Consumer Attitudes, Labeling Regimes and the Market Success of Food Nanotechnology

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By Van T. Tran, Amalia Yiannaka and Konstantinos Giannakas

Abstract

The study explores the market and welfare effects of the introduction of a food nanotechnology innovation under different labeling regimes. An analytical framework of heterogeneous consumers who differ in their attitudes towards interventions in the production process and imperfectly competitive producers is developed to analyze the effects of food nanotechnology under different labeling regimes while considering different consumer preferences for food nanotechnology. Analytical results show that high consumer valuation of the enhanced attributes of nanofoods can lead to consumer acceptance of nanofoods even when consumers are averse to nanotechnology. In most cases, the introduction of food nanotechnology leads to a reduction in the prices and quantities of the existing food alternatives with the price and quantity decreases being greater when nanotechnology adoption costs are low. When this happens, welfare is lower for non-adopting producers and greater for nanofood adopters and for all consumers; consumers who benefit the most from the introduction of food nanotechnology are those who switch their consumption to nanofoods. Finally, labeling regulation has an adverse impact on consumer welfare when consumers are averse to food nanotechnology. Under this case, producers of substitute food products experience welfare gains at the expense of nanofood producers. The results, yet, are intriguingly divergent if consumers have no knowledge of or are indifferent to food nanotechnology in the absence of labeling. Moreover, if consumers perceive food nanotechnology as less invasive than conventional food technology, welfare gains and losses might be realized by different groups of consumers and producers depending on the relative magnitude of the model parameters.

Keywords: food nanotechnology, nanofood, heterogeneous consumers, consumer attitudes, consumer and producer welfare, nanofood labeling.

1 Introduction

Nanotechnology, 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; henceforth, NNI), is expected to become a broad-based technology by 2020 that will seamlessly integrate with existing key technologies in almost every field (Roco, Mirkin and Hersam 2010). Owing to the massive increase in the surface area and the consequential highly reactive property of particles at the nanoscale, nanoparticles impart unusual and desirable properties which nanoscientists employ to create novel products and processes. Among early adopting industries of nanotechnology have been high profit margin sectors like cosmetics, sports equipment and apparel. As the development of nanotechnology progressed from first-generation (material) to second-generation (component) and third-generation (device) technologies, applications to industrial sectors such as pharmaceuticals, biotechnology, medicine and medical devices, energy, national security and defense and the agri-food sector have become possible (The Nanotechnology Institute 2012). Nanotechnology advocates point to its potential to address various complex societal problems.[1]

In the agri-food sector, the use of nanotechnology in all phases of the food cycle has the potential to revolutionize the sector by increasing food supply and enhancing food quality and safety. Current and potential food nanotechnology applications include: nanosensors for monitoring crop growth and pest control and identifying animal and plant diseases as well as food contaminants;[2] nanoencapsulated additives and ingredients that enable changes in food texture, taste, processability and quality;[3] and packaging material that is more durable, light, can repair tears, can respond to environmental conditions, release preservatives that extend food life, signal certain food qualities[4] and improve food safety by signaling whether food is contaminated or spoiled (Sekhon 2010).

While the potential benefits of food nanotechnology can be immense, its potential risks are not well understood. Concerns involve the potential toxicity of nanoparticles whose chemical and physical properties can be very different from those of macro particles of the same composition, thus, while the latter may be harmless, the former could be toxic to humans and/or the environment (NanoBio-Raise 2011). Skeptics

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[1] Examples in the medical field include the nano-based "lab-on-the-chip" device that permits prompt and accurate diagnosis of diseases as the results can come out in an instant; nano-imaging devices that enable the precise delivery of nutrients to the targeted tissues, reducing the quantities of prescription drugs and thus the amount of toxicity or the side effects to the sick body. In the energy sector, nanotechnology can contribute to a sustainable environment by serving, for instance, as a mechanism for improving the photosynthesis process, which transforms sunlight, water, or carbon-dioxide into fuel and other types of energy or combating non-point source pollution.

[2] An example are nanosensors capable of providing a visual detection of melamin in dairy products; in the presence of melamin, the milk solution changes from pink to blue. Melamin in dairy products is believed to be the cause of 300,000 deaths (including children and infants) in the 2008 Chinese milk incident.

[3] An example is ice-cream (and mayonnaise) produced using nanoemulsions which are less fatty (fat potentially reduced from 8-16% to 1%) but as creamy and tasty as the full equivalent (Hall 2005; Cushen et al 2012).

[4] An example of this application, that is already in the market in New Zealand and Canada, is the ripeSense® packaging which incorporates a nanosensor that changes color with the oxidation of food inside the package to indicate the degree of ripeness in fruit (Patterson 2009). See http://www.ripesense.com.

worry that nanoparticles may be inhaled by humans during their production or escape from engineered structures into food or the environment. The lack of scientific consensus on the health and environmental risks of nanotechnology and the ambiguity in the risk assessments of food nanotechnology is mainly due to the current lack of appropriate toxicity tests (Cushen, 2012).

Nanofoods which, according to a commonly used definition, are food products that has been cultivated, produced, processed or packaged using nanotechnology techniques/tools or to which engineered nanomaterials have been added (Sekhon 2010) are already in the market (NanoBio-Raise 2011).[5] While skeptics voice concerns regarding testing and approval of nanofoods, efforts are currently underway in a number of countries to regulate food nanotechnology.[6] In the United States (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). The European Union (EU) is implementing a new Classification Labeling and Packaging regulation requiring that the classification and labeling of nanomaterials will be done on a case-by-case basis and based on the precautionary principle. Thus, while in the EU proposed regulations mandate labeling for nanotech products, it is unclear whether these products will be mandatorily labeled in the US.

Given the current lack of labeling of nanotechnology, it comes as no surprise that approximately 80% of the public reports to know "a little" or "nothing at all" about

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[5] A list of nanofoods can be found in the Nanotechnology Consumer Products Inventory (PEN 2010).

