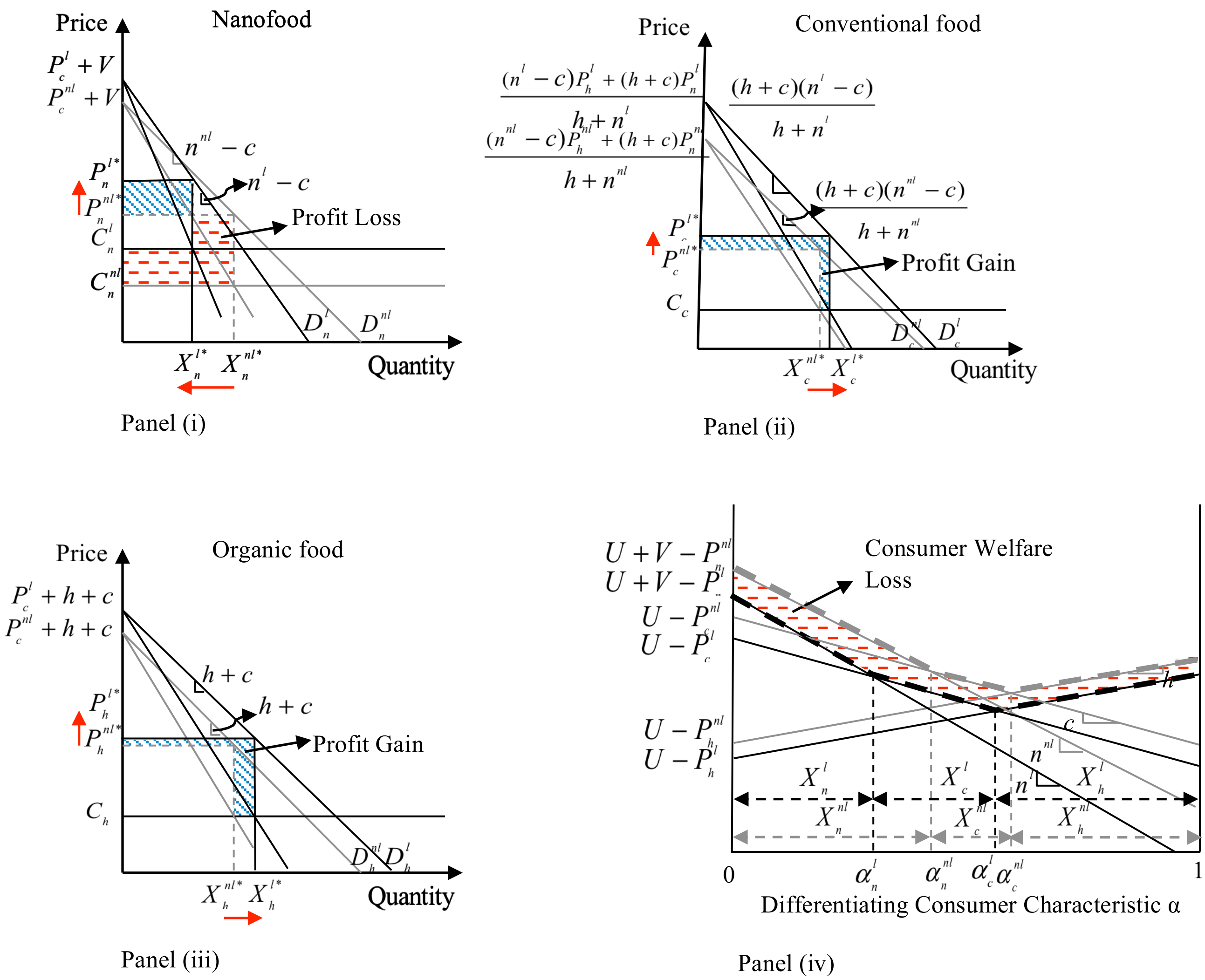


Figure 3: Overall effects of the labeling regime on the market equilibrium and welfare under case I *(i.e., from* $n^{nl} > c$ *to* $n^{l} > n^{nl}$*).*

We next consider case II where under no labeling consumers are less averse to food nanotechnology than to conventional food technology $(n^{nl} < c)$ and labeling regulation makes them either more or less averse. Consumers become (a) *more averse* under the labeling regime (i.e., $n^{l} > n^{nl}$) when, for example, the labels signal to them that the use of food nanotechnology might involve unwelcomed risks, or (b) *less averse* when labeling has no or very small stigma effect such that $\varepsilon \simeq 0$ (i.e., $n^{l} < n^{nl}$).

Analogous to equations (11) and (12) under case I, the changes in the market demand and price for the nanofood due to nanofood labeling under case II are given in equations (13) and (14).

$$\Delta X_n^l = X_n^l - X_n^{nl}$$
$$= \frac{(c-n^l)P_h^l + (h+n^l)P_c^l + (h+c)(V-C_n^l)}{(1+\theta_n)(c-n^l)(h+n^l)} - \frac{(c-n^{nl})P_h^{nl} + (h+n^{nl})P_c^{nl} + (h+c)(V-C_n^{nl})}{(1+\theta_n)(c-n^{nl})(h+n^{nl})} \quad (13)$$

$$\Delta P_n^l = P_n^l - P_n^{nl} = \frac{\theta_n[(c-n^l)P_h^l - (c-n^{nl})P_h^{nl} + (h+n^l)P_c^l - (h+n^{nl})P_c^{nl}] + (h+c)(C_n^l - C_n^{nl})}{(1+\theta_n)(h+c)}$$
$$= \underbrace{[(h+c)\Delta C_n^l + \theta_n c\Delta P_h^l + \theta_n h\Delta P_c^l]}_{\text{Cost effect (+)}} + \underbrace{\theta_n[n^{nl}(P_h^{nl} - P_c^{nl}) - n^l(P_h^l - P_c^l)]}_{\text{Preference effect (+/-)}} \quad (14)$$

When consumers become more averse after the labels are introduced, the market demand for the nanofood decreases. Consumers switch from the nanofood to the conventional and organic food substitutes, causing an increase in the demand for these alternatives. The market price for the nanofood increases and so do the conventional and organic food prices if the cost effect dominates the preference effect and vice versa (Figures 4 and 5). The market and welfare impacts of labeling under case II and when the cost effect is dominant are qualitatively the same as under case I (Figure 5). Put differently, regardless of whether consumers are more averse or less averse to nanotechnology than to conventional technology, the introduction of nanofood labeling reduces the consumption for the nanofood, increases the consumption of the conventional and organic food substitutes, and increases the market prices of all three products if the cost effect dominates the preference effect. In addition, consumers and suppliers of the nanofood lose while suppliers of the conventional and organic food gain. The difference between the two cases is, however, the distributional effects of the labeling regulation on consumers; consumers who lose the most under case II-a are those with relatively high aversion towards interventions in the production process as compared with those under case I.

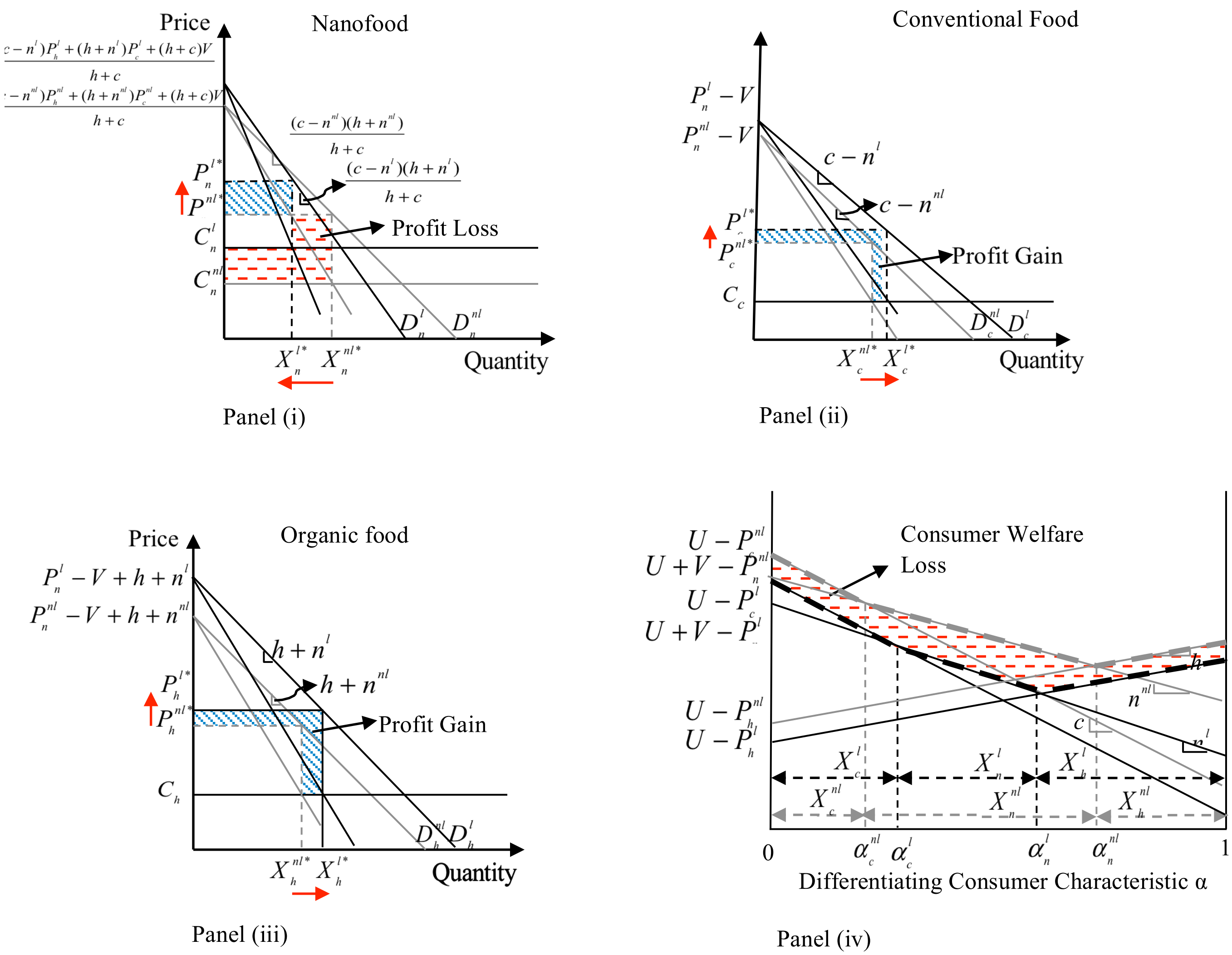


Figure 4: Overall effects of the labeling regime under case II-a *(i.e., from* $n^{nl} < c$ *to* $n^{l} > n^{nl}$*)* when the cost effect dominates the preference effect.

If, under the labeling regime, consumer attitudes towards food nanotechnology change dramatically such that consumers become more averse to food nanotechnology than conventional technology and the preference effect dominates the cost effect, introducing nanofood labels discourages nanofood consumption and puts a downward pressure on the nanofood price (Figure 5). There are two types of consumption changes in this case: some consumers switch from the conventional to the nanofood product and some consumers switch from the nanofood to the conventional food product. The former group includes those with relatively low aversion to interventions in the production process who switch to avoid the current increase in the conventional food price and benefit from the decrease in the nanofood price (Figure 5, panel (iv)). The latter group includes those with relatively moderate aversion who are reluctant to consume the nanofood as the product is perceived as more intrusive than the conventional food when the labeling regulation is in place. These consumers find themselves better off changing their consumption to a different product. Overall, the beneficiaries of the labeling policy in this case are suppliers of conventional and organic food products who see their profits increase due to the increase in their product demand.

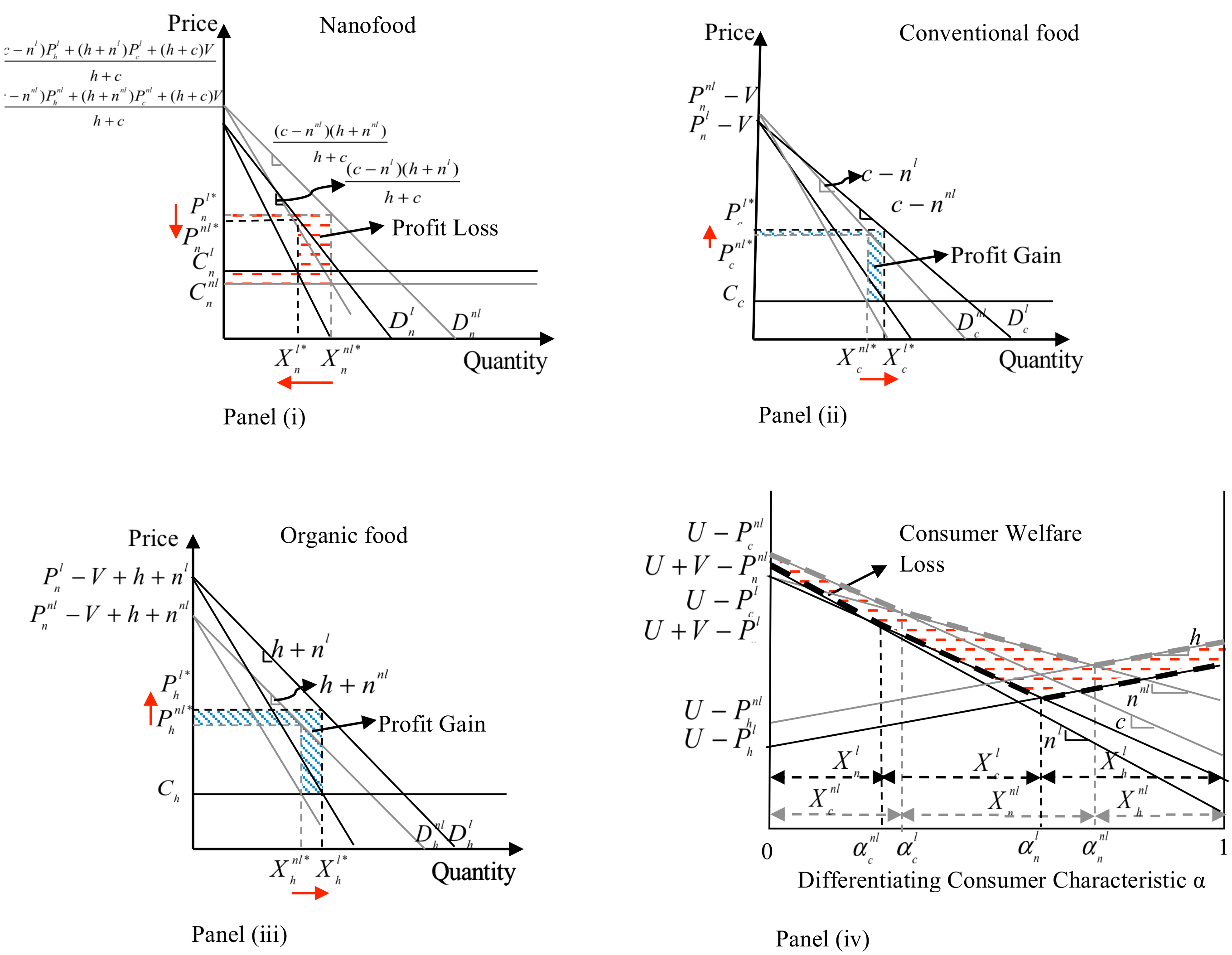
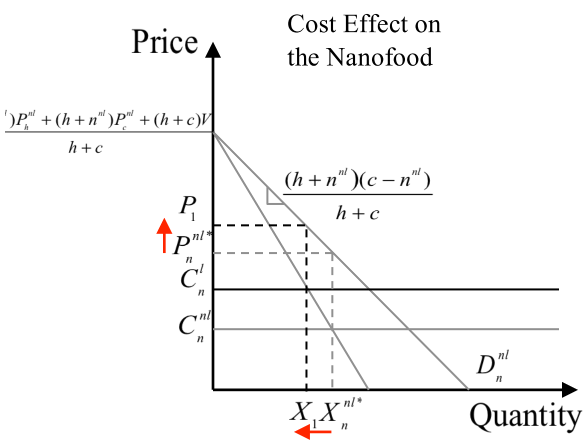
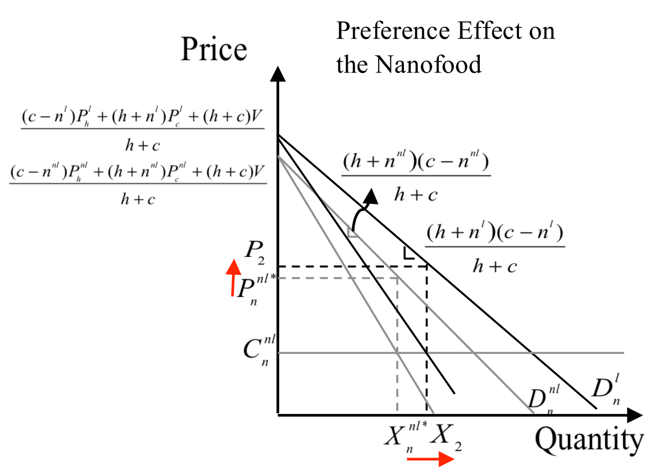