[6] A report by Friends of the Earth finds that "untested nanotechnology is being used in more than 100 food products, food packaging and contact materials currently on the shelf, without warning or new FDA testing" and urges the Food and Drug Administration (FDA) to stop the sale of all nanofood, packaging, and agricultural chemicals until strong scientific regulations are enacted to ensure consumer safety and until ingredients are labeled (FOE 2008).

nanotechnology in general and food nanotechnology in particular (IFIC 2012; Gaskel et al. 2010; Kahan 2009; Cobb and Macoubrie 2004). Interestingly, research shows that, despite this lack of knowledge and understanding of nanotechnology, the public has, nevertheless, opinions as to its potential risks and benefits. For instance, in the US the public currently views the benefits of nanotechnology as outweighing potential risks; however, a large minority (44%) is unsure, which indicates that perceptions are malleable (Pidgeon et al. 2008; Satterfield et al. 2009). Given the critical role that public perceptions and attitudes have played in shaping the future of a number of scientific fields (e.g., nuclear power, genetic modification and embryonic stem cell research) (Curral et al. 2006), a large number of studies have focused on understanding what drives and shapes perceptions and attitudes towards nanotechnology. A common finding in this research is that when people lack information, as is the case with nanotechnology, or do not have enough time to assess information, they use heuristics (shortcuts) to form perceptions and attitudes (Kahan et al. 2007, 2008, 2009, 2013; Satterfield et al. 2009). Among the most important heuristics were affect, where people's perceptions about nanotechnology mirrored their emotional appraisals of it (Kahan et al. 2007), trust in the industry, government and/or scientists and attitudes towards other more familiar technologies (Cobb and Macoubrie 2004; Siegrist et al. 2007; Siegrist 2008, Vandermoere et al. 2010, 2011), religious orientation (Scheufele et al. 2008) and cultural values which influenced both where information about nanotechnology was sought and how it was processed (Kahan 2008, 2009, 2013; Satterfield et al. 2009). Psychometric parameters, which included whether nanotechnology was perceived as being involuntarily imposed, unfamiliar, invisible, unequally distributed, beyond one's control or unnatural (Siegrist et al. 2008, 2009), attitudinal predispositions such as political leanings and intuitive toxicology as well as demographic attributes were also shown to influence nanotechnology perceptions and attitudes (Kahan et al. 2007, 2009; Satterfield et al. 2009).[7]

An important conclusion in the above studies is that application matters; nanotechnology involves numerous and diverse areas of science so public perceptions and attitudes need to be associated with specific applications (Satterfield et al. 2009). This need is evident in a study by Siegrist et al. 2008 who show that attitudes towards nanofoods were very much dependent on applications (i.e., nano-inside versus nano-outside applications) and the findings of Beiberstein et al. (2013) who elicit willingness to pay for nanopackaging and nanofortification in Germany and France.

Even though existing studies shed important light into the determinants of public perceptions and attitudes towards nanotechnology and its use in the food sector, there are no studies, to the best of our knowledge, that systematically examine the economic impacts of the introduction of nanotechnology in the food sector. Along with consumer attitudes towards nanotechnology, factors like producer adoption costs, the degree of market power and the labeling regime of nanofoods can play a critical role in the market acceptance and success of food nanotechnology. Understanding the conditions under which a food nanotechnology innovation will end up being ineffective, co-existent with substitutes or drastic and its effects on the welfare of different interest groups (e.g., consumers and producers of nanotechnology and of alternative technologies) is critical as it can inform the design of effective policies and strategies for food nanotechnology innovations.

The objective of this paper is threefold. We first examine the determinants of the market acceptance and success of a food nanotechnology innovation and identify the exact conditions under which the innovation will end up being (a) ineffective (i.e., not accepted in the market), (b) non-drastic (i.e., accepted and co-existent with its

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[7] e.g. Kahan et al. 2008, 2009 provide evidence that male, white, well-educated and high income earners are more likely to view risks as lower than those in all other demographic categories.

conventional and organic food counterparts), and (c) drastic (i.e., successful enough to drive its conventional food counterparts out of the market). Second, we analyze the market and welfare effects of the introduction of the nanofood innovation on the interest groups involved (i.e., consumers and suppliers of nanofoods and their conventional and organic counterparts). Lastly, we uncover the effects of labeling on the use of nanotechnology on consumer and producer welfare. In addressing these issues, the study accounts for (1) differences in consumer attitudes towards interventions in the production process and (2) imperfect competition in the supply channels of interest.

The paper is divided into three main sections: Section 2 describes the theoretical framework and assesses the market and welfare impact of food nanotechnology, Section 3 discusses the welfare impact of the labeling regulation on nanofood products and Section 4 concludes the paper.

2 The Framework

2.1 Model Assumptions

We employ an analytical framework of heterogeneous consumers and imperfectly competitive producers to examine the market and welfare impacts of the introduction of food nanotechnology innovations. Our model builds on previous work by Giannakas (2002, 2011), Fulton and Giannakas (2004) and Giannakas and Yiannaka (2008) who examine labeling in GM product markets. We consider a market where a food product can be produced with different production technologies, namely, conventional technology, nanotechnology or an alternative technology (e.g., organic production).[8] In

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[8] An example is vanilla ice-cream that can be produced using conventional technology (e.g., Breyers), nanotechnology (possibly, a future product by Unilever) or organic methods (e.g, Straus Family organic ice-cream, Julie Organic Ice-cream).

our model, consumers differ in their attitudes towards interventions in the production process, each consumes one unit of the product of their choice and their consumption represents a small share of their budget. The utility associated with each choice is given by:

$$\begin{aligned} &U_c = U - P_c - c\alpha, \text{if a unit of the conventional food is consumed} \\ &U_n = U + V - P_n \ - n\alpha, \text{if a unit of the nanofood is consumed} \\ &U_h = U - P_h + h\alpha, \text{if a unit of the high quality substitute food is consumed} \end{aligned} \tag{2.1}$$

where U represents a base level of utility derived from the consumption of a unit of the food product and it is the same for all product forms regardless of their production technology. The parameter V captures consumer valuations of the enhanced attributes enabled by food nanotechnology (e.g., longer self-life, smart or active packaging). For tractability and to keep the focus on consumer attitudes towards nanotechnology, V is assumed to be common across consumers and positive. P_c, P_n, and P_h are market prices for the conventional food, nanofood, and high quality food, respectively.