Figure 5: Overall effects of the labeling regime under case II-a *(i.e., from* $n^{nl} < c$ *to* $n^{l} > n^{nl}$*)* when the preference effect dominates the cost effect.

Unlike the previous case where consumers become more averse to food nanotechnology after labels are imposed, consumers under case II-b prefer nanofoods to conventional foods under labeling as the certainty effect dominates the stigma effect (which in this case is insignificant). As consumers perceive that the use of food nanotechnology is more desirable than conventional technology, the demand for the nanofood increases and so does its price. The increase in the production cost, however, reduces the nanofood consumption as nanofoods are sold at a higher price. Therefore, whether the market demand for the nanofood increases or decreases are contingent on the relative magnitude of the two effects: if the cost effect dominates (is dominated by) the preference effect, nanofood consumption increases (decreases). Panels (iii) and (iv) of Figure 6 demonstrate the combined direct effect of labeling on the nanofood sector under these conditions.



Panel (i)



Panel (ii)

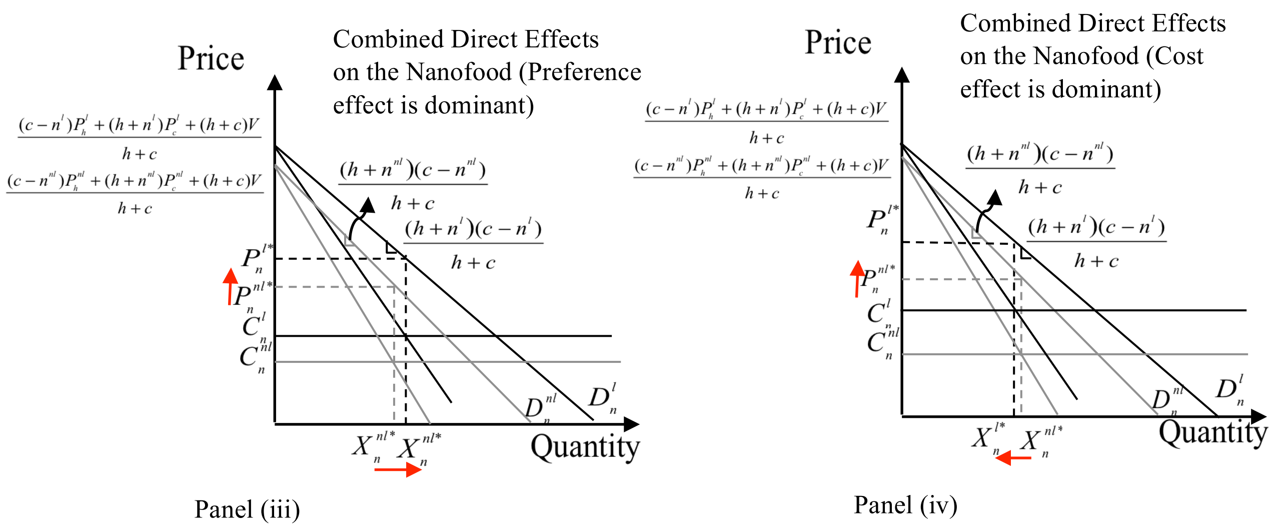
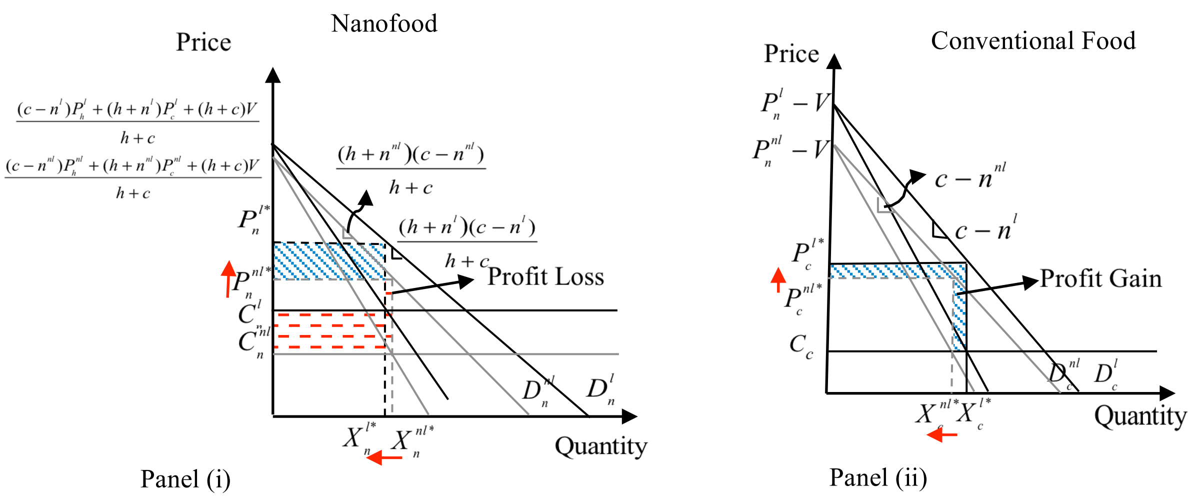
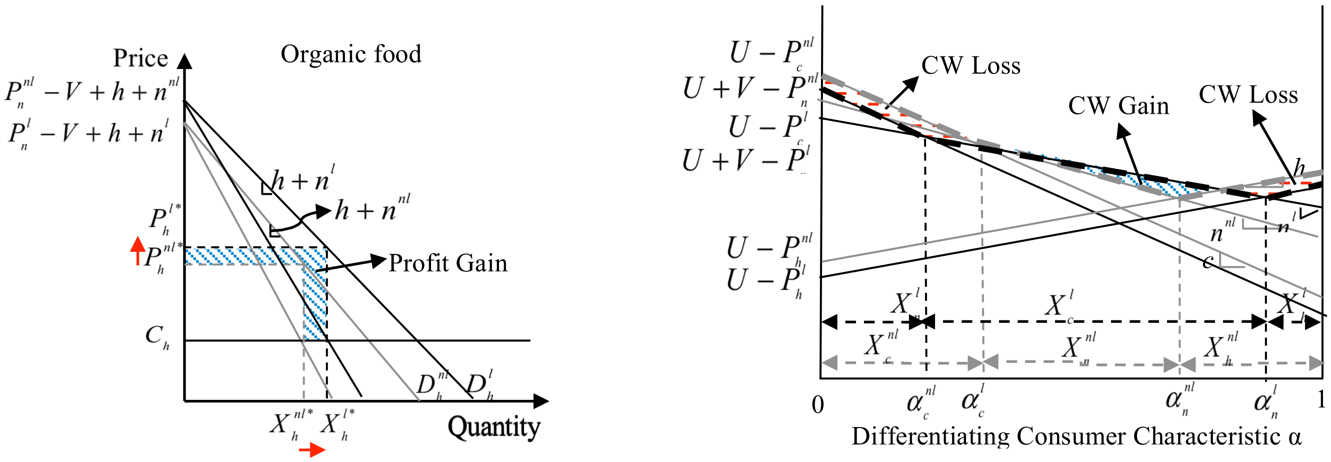


Figure 6: Overall effects of the labeling regime under case II-b *(i.e., from* $n^{nl} < c$ *to* $n^l < n^{nl}$*)* when the cost effect dominates the preference effect.

As can be seen from Figure 7 which illustrates the overall effects of the nanofood labeling on all food markets when the cost effect is dominant, the increase in the nanofood price results in an increase in the market demand for the conventional and organic food substitutes which in turn causes an increase in the prices of these products. As a result, profits are lower for nanofood suppliers and higher for conventional and organic food suppliers. Due to the increase in the price of all food products, welfare is lower for all consumers with nanofood consumers incurring the greatest welfare losses.





Panel (iii)

Panel (iv)

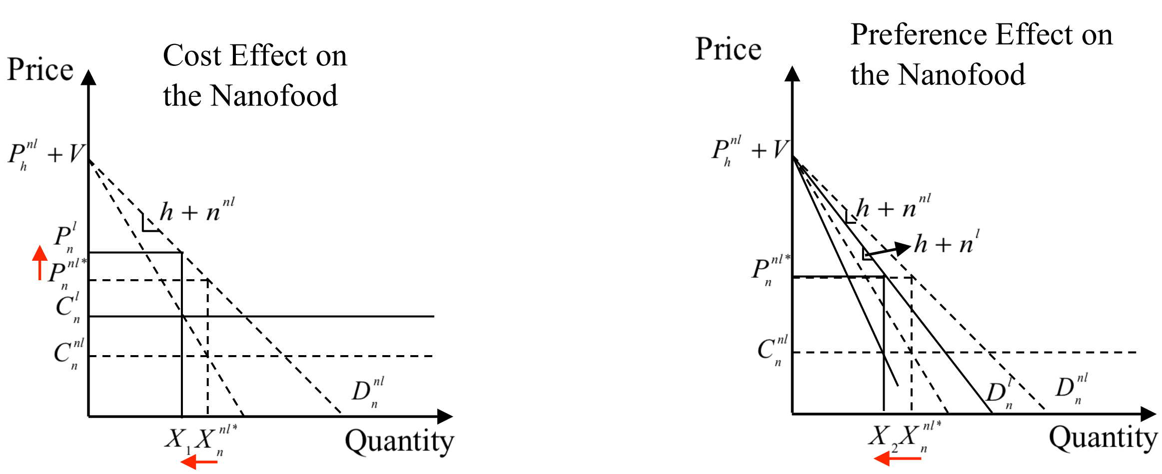
Figure 7: Overall effects of the labeling regime under case II-b *(i.e., from* $n^{nl} < c$ *to* $n^{l} < n^{nl}$*)* when the cost effect dominates the preference effect.

Unlike the previous cases where consumers have some knowledge of the presence of food nanotechnology, consumers under case III are completely unaware of the existence of nanotechnology in the food industry due to the lack of labeling, consumers view nanofoods as conventional foods with enhanced attribute(s) and their utility discount for nanofoods is identical to that for conventional food products (i.e., $n^{nl} = c$).[16] As indicated by condition A.1 in Appendix A, if the price premium for the nanofood is less than the value consumers place on its enhanced attribute (i.e., $P_n^{nl} - P_c^{nl} < V$), the nanofood completely replaces the conventional food. The market demands and prices for the nanofood and organic food products under the no labeling regime are derived in equation A.2 in Appendix A (or equation (9)). If the labeling policy is imposed, consumers are likely to become either (i) *more averse* $(n^{l} > n^{nl})$ or (ii) *less*

[16] The scenario $(n^{nl} = c)$ also refers to the situations where consumers are indifferent between the use of food nanotechnology and conventional technology and, thus, the effects of nanofood labeling are the same as when they are unaware of food nanotechnology.

averse $(n^l < n^{nl})$ to food nanotechnology than they are prior to labeling (and also as opposed to conventional technology).

Under the labeling regime, if consumers become more averse than under the no labeling regime $(n^l > n^{nl})$, the market demand for the nanofood is reduced and more consumers want to purchase the conventional or organic food substitutes. The increase in the nanofood price, which is caused by the increase in the production cost, magnifies the reduction in the market demand for this product. Figure 9 illustrates the individual effect and combined direct effects of labeling (cost and preference effects) on the nanofood. Panel (i) of Figure 9 demonstrates the cost effect of the nanofood label: as the production cost increases from C_n^{nl} to C_n^l, the nanofood price increases from P_n^{nl*} to P_n^l and the market quantity for the nanofood declines from X_n^{nl*} to X_1. Under the preference effect, consumer attitudes towards the use of food nanotechnology change from n^{nl} to n^l; graphically, the demand curve rotates leftward causing the demand for the nanofood to decrease further (Figure 9, panel (ii)). The two effects considered, the demand for the nanofood decreases and the price increases (Figure 9, panel (iii)).



Panel (i) Panel (ii)

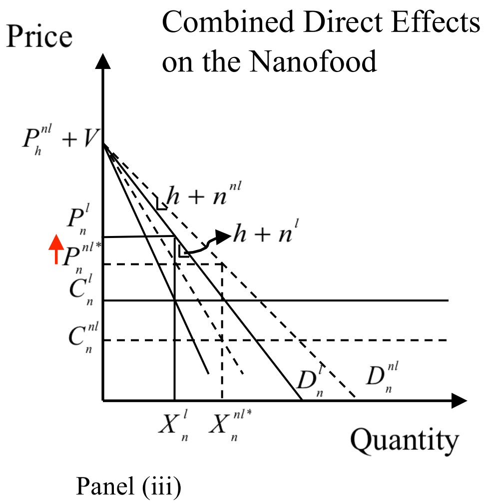
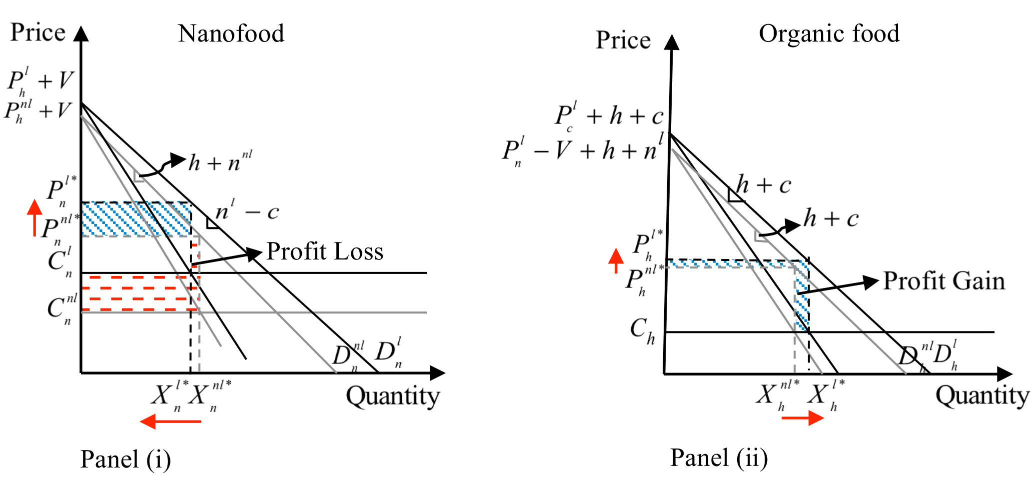
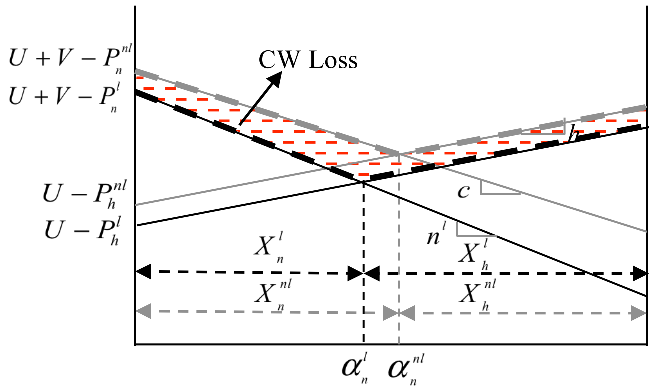


Figure 9: Combined direct effects of the labeling regime under case III *(i.e., from* $n^{nl} = c$ *to* $n^l > n^{nl}$*)* when only the nanofood and the organic food coexist before and after the labels are introduced.