The parameter α where $\alpha \in [0, 1]$ is the differentiating consumer characteristic which captures differences in consumer attitudes towards interventions in the production process. Consumers with an α value of zero are not averse to interventions in the production process and are thus indifferent to the production technologies; hence, their consumption decision is solely determined by the product prices and the values they place on the enhanced product attributes. Consumers with an α value equal to one are those highly averse to interventions in the production process.

While the parameter α differentiates consumers according to their preferences for different production technologies, the parameters c, h and n capture the intensity of these preferences. Specifically, the non-negative parameters c and h are utility discount and enhancement factors, respectively, associated with consuming a unit of the conventional and high quality substitute product. Thus, the conventional and high quality substitute food products are treated as vertically differentiated in our model; if the two products were offered at the same price, all consumers would prefer the high quality substitute.[9]

We allow the parameter n to take both negative and positive values to capture all possible cases that might emerge concerning consumer attitudes towards nanotechnology. This is important because, as previously mentioned, evidence from the literature suggests that, given the current low levels of consumer awareness of food nanotechnology, preferences and attitudes towards nanotechnology are highly malleable and dependent on the application.

Given the above, the parameter n can be interpreted as either the utility discount ($n > 0$) or enhancement ($n < 0$) factor associated with the consumption of a unit of the nanofood; n could be a discount factor when consumers are concerned about the potential health and/or environmental risks associated with the use of nanotechnology while it could be an enhancement factor when consumers are not concerned about those risks, value the enhanced attribute and realize that it is made possible only via nanotechnology. Following this, the difference $(n - c)$ measures the degree of consumer aversion towards food nanotechnology as compared to conventional technology. In particular, when $n > c$, consumers are more averse towards the use of food nanotechnology than conventional technology. When $n = c$, consumers are either indifferent between nanotechnology and conventional technology or unaware of the existence of nanotechnology in the food industry. Lastly, when $n < c$, consumers

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[9] Thompson and Kidwell (1998) find that consumers' willingness-to-pay is higher for organic food products than for their conventional counterparts.

are less averse towards food nanotechnology. Consumer willingness-to-pay for a unit of the conventional food, nanofood and high quality food product is measured by $U - c\alpha, U + V - n\alpha$ and $U + h\alpha$, respectively.

In our model, producers maximize their profits subject to the demand they face for their product as shown in equation (2.2):

$$\begin{aligned}
&\underset{x_i}{\text{Max}}\ \pi_c = (P_c(X_c) - C_c)x_i,\\
&\textit{subject to } P_c(X_c) = g_1(P_h, P_n) \text{ if a unit of the conventional food is produced}\\
&\underset{x_k}{\text{Max}}\ \pi_n = (P_n(X_n) - C_n)x_k,\\
&\textit{subject to } P_n(X_n) = g_2(P_h, P_c) \text{ if a unit of the nanofood is produced}\\
&\underset{x_j}{\text{Max}}\ \pi_h = (P_h(X_h) - C_h)x_j,\\
&\textit{subject to } P_h(X_h) = g_3(P_c, P_n) \text{ if a unit of the high quality food is produced}
\end{aligned} \tag{2.2}$$

where x_i, x_k, and x_j are the quantities supplied by firms i, k and j in the conventional food, nanofood, and high quality food supply sector, respectively, where $i = 1, 2, ..., N_c;\ k = 1, 2, ..., N_n;\ j = 1, 2, ..., N_h$ and N_c, N_n and N_h are the number of firms in each sector. g(.) is a continuous function of market demand, which is derived from the solution of the consumer utility maximization problem. C_h, C_c, and C_n are production costs associated with producing a unit of the high quality, conventional food or nanofood product, respectively. Note that at this stage all costs related to the generation and adoption of the food nanotechnology innovation (e.g., R&D costs) are sunk.

The solutions of the profit maximization problems in equation (2.2) give the market equilibrium prices and quantities. To evaluate the impact of food nanotechnology, the market equilibrium and welfare before and after the introduction of food nanotechnology are derived and compared in the following sections.

2.2 Market equilibrium and welfare before the introduction of food nanotechnology

Before the introduction of food nanotechnology, consumers have two choices: a conventional food product and a high quality substitute. Their utility functions are as follows:

$$\begin{aligned} &U_c^o = U - P_c^o - c\alpha, \text{if a unit of the conventional food is consumed} \\ &U_h^o = U - P_h^o + h\alpha, \text{if a unit of the high quality substitute food is consumed} \end{aligned} \tag{2.3}$$

where the superscript "o" refers to parameter values *prior to* the introduction of nanofoods. Consumers choose the product option that maximizes their utility so consumers with the differentiating characteristic $\alpha_c^o = \dfrac{P_h^o - P_c^o}{h + c}$ such that $U_c^o(\alpha_c^o) = U_h^o(\alpha_c^o)$ are indifferent between consuming the conventional product and the high quality substitute product. Consumers with a differentiating characteristic $\alpha \in [0, \alpha_c^o]$ maximize their utility by consuming the conventional product while those with $\alpha \in (\alpha_c^o, 1]$ find it optimal to consume the high quality substitute (see Figure 1). Such decisions are intuitively justified in that the more averse a consumer is towards interventions in the production process (α is closer to 1), the greater the likelihood that they will choose the high quality substitute food product. The dashed kinked curve in Figure 1 depicts the effective utility curve and the area below it aggregate consumer welfare.