If nanofood suppliers continue their pricing strategy such that $P_n^l < P_c^l + V - \dfrac{n^l - c}{h + c}(P_h^{nl} - P_c^{nl})$ then the conventional food continues to be kept out of the competition; only the nanofood and the organic food products are sold in the market. In this case, consumer welfare decreases because the prices of all food products increase. Profits are greater for organic suppliers and smaller for nanofood suppliers due to the shrinking market demand.

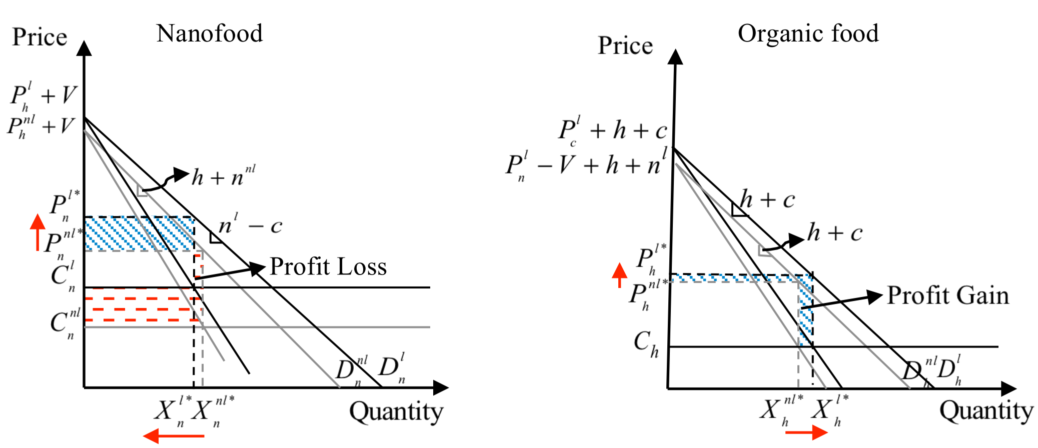




Panel (iii)

Figure 10: Overall effects of the labeling regime under case III *(i.e., from* $n^{nl} = c$ *to* $n^l > n^{nl}$*)* when only the nanofood and the organic food coexist before and after the labels are introduced.

The interactions between the three alternative sectors under case III are the same as under the previous cases. Once again, consumer welfare change depends on which group of consumers they belong to in terms of the differentiating characteristic α. In this case consumers who incur the greatest welfare losses are nanofood consumers who have relatively high aversion towards interventions in the production process. Put differently, those who switch their consumption to the conventional foods under the preference and cost effects of the nanofood labeling would lose less than what they would have incurred if they continued their consumption (Figure 11, panel (iii)).



Panel (i) Panel (ii)

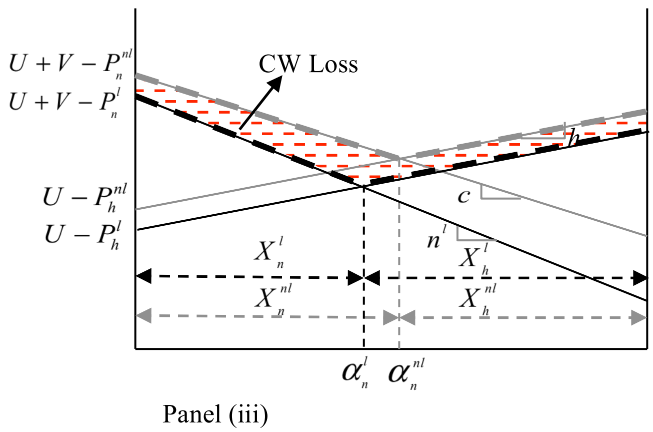


Figure 11: Overall effects of the labeling regime under case III *(i.e., from* $n^{nl} = c$ *to* $n^l > n^{nl}$*)* and when the nanofood, the organic food, and the conventional food coexist after the nanofood labels are introduced.

If consumers are less averse to the use of food nanotechnology after the labeling policy is imposed, the effect of labeling depends on whether the cost or preference effect is dominant. If the cost effect is dominant, then the market demand for the nanofood decreases. Some consumers switch to the conventional or organic food substitute. Consumers lose as all food product prices increase. If the preference effect is dominant, more consumers desire the nanofood. In this case, suppliers of the nanofood and conventional food gain at the expense of the organic suppliers and consumers with relatively high aversion to interventions in the production process enjoy welfare gains.

If, in the absence of labeling, nanofoods are priced such that the price premium reflects consumer valuation of the enhanced attributes of the nanofood $(P_n^{nl} = P_c^{nl} + V)$, the three products coexist and if, under the labeling regime, consumers find the use of food nanotechnology more intrusive than the use of conventional production methods, there would be no demand for the nanofood (Figure 12). The market demand for the conventional and organic food substitutes increase, raising their prices eventually. Consumers, therefore, see their welfare decrease not only from the disappearance of the nanofood but also from the price increase in the existing products.