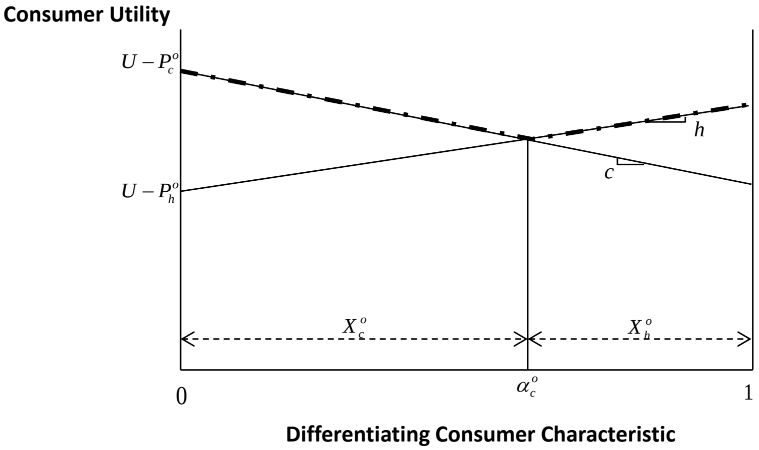

Figure 1: *Consumer decisions and market shares before the introduction of nanofoods.*

Assuming that consumers are uniformly distributed along the differentiating characteristic, the consumption shares of the conventional, X_c^o, and high quality food product, X_h^o, are given by:

$$X_c^o = \alpha_c^o = \frac{P_h^o - P_c^o}{h+c} \tag{2.4}$$

$$X_h^o = 1 - \alpha_c^o = \frac{h + c - P_h^o + P_c^o}{h+c} \tag{2.5}$$

Equations (2.4) and (2.5) suggest that the price premium, $P_h^o - P_c^o$, has to satisfy the condition $0 < P_h^o - P_c^o < h + c$ for both the conventional and high quality food product to coexist in the market. By normalizing the mass of consumers to unity, the consumption shares also reflect the consumption demands for the conventional and high quality substitute products. Finally, the inverse demands for the conventional and high quality substitute products are given by:

$$P_c^o = P_h^o - (h+c)X_c^o \tag{2.6}$$

$$P_h^o = P_c^o + h + c - (h+c)X_h^o \tag{2.7}$$

Using the inverse demand equations (2.6) and (2.7), the producers' profit maximization problems before the introduction of nanofoods become:

$$\begin{aligned}
&\max_{x_i} \pi_c^o = (P_c^o(X_c^o) - C_c)x_i, \\
&\textit{subject to } P_c^o(X_c^o) = P_h^o - (h+c)X_c^o \\
&\max_{x_j} \pi_h^o = (P_h^o(X_h^o) - C_h)x_j, \\
&\textit{subject to } P_h^o(X_h^o) = P_c^o + h + c - (h+c)X_h^o
\end{aligned} \tag{2.8}$$

Optimization of the objective functions in (2.8) yields the following first order conditions (FOCs) for a maximum:

$$\begin{aligned}
&\frac{dP_c^o}{dX_c^o}\frac{dX_c^o}{dx_i}x_i + P_c^o(X_c^o) - C_c = 0 \\
&\qquad \Rightarrow -(h+c)\theta_c^o X_c + P_h - (h+c)X_c - C_c = 0 \\
&\frac{dP_h^o}{dX_h^o}\frac{dX_h^o}{dx_j}x_j + P_h^o(X_h^o) - C_h = 0 \\
&\qquad \Rightarrow -(h+c)\theta_h^o X_h + P_c + h + c - (h+c)X_h - C_h = 0
\end{aligned} \tag{2.9}$$

In equations (2.9), θ_c^o and θ_h^o are the conjectural variation elasticities which measure market power in the conventional and high quality food product sectors prior to the introduction of nanofoods.[10] Simultaneously solving the FOCs yields the market equilibrium quantities and prices as follows:

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[10] $\theta_c^o = \frac{1}{N_c}\sum_{i=1}^{N_c} \frac{dX_c^o}{dx_i}\frac{x_i}{X_c^o}$ and $\theta_h^o = \frac{1}{N_h}\sum_{j=1}^{N_h} \frac{dX_h^o}{dx_j}\frac{x_j}{X_h^o}$ where N_c and N_h are the number of firms in the conventional and high quality food sector, respectively.

$$
\begin{aligned}
X_c^{o*} &= \frac{\theta_h^o(h+c) + C_h - C_c}{(1+\theta_c^o+\theta_h^o)(h+c)} \\
X_h^{o*} &= \frac{(1+\theta_c^o)(h+c) + C_c - C_h}{(1+\theta_c^o+\theta_h^o)(h+c)} \\
P_c^{o*} &= \frac{\theta_c^o\left[\theta_h^o(h+c) + C_h\right] + (1+\theta_h^o)C_c}{1+\theta_c^o+\theta_h^o} \\
P_h^{o*} &= \frac{\theta_h^o\left[(1+\theta_c^o)(h+c) + C_c\right] + (1+\theta_c^o)C_h}{1+\theta_c^o+\theta_h^o}
\end{aligned}
\tag{2.10}
$$

The market equilibrium quantities and prices of the available food products depend on production costs, the utility discount/enhancement factors, and the degree of market power in both sectors. Specifically, the greater the production costs, the utility discount factor, and/or the lower the degree of market competition, the higher the price and the lower the quantity of the conventional food product. These conclusions also apply to the high quality food product except that the market demand increases when the utility enhancement factor from consuming a unit of the high quality product increases.