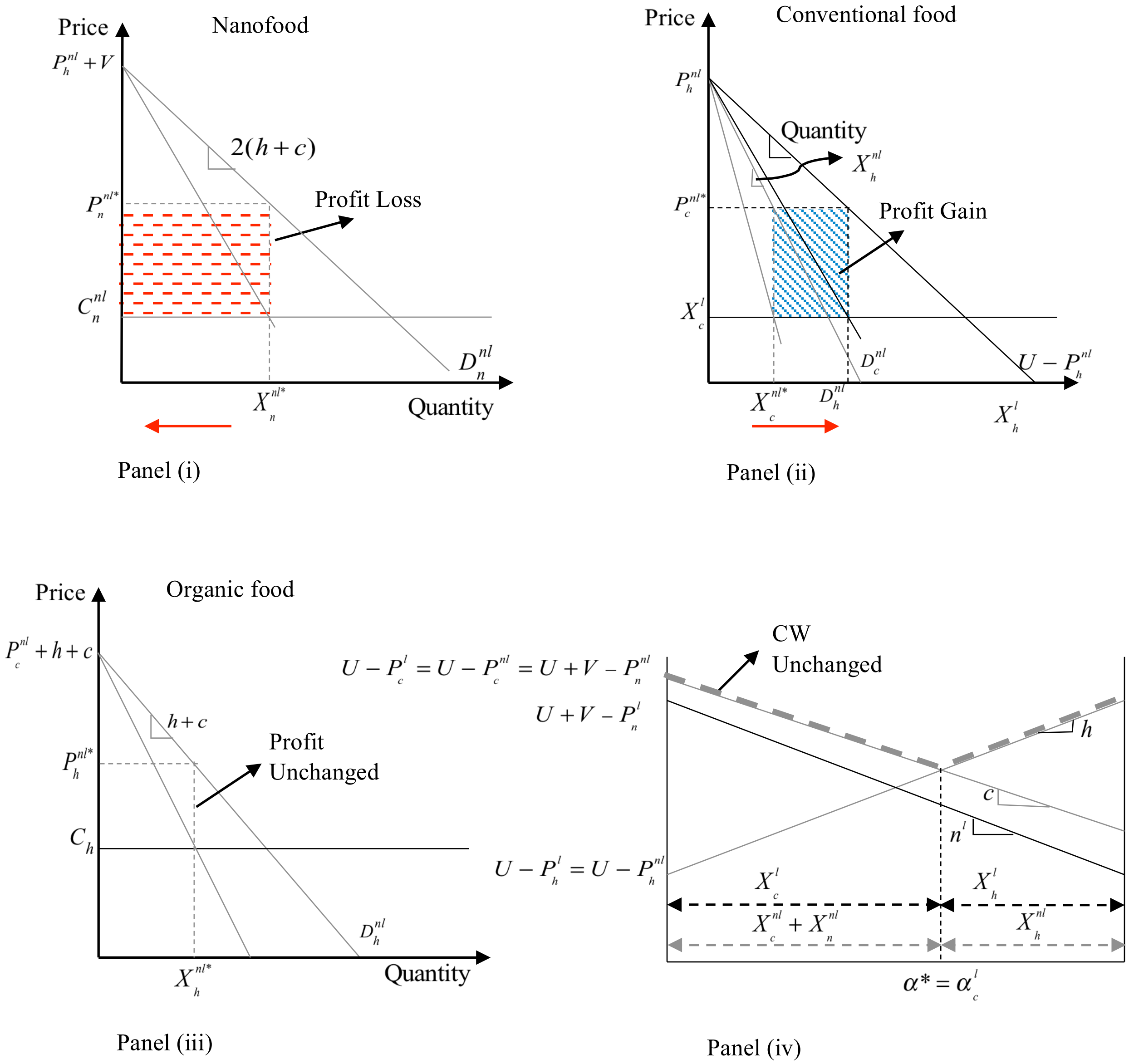


Figure 12: Overall effects of the labeling regime under case III *(i.e., from* $n^{nl}=c$ *to* $n^l>n^{nl}$*)* when the nanofood is driven out of the market after nanofood labels are introduced.

By contrast, if consumers become less averse after the introduction of the labeling policy, more consumers buy the nanofood and fewer buy the conventional and organic substitutes than before (Figure 13). Profits for nanofood suppliers increase at the expense of conventional and organic food suppliers. Consumers enjoy welfare gains, especially nanofood consumers.

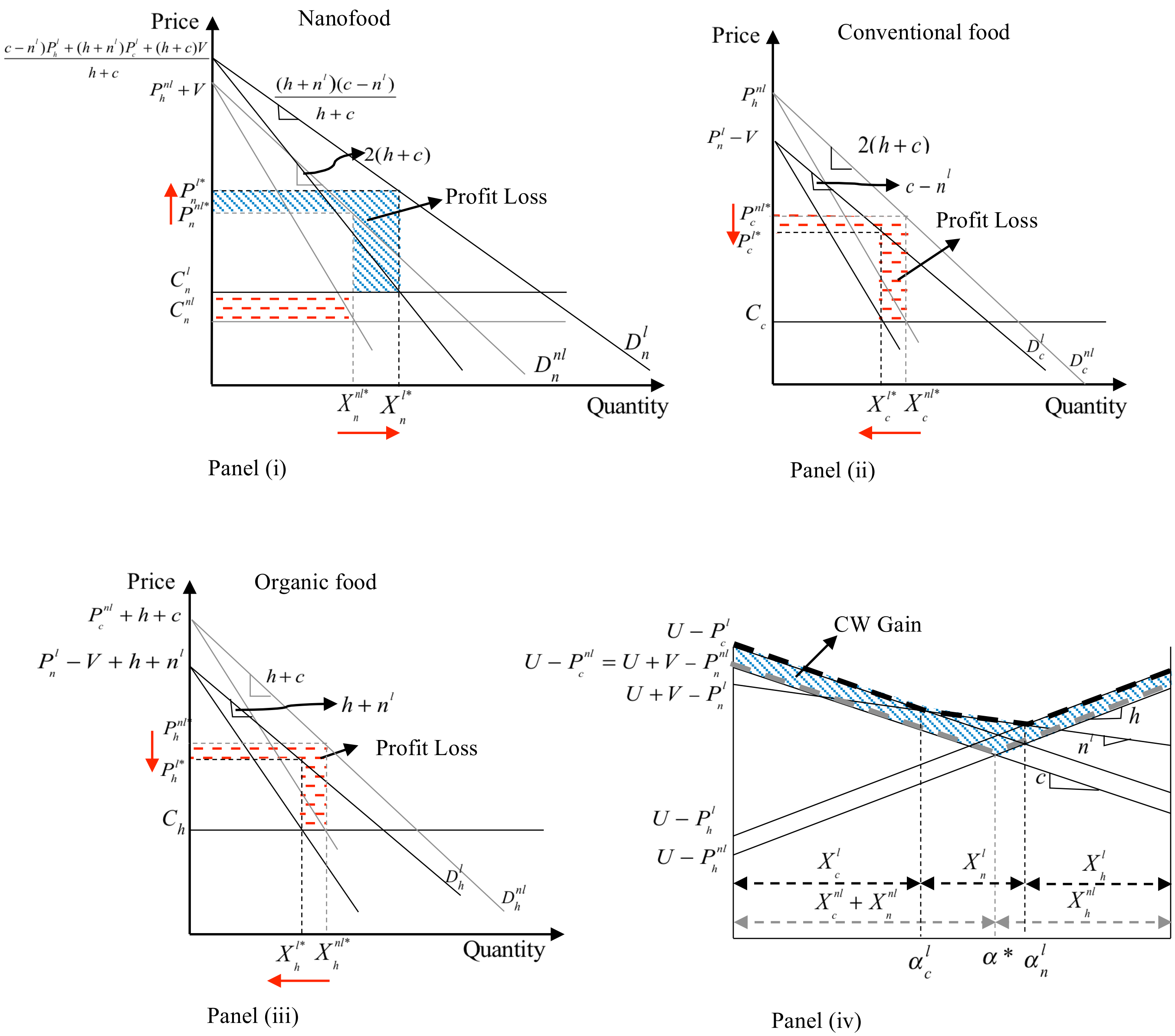


Figure 13: Overall effects of the labeling regime under case III *(i.e., from* $n^{nl} = c$ *to* $n^{l} > n^{nl}$*)* when the nanofood, the organic food, and the conventional food coexist before and after the nanofood labels are introduced.

IV. Conclusions

Consumers' right to be informed and the establishment of trust in the food nanotechnology industry have been major arguments in support of labeling regulation for food nanotechnology products. Meanwhile, labeling of nanofoods is being objected for fear of generating invalidated misperceptions of the use of food nanotechnology. Our analytical results have shown that consumer preferences for the use of food nanotechnology, coupled with the additional production cost incurred under the labeling regime, are crucial in determining the effects of nanofood labeling. Under the cost effect, the increase in the production cost of nanofoods causes a rise in the price of the nanofood and, thus, a reduction in its market demand. Under the preference effect, the market demand for the nanofood further decreases if nanofood labels are perceived as a bad signal that food nanotechnology is harmful to the environment or human health. Yet, if nanofood labels have a positive impact on consumer preferences nanofood consumption may increase. In other words, when the preference and cost effects work in the same direction, the market demand for the nanofood decreases following the increase in the price of the nanofood. As such, consumer welfare and nanofood supplier profits decrease while profits for conventional and organic food suppliers increase. On the other hand, when the preference effect works in the opposite direction with the cost effect (i.e., nanofoods become more favorable after the labels are introduced), whether the nanofood consumption increases depends on the relative magnitude between the preference and cost effects. The more favorable consumers are to the use of food nanotechnology under the labeling regime, the more profitable are nanofood suppliers.

In particular, the labeling regulation negatively affects consumer welfare due to the increase in the prices of all existing food products. If labeling costs are only incurred by the nanofood sector, the regulation benefits the non-adopting sectors which experience increases in supplier profits. Furthermore, the greater are the labeling costs and the higher is aversion towards nanotechnology under a labeling system, the greater is the impact of the labeling regime on consumer welfare and supplier profits. Such impacts, however, are tempered when the degree of market power increases and/or the labeling cost is smaller. However, when, without labeling, consumers are less averse to the use of food nanotechnology than conventional production methods and become less and less averse under the labeling regime and these preference effects are dominant, nanofood suppliers might benefit from labeling at the expense of conventional suppliers. When consumers have no knowledge of food nanotechnology before labeling is introduced, consumer welfare increases even if they become more averse under a labeling system. This result is induced by the price reduction in all existing food products as an attempt of food suppliers to maximize their profits under the above circumstance. Nanofood producers are negatively impacted by the introduction of food labels in most cases.

APPENDICES

A1. The conditions under which a food nanotechnology innovation coexists with the conventional and organic food substitutes (non-drastic), drives the conventional substitute out of the market (drastic), or is driven out of the market (ineffective).

- ***Scenarios A and C:***

Ineffective: $V < P_n - P_c$

Drastic: $P_n < P_c + V - \frac{(n-c)(P_h - P_c)}{h+c} \Rightarrow V > P_n - P_c + \frac{(n-c)(P_h - P_c)}{h+c} \Rightarrow n - c < \frac{h+c}{P_h - P_c}(P_c + V - P_n)$

Non-drastic:

$$P_c + V - \frac{(n-c)(P_h - P_c)}{h+c} \le P_n \le P_c + V \Rightarrow P_n - P_c \le V \le P_n - P_c + \frac{(n-c)(P_h - P_c)}{h+c} \Rightarrow n - c \ge \frac{h+c}{P_h - P_c}(P_c + V - P_n)$$

- ***Scenario B:***

Ineffective:

$$P_n > P_c + V - \frac{(n-c)(P_h - P_c)}{h+c} \Rightarrow V < P_n - P_c + \frac{(n-c)(P_h - P_c)}{h+c} \Rightarrow n - c > \frac{h+c}{P_h - P_c}(P_c + V - P_n)$$

Non-drastic:

$$P_c + V \le P_n \le P_c + V - \frac{(n-c)(P_h - P_c)}{h+c} \Rightarrow P_n - P_c + \frac{(n-c)(P_h - P_c)}{h+c} \le V \le P_n - P_c \Rightarrow n - c \le \frac{h+c}{P_h - P_c}(P_c + V - P_n)$$

Drastic: $P_n < P_c + V \Rightarrow V > P_n - P_c$

A2. The market equilibrium prices and quantities of the conventional food, nanofood, and organic food products in the absence of nanofood labels.

a. When consumers are unaware of the presence of food nanotechnology $(n^{nl} = c)$*:*

- Drastic innovation:

$$X_h^{nl*} = \frac{(1+\theta_n)(h+c) + C_n^{nl} - V - C_h}{(h+c)(1+\theta_n+\theta_h)}$$

$$X_n^{nl*} = \frac{\theta_h(h+c) + C_h + V - C_n^{nl}}{(h+c)(1+\theta_n+\theta_h)}$$

$$P_h^{nl*} = \frac{\theta_h[(1+\theta_n)(h+c) + C_n^{nl} - V] + (1+\theta_n)C_h}{1+\theta_n+\theta_h}$$

$$P_n^{nl*} = \frac{\theta_n[\theta_h(h+c) + C_h + V] + (1+\theta_h)C_n^{nl}}{1+\theta_n+\theta_h}$$

❖ Non-drastic innovation:

$$X_c^{nl*} = \frac{C_h + \theta_h(h+c) - C_c}{2(h+c)(1+\theta_c+\theta_h)}$$

$$X_n^{nl*} = \frac{C_h(1+\theta_c) + \theta_h[C_c + (h+c)(1+\theta_c)] - C_n^{nl}(1+\theta_c+\theta_h)}{2(h+c)(1+\theta_c+\theta_h)(1+\theta_n)}$$

$$X_h^{nl*} = \frac{C_c + (h+c)(1+\theta_c) - C_h}{(h+c)(1+\theta_c+\theta_h)}$$

$$P_c^{nl*} = \frac{\theta_c[C_h + \theta_h(h+c)] + (1+\theta_h)C_c}{1+\theta_c+\theta_h}$$

$$P_n^{nl*} = P_c^{nl*} + V = \frac{\theta_c[C_h + \theta_h(h+c)] + (1+\theta_h)C_c + V(1+\theta_c+\theta_h)}{1+\theta_c+\theta_h}$$

$$P_h^{nl*} = \frac{\theta_h[C_c + (1+\theta_c)(h+c)] + (1+\theta_h)C_h}{1+\theta_c+\theta_h}$$

b. When consumers are more averse to food nanotechnology than conventional food production methods $(n^{nl} > c)$*:*

❖ Drastic innovation: Same as that in part a.

❖ Non-drastic innovation:

$$P_c^{nl*} = \frac{C_c(h+n^{nl})(1+\theta_h)(1+\theta_n) + \theta_c\left\{(n^{nl}-c)(1+\theta_n)\left[(h+c)\theta_h + C_h\right] + (h+c)(1+\theta_h)(C_n^{nl} - V)\right\}}{(h+n^{nl})(1+\theta_h)(1+\theta_n) + \theta_c\left[h+n^{nl}+(h+c)\theta_h + (n^{nl}-c)\theta_n\right]}$$

$$P_n^{nl*} = \frac{C_n^{nl}\left\{(h+n^{nl})(1+\theta_h) + \theta_c\left[h+n^{nl}+(h+c)\theta_h\right]\right\} + \theta_n\left\{(h+n^{nl})(1+\theta_h)(C_n^{nl}+V) + (n^{nl}-c)\theta_c\left[V + C_h + (h+c)\theta_h\right]\right\}}{(h+n^{nl})(1+\theta_h)(1+\theta_n) + \theta_c\left[h+n^{nl}+(h+c)\theta_h + (n^{nl}-c)\theta_n\right]}$$

$$P_h^{nl*} = \frac{C_h\left\{(h+n^{nl})(1+\theta_n) + \theta_c\left[h+n^{nl}+(n^{nl}-c)\theta_n\right]\right\} + \theta_n\left\{(h+n^{nl})(1+\theta_n)(C_n^{nl}+c+h) + (h+c)\left[(h+n^{nl}+C_n^{nl}-V)\theta_c + (n^{nl}-c)\theta_n\right]\right\}}{(h+n^{nl})(1+\theta_h)(1+\theta_n) + \theta_c\left[h+n^{nl}+(h+c)\theta_h + (n^{nl}-c)\theta_n\right]}$$

$$X_c^{nl*} = \frac{(h+n^{nl})(1+\theta_c)\left\{(n^{nl}-c)(1+\theta_n)C_h - (h+c)\left[(V-C_n^{nl})(1+\theta_h)\right] - \theta_h(1+\theta_n)(n^{nl}-c)\right\}}{(h+c)(n^{nl}-c)(1+\theta_c)\left\{(h+n^{nl})(1+\theta_h)(1+\theta_n) + \theta_c\left[h+n^{nl}+(h+c)\theta_h+(n^{nl}-c)\theta_n\right]\right\}}$$

$$-\frac{C_c\left\{\theta_c\left[h+n^{nl}+(h+c)\theta_h+(n^{nl}-c)\theta_n\right] + (h+n^{nl})\{1+(1-c-h)\theta_n + \theta_h\left[1-n^{nl}+c+(1-h-n^{nl})\theta_n\right]\}\right\}}{(h+c)(n^{nl}-c)(1+\theta_c)\left\{(h+n^{nl})(1+\theta_h)(1+\theta_n) + \theta_c\left[h+n^{nl}+(h+c)\theta_h+(n^{nl}-c)\theta_n\right]\right\}}$$