We can estimate aggregate consumer welfare prior to the introduction of food nanotechnology (as depicted in Figure 2, panel (iii)) by integrating the effective utility curve that corresponds to the optimal consumption decisions:

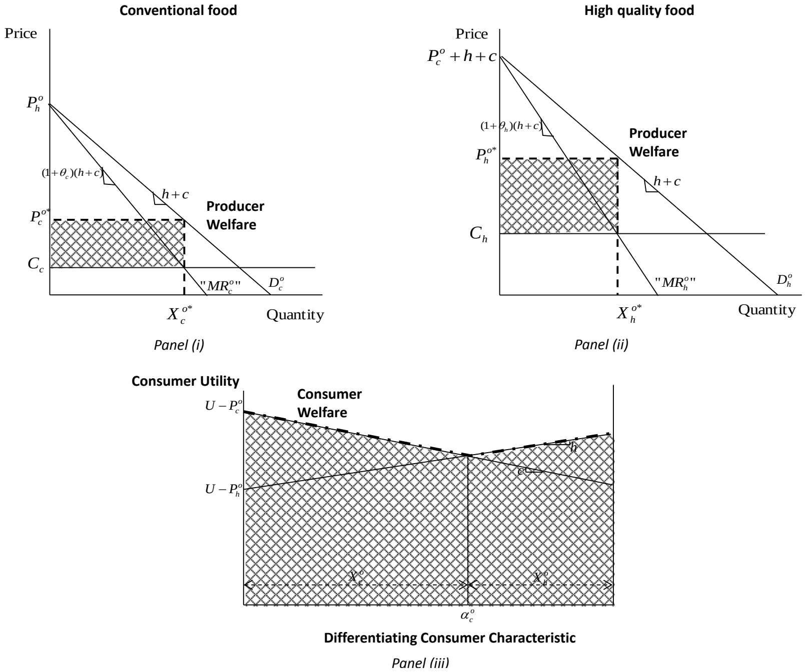
$$CS_c^o = \int_0^{\alpha_c^o} U_c^o(\alpha)\, d(\alpha) = \int_0^{X_c^{o*}} (U - P_c^{o*} - c\alpha)\, d(\alpha) \tag{2.11}$$

$$CS_h^o = \int_{\alpha_c^o}^1 U_h^o(\alpha)\, d(\alpha) = \int_{X_c^{o*}}^1 (U - P_h^{o*} + h\alpha)\, d(\alpha) \tag{2.12}$$

Producer welfare for the conventional and high quality food product producers is given, respectively, by equations (2.13) and (2.14), and illustrated in Figure 2, panels (i) and (ii).

$$PS_c^o = (P_c^{o*} - C_c)X_c^{o*} \tag{2.13}$$

$$PS_h^o = (P_h^{o*} - C_h)X_h^{o*} \tag{2.14}$$



Panel (i)

Panel (ii)

Panel (iii)

Figure 2: *Market equilibrium and welfare before the introduction of nanofoods.*

2.3 Market equilibrium and welfare after the introduction of food nanotechnology

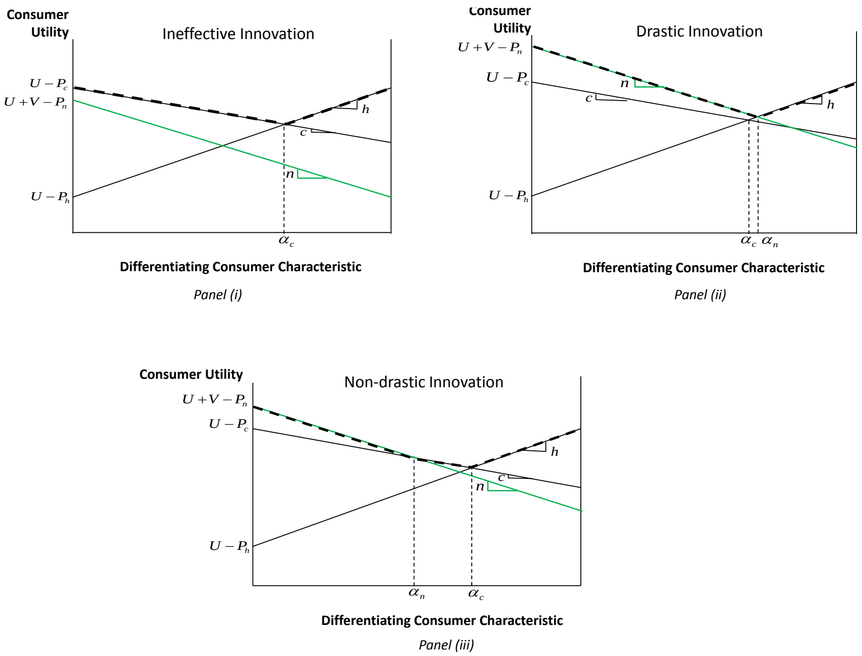
When the nanofood innovation is introduced in the market the utility associated with each consumption choice that is available to consumers is given by:

$$\begin{aligned} &U_c = U - P_c - c\alpha, \text{if a unit of the conventional food is consumed} \\ &U_n = U + V - P_n \ - n\alpha, \text{if a unit of the nanofood is consumed} \\ &U_h = U - P_h + h\alpha, \text{if a unit of the high quality substitute food is consumed} \end{aligned} \tag{2.15}$$

In assessing the market and welfare outcomes after the introduction of food nanotechnology three scenarios are considered that capture consumer attitudes towards the use of nanotechnology in the food sector; scenario A where consumers are more averse to nanotechnology than conventional food technology ($n > c$), scenario B where consumers are indifferent between nanotechnology and conventional food technology or unaware of the existence of food nanotechnology ($n = c$) and scenario C where consumers are less averse ($n < c$) to nanotechnology than conventional food technology. Under each scenario three cases are examined that capture the market outcome from the introduction of the food nanotechnology innovation. Under case I the nanofood innovation is *ineffective* (i.e., not accepted into the market), under case II it is *non-drastic* (i.e., coexistent with the conventional and high quality food products) and under case III it is *drastic* (i.e., the introduction of the nanofood product drives the conventional food product out of market). The case where the introduction of the nanofood product drives both the conventional and the high quality product out of the market is also considered as a special case under the drastic innovation case.

Scenarios A and B

Under scenarios A and B the nanofood innovation is *ineffective* when $U_c > U_n$ at $\alpha = 0$. This implies that $P_n > P_c + V \Rightarrow V < P_n - P_c$. This case is depicted graphically for scenario A ($n > c$) in Figure 3, panel (i) where the utility schedule of the nanofood innovation, U_n, is below the utility schedule of the conventional product, U_c, for all α values.



Panel (i)

Panel (ii)

Panel (iii)

Figure 3: *Illustrations of the three market outcomes of food nanotechnology (i.e., ineffective, drastic and non-drastic) under scenario A ($n > c$).*

The *drastic* case emerges when $U_n > U_c$ at α_c and α_n where $\alpha_c : U_c(\alpha_c) = U_h(\alpha_c)$, $\alpha_n : U_n(\alpha_n) = U_h(\alpha_n)$ and $\alpha_n > \alpha_c$. The condition for a drastic nanotechnology innovation is derived as follows:

$$\begin{aligned} P_n &< P_c + V - \frac{(n-c)(P_h - P_c)}{h+c} \\ V &> P_n - P_c + \frac{(n-c)(P_h - P_c)}{h+c} \\ n - c &< \frac{h+c}{P_h - P_c}(P_n + V - P_c) \end{aligned} \tag{2.16}$$

This case is depicted graphically for scenario A in Figure 3, panel (ii) where U_n is above U_c at any point on and to the left of α_c. Note that if U_n is above U_c for all α values, then we have a special case where both the conventional and the high quality food are driven out of the market, i.e., the nanofood innovation is dominant.[11]

The intermediate values of P_n or V bounded by the two extremes identify the *non-*

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[11] By setting $U_n > U_h$ at $\alpha = 1$, we can derive the condition for this special case as $P_n < P_h + V - (n + h)$, or equivalently, $V > P_n - P_h + n + h$.

drastic case. In particular, when condition (2.17) is satisfied, nanofoods are coexistent with conventional foods.

$$\begin{aligned} P_c + V - \frac{(n-c)(P_h - P_c)}{h+c} &\leq P_n \leq P_c + V \\ P_n - P_c \leq V &\leq P_n - P_c + \frac{(n-c)(P_h - P_c)}{h+c} \\ n - c &\geq \frac{h+c}{P_h - P_c}(P_n + V - P_c) \end{aligned} \tag{2.17}$$

This case is depicted graphically for scenario A in Figure 3, panel (iii).

<u>*Scenario C*</u>

When consumers are more averse towards conventional food technology than food nanotechnology ($n < c$) the conditions for a food nanotechnology innovation to be ineffective, non-drastic and drastic are given by equations (2.18), (2.19) and (2.20), respectively:

Ineffective:

$$\begin{aligned} P_n &> P_c + V - \frac{(n-c)(P_h - P_c)}{h+c} \\ V &< P_n - P_c + \frac{(n-c)(P_h - P_c)}{h+c} \\ n - c &> \frac{h+c}{P_n - P_c}(P_n + V - P_c) \end{aligned} \tag{2.18}$$

Non-drastic:

$$\begin{aligned} P_c + V \leq P_n &\leq P_c + V - \frac{(n-c)(P_h - P_c)}{h+c} \\ P_n - P_c + \frac{(n-c)(P_h - P_c)}{h+c} &\leq V \leq P_n - P_c \\ n - c &\leq \frac{h+c}{P_n - P_c}(P_n + V - P_c) \end{aligned} \tag{2.19}$$

Drastic:

$$\begin{aligned} P_n &< P_c + V \\ V &> P_n - P_c \end{aligned} \tag{2.20}$$

A comparison across the three cases shows that different values of the nanofood price, P_n, lead to different market outcomes, whereby P_n must at least satisfy the upper bound of the condition (2.17) or (2.19) for the nanofood to be accepted into the market. The non-drastic conditions also underline the significance of consumer attitudes towards food nanotechnology, n, or equivalently, relative to conventional technology as captured by $n - c$. That is, when consumers are more averse to food nanotechnology than conventional food technology, for a certain level of prices of the nanofood, what determines the extent of consumer market acceptance of the nanofood is the degree of consumer aversion towards food nanotechnology, $n - c$. In particular, if $n - c \geq \frac{h + c}{P_h - P_c}(P_n + V - P_c)$, a food nanotechnology innovation ends up being non-drastic; drastic otherwise.

A comparison across the three scenarios shows that a change in consumer attitudes from being more to less averse to food nanotechnology than conventional food technology (from $n \geq c$ to $n < c$) results in a switch from an ineffective food nanotechnology innovation to a non-drastic one. Figure 4 shows that when $P_n > V + P_c$ and if consumers express more aversion towards nanotechnology than conventional technology, the food nanotechnology innovation is ineffective (as in scenarios A and B). However, if for some reason consumers change their attitudes in favor of the use of food nanotechnology (e.g., due to new information about the potential of nanotechnology to solve environmental problems), the nanotechnology innovation can become non-drastic (as in scenario C). Finally, an interesting result from condition (2.16) and (2.17) is that even when consumers are averse to food nanotechnology, they can still consume the nanofood if they place a high value on the enhanced attributes offered by food nanotechnology.