$$X_n^{nl*} = \frac{V\left[(h+n^{nl})(1+\theta_h)+(n^{nl}-c)\theta_c\right] + (h+n^{nl})(1+\theta_h)C_c - C_n\left[(n^{nl}-c)\theta_c + (h+n^{nl})(1+\theta_h)\right]}{(n^{nl}-c)\left\{(h+n^{nl})(1+\theta_h) + (n^{nl}-c)(1+\theta_n) + \theta_c\left[h+n^{nl}+(h+c)\theta_h+(n^{nl}-c)\theta_n\right]\right\}}$$

$$X_h^{nl*} = \frac{(h+n^{nl})(1+\theta_n)C_n^{nl} + (h+c)\left\{(h+n^{nl})(1+\theta_n) + \theta_c\left[h+n^{nl}-V+(n^{nl}-c)\theta_n\right]\right\} - C_h\left[(h+c)\theta_c + (h+n^{nl})(1+\theta_n)\right]}{(h+c)\left\{(h+n^{nl})(1+\theta_h)(1+\theta_n) + \theta_c\left[h+n^{nl}+(h+c)\theta_h+(n^{nl}-c)\theta_n\right]\right\}}$$

c. When consumers are less averse to food nanotechnology than conventional food production methods $(n < c)$*:*

- Drastic innovation: Same as that in part a.
- Non-drastic innovation:

$$X_c^{nl*} = \frac{(h+c)(1+\theta_h)(C_n^{nl}-V) + \theta_n(c-n^{nl})\left[C_h + (h+n^{nl})\theta_h\right] - C_c\left[(h+c)(1+\theta_h) + (c-n^{nl})\theta_n\right]}{(c-n^{nl})\left\{(h+c)(1+\theta_n) + \theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right] + \theta_h\left[h+c+(h+n^{nl})\theta_n\right]\right\}}$$

$$X_n^{nl*} = \frac{(h+c)\left\{(h+n^{nl})(1+\theta_h)C_c + (c-n^{nl})(1+\theta_c)\left[C_h + (h+n^{nl})\theta_h\right]\right\}}{(c-n^{nl})(h+n^{nl})(1+\theta_n)\left\{(h+c)(1+\theta_n) + \theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right] + \theta_h\left[h+c+(h+n^{nl})\theta_n\right]\right\}}$$

$$-\frac{V(h+c)\left\{h+c+(2c+h-n^{nl})\theta_h + \theta_c\left[c+2h+n^{nl}+2(h+c)\theta_h\right]\right\}}{(c-n^{nl})(h+n^{nl})(1+\theta_n)\left\{(h+c)(1+\theta_n) + \theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right] + \theta_h\left[h+c+(h+n^{nl})\theta_n\right]\right\}}$$

$$+\frac{\theta_n(h+c)\left\{(h+n^{nl})(1+\theta_h)C_c + (c-n^{nl})(1+\theta_c)C_h + \theta_n(h+n^{nl})\left[(c-n^{nl})(1+\theta_c) - V\right]\right\}}{(c-n^{nl})(h+n^{nl})(1+\theta_n)\left\{(h+c)(1+\theta_n) + \theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right] + \theta_h\left[h+c+(h+n^{nl})\theta_n\right]\right\}}$$

$$-\frac{C_n^{nl}(h+c)(1+\theta_n)\left[h+c+(c-n^{nl})\theta_c + (h+n^{nl})\theta_h\right]}{(c-n^{nl})(h+n^{nl})(1+\theta_n)\left\{(h+c)(1+\theta_n) + \theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right] + \theta_h\left[h+c+(h+n^{nl})\theta_n\right]\right\}}$$

$$X_h^{nl*} = \frac{(h+c)(1+\theta_c)(h+n^{nl}-V+C_n^{nl} + \left[h+c+C_c+(c-n^{nl})\theta_c\right](h+n^{nl})\theta_n}{(h+c)\left\{(h+n^{nl})(1+\theta_h)(1+\theta_n) + \theta_c\left[h+n^{nl}+(h+c)\theta_h-(c-n^{nl})\theta_n\right]\right\}}$$

$$-\frac{C_h\left[(h+c)(1+\theta_c) + (h+n^{nl})\theta_n\right]}{(h+n^{nl})\left\{(h+c)(1+\theta_n) + \theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right] + \theta_h\left[h+c+(h+n^{nl})\theta_n\right]\right\}}$$

$$P_c^{nl*} = \frac{C_c\left\{(h+c)(1+\theta_n)+\theta_h\left[h+c+\theta_n(h+n^{nl})\right]\right\}}{(h+c)(1+\theta_n)+\theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right]+\theta_h\left[h+c+\theta_n(h+n^{nl})\right]}$$
$$+\frac{\theta_c\left\{(h+c)(1+\theta_h)(C_n^{nl}-V)+(c-n^{nl})\theta_n\left[C_h+\theta_h(h+n^{nl})\right]\right\}}{(h+c)(1+\theta_n)+\theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right]+\theta_h\left[h+c+\theta_n(h+n^{nl})\right]}$$

$$P_n^{nl*} = \frac{C_n^{nl}(h+c)(1+\theta_h)(1+\theta_c)}{(h+c)(1+\theta_n)+\theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right]+\theta_h\left[h+c+\theta_n(h+n^{nl})\right]}$$
$$+\frac{\theta_n\left\{V\left[h+c+(c-n^{nll})\theta_n+(h+n^{nl})\theta_h\right]+(c-n^{nl})(1+\theta_c)\left[\theta_h(h+n^{nl})+C_h\right]+(h+n^{nl})(1+\theta_h)C_c\right\}}{(h+c)(1+\theta_n)+\theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right]+\theta_h\left[h+c+\theta_n(h+n^{nl})\right]}$$

$$P_h^{nl*} = \frac{C_h\left\{(h+c)(1+\theta_n)+\theta_c\left[h+c+\theta_n(c-n^{nl})\right]\right\}}{(h+c)(1+\theta_n)+\theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right]+\theta_h\left[h+c+\theta_n(h+n^{nl})\right]}$$
$$+\frac{\theta_h\left\{(h+c)(1+\theta_c)(C_n-V+h+n^{nl})+(h+n^{nl})\theta_n\left[h+c+C_c+\theta_c(c-n^{nl})\right]\right\}}{(h+c)(1+\theta_n)+\theta_c\left[(h+c)(1+\theta_h)+(c-n^{nl})\theta_n\right]+\theta_h\left[h+c+\theta_n(h+n^{nl})\right]}$$

A3. Simulation results

Figure A1 depicts the changes of the profits of nanofood producers for $n \in [0,2]$. As consumers become more averse to food nanotechnology, the profits of nanofood producers decrease. We also allow the production costs of nanofood to fluctuate from 1 to 3. The profits decrease as costs increase.

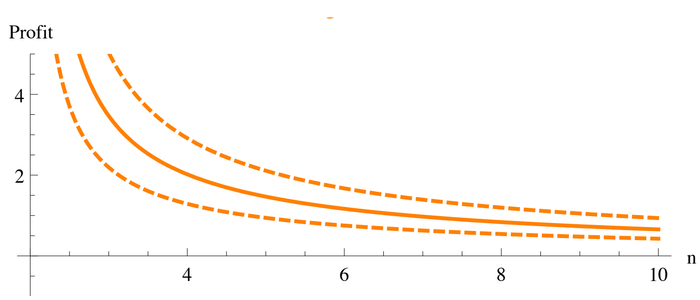


Figure A1: The profits of nanofood suppliers when consumers are more averse to food nanotechnology than conventional technology under a no labeling regime and consumer aversion increases under a labeling regime (Case I). Parameter values: $V=5$, $C_n=2$, $C_c=1.7$, $C_h=2.4$, $\theta_n=0.54$, $\theta_c=0.44$, $\theta_h=0.7$, $c=1.91$, $h=1.2$. **The three curves represent the profits of nanofood suppliers when the production cost runs from 1 to 3 with the dashed curves being the upper bound and lower bound.**

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