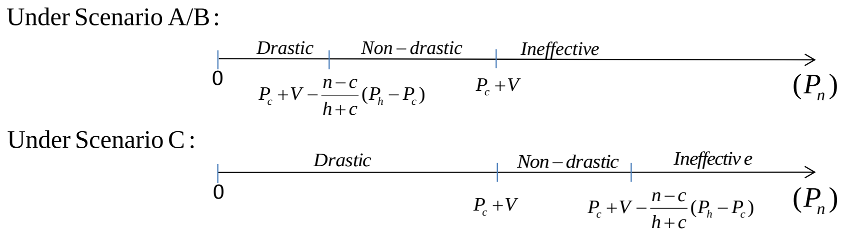

Figure 4: *Impact of the change in consumer attitudes towards the use of food nanotechnology on market outcomes.*

2.3.1 Market equilibrium and welfare under scenario A $(n > c)$

As one would expect, when the nanofood innovation is ineffective (case I), there is no change in the market equilibrium quantities and prices of the conventional and high quality food products. However, total market welfare is reduced under this case by the amount of R&D investment in food nanotechnology.

When the nanofood innovation is accepted in the market consumers choose the product option that maximizes their utility as shown in equation (2.15). We denote by α_n the consumer who obtains the same utility from the consumptions of the nanofood and the conventional food, $\alpha_n = \dfrac{P_c - P_n + V}{n - c}$, and is thus indifferent between the two options (i.e., $U_n(\alpha_n) = U_c(\alpha_n)$). The consumer with a differentiating characteristic α_c such that $\alpha_c = \dfrac{P_h - P_c}{h + c}$ is indifferent between the conventional food and the high quality food (i.e., $U_c(\alpha_c) = U_h(\alpha_c)$). Given the above, the consumer with a differentiating characteristic α such that $\alpha \in [0, \alpha_n], \alpha \in (\alpha_n, \alpha_c]$, and $\alpha \in (\alpha_c, 1]$ prefers the nanofood, the conventional food, and the high quality food, respectively (see Figure 5).

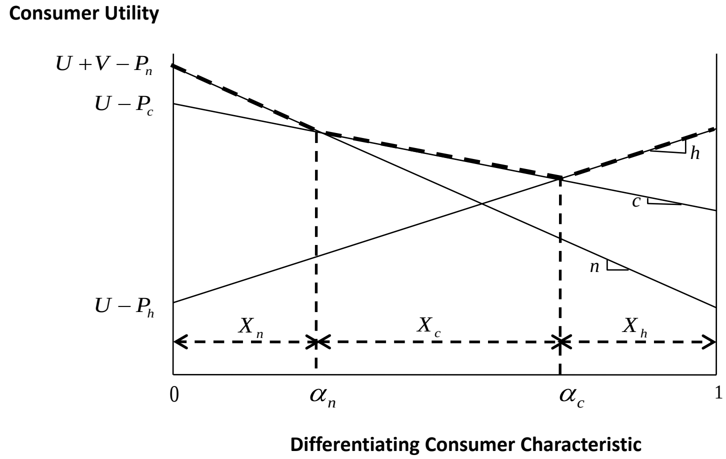

Figure 5: *Consumer decisions and market shares after the introduction of nanofoods under scenario A ($n > c$).*

When the three food products coexist in the market, (the coexistence condition (2.17) is satisfied), the inverse demands are derived as follows:

$$P_n(X_n) = P_c + V - (n-c)X_n \tag{2.21}$$

$$P_c(X_c) = \frac{(n-c)P_h + (h+c)P_n - (h+c)V - (h+c)(n-c)X_c}{n+h} \tag{2.22}$$

$$P_h(X_h) = P_c + h + c - (h+c)X_h \tag{2.23}$$

Similar to the case prior to the introduction of nanofoods, producers maximize their profits subject to the demand they face from the consumer market as follows:

$$\begin{aligned}
&\max_{x_i} \pi_c = (P_c(X_c) - C_c)x_i, \\
&\textit{subject to } P_c(X_c) = \frac{(n-c)P_h + (h+c)P_n - (h+c)V - (h+c)(n-c)X_c}{n+h} \\
&\max_{x_k} \pi_n = (P_n(X_n) - C_n)x_k, \textit{ subject to } P_n(X_n) = P_c + V - (n-c)X_n \\
&\max_{x_j} \pi_h = (P_h(X_h) - C_h)x_j, \textit{ subject to } P_h(X_h) = P_c + h + c - (h+c)X_h
\end{aligned} \tag{2.24}$$

Optimization of the objective functions in (2.24) yields the FOCs:

$$\begin{aligned}
&\frac{dP_c}{dX_c}\frac{dX_c}{dx_i}x_i + P_c(X_c) - C_c = 0\\
&\frac{dP_n}{dX_n}\frac{dX_n}{dx_k}x_k + P_n(X_n) - C_n = 0\\
&\frac{dP_h}{dX_h}\frac{dX_h}{dx_j}x_j + P_h(X_h) - C_h = 0
\end{aligned} \tag{2.25}$$

Simultaneously solving the above FOCs in terms of the production costs, degree of market power, consumer attitudes towards the use of different production technologies, and consumer valuations of the enhanced attributes of the nanofood yields the equilibrium prices and quantities for each product:

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

$$\begin{aligned}
P_n^* &= \frac{C_n\{(h+n)(1+\theta_h) + \theta_c[h+n+(c+h)\theta_h]\}}{(h+n)(1+\theta_h)(1+\theta_n) + \theta_c[h+n+(c+h)\theta_h + (n-c)\theta_n]}\\
&+ \frac{\theta_n\{(h+n)(1+\theta_h)(V+C_c) - (c-n)\theta_c[V + C_h + (c+h)\theta_h]\}}{(h+n)(1+\theta_h)(1+\theta_n) + \theta_c[h+n+(c+h)\theta_h + (n-c)\theta_n]}
\end{aligned}$$

$$\begin{aligned}
P_h^* &= \frac{C_h\{(h+n)(1+\theta_n) + \theta_c[h+n+(n-c)\theta_n]\}}{(h+n)(1+\theta_h)(1+\theta_n) + \theta_c[h+n+(c+h)\theta_h + (n-c)\theta_n]}\\
&+ \frac{\theta_h\{(h+n)(1+\theta_n)(C_c + c + h) + (c+h)[(h+n+C_n-V)\theta_c + (n-c)\theta_n]\}}{(h+n)(1+\theta_h)(1+\theta_n) + \theta_c[h+n+(c+h)\theta_h + (n-c)\theta_n]}
\end{aligned}$$

$$\begin{aligned}
X_c^* &= \frac{(h+n)(1+\theta_c)\{(n-c)(1+\theta_n)C_h - (c+h)[(V-C_n)(1+\theta_h) - \theta_h(n-c)(1+\theta_n)]\}}{(c+h)\{(c+h)(n-c)(1+\theta_c)\{(h+n)(1+\theta_h)(1+\theta_n) + \theta_c[h+n+(c+h)\theta_h + (n-c)\theta_n]\}}\\
&- \frac{C_c[\theta_c[h+n+(c+h)\theta_h + (n-c)\theta_n] + (h+n)\{1 + (1-c-h)\theta_n + \theta_h[1-n+c+(1-h-n)\theta_n]\}]}{(c+h)(n-c)(1+\theta_c)\{(h+n)(1+\theta_h)(1+\theta_n) + \theta_c[h+n+(c+h)\theta_h + (n-c)\theta_n]\}}
\end{aligned}$$

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

$$
\begin{aligned}
X_h^* = {} & \frac{(h+n)(1+\theta_n)C_n + (c+h)\{(h+n)(1+\theta_n) + \theta_c[h+n-V+(n-c)\theta_n]\}}{(c+h)\{(h+n)(1+\theta_h)(1+\theta_n) + \theta_c[h+n+(c+h)\theta_h+(n-c)\theta_n]\}} \\
& - \frac{C_h[(c+h)\theta_c + (h+n)(1+\theta_n)]}{(c+h)\{(h+n)(1+\theta_h)(1+\theta_n) + \theta_c[h+n+(c+h)\theta_h+(n-c)\theta_n]\}}
\end{aligned}
$$

One should note that, for the three products to coexist, these market equilibrium quantities and prices must satisfy the coexistence condition when $n > c$, implying that the inequality in (2.17) must be satisfied. For example, the numeric values of V must fall within the range $[VLO, VUP]$, where

$$
\begin{aligned}
VLO &= C_n - \frac{(n-c)\theta_c[C_h + (c+h)\theta_h] + (h+n)(1+\theta_h)C_c}{(n-c)\theta_c + (h+n)(1+\theta_h)} \\
VUP &= C_n + \frac{(n-c)(1+\theta_n)[C_h + (c+h)\theta_h] - [(h+n)+(c+h)\theta_h+(n-c)\theta_n]C_c}{(c+h)(1+\theta_h)}
\end{aligned}
$$

The market and welfare impacts of food nanotechnology under scenario A can be summarized in the following three propositions.

Proposition 1: When consumers are more averse to nanotechnology than conventional food technology, the introduction of a food nanotechnology innovation causes (*a*) *a reduction in the market prices and* (*b*) *a reduction in the market quantities of the existing food substitutes under coexistence of the available food products.*

▷ Proof of Proposition 1a:

The FOCs of the profit maximization problems before and after the introduction of food nanotechnology (equations 2.9 and 2.25) give the changes in prices of the conventional food and high quality substitute food as follows:

$$
\begin{aligned}
\Delta P_c = P_c^o - P_c &= \frac{\theta_c^o P_h^o + C_c}{1+\theta_c^o} - \frac{\theta_c[(n-c)P_h + (h+c)(P_n - V)] + (n+h)C_c}{(n+h)(1+\theta_c)} \\
\Delta P_h = P_h^o - P_h &= \frac{\theta_h^o(P_c^o + h + c) + C_h}{1+\theta_h^o} - \frac{\theta_h(P_c + h + c) + C_h}{1+\theta_h}
\end{aligned}
$$

Given our assumption of invariant market power in the high quality and conventional food sectors[12] and the coexistence condition (2.17) which ensures $P_h - P_n + V > 0$,[13] we solve the system simultaneously and get:

$$\begin{aligned}
\Delta P_c &= \frac{\theta_c(h+c)\overbrace{(P_h - P_n + V)}^{(+)}}{(1+\theta_c)(n+h)(1+\theta_c+\theta_h)} \geq 0 \\
\Delta P_h &= \frac{\theta_h}{1+\theta_h}\frac{\theta_c(h+c)(P_h - P_n + V)}{(1+\theta_c)(n+h)(1+\theta_c+\theta_h)} = \frac{\theta_h}{1+\theta_h}\Delta P_c \geq 0
\end{aligned}$$

which imply a decrease in the prices of the respective existing food products upon the arrival of nanofoods.[14] Moreover, the price decrease in the high quality food sector is not as great as the price decrease in the conventional food sector ($\Delta P_c > \Delta P_h$).

Figure 6 depicts the underlying mechanism outlined in Proposition 1. Recall that there are two existing markets before the introduction of nanofoods: the conventional food and the high quality food. Upon the arrival of nanofoods, some of consumers who previously purchased the conventional food switch their consumption to the nanofood because of its enhanced attributes such as food safety, better taste, or food freshness. As a result, the market demand curve for the conventional food simultaneously shifts to the left while rotating counterclockwise, lowering its price – this is the direct effect from the introduction of nanofoods. The reduction in the conventional food price, in turn, causes the leftward shift of the market demand curve for the high quality food, resulting in the reduction in its price – this is the indirect effect from the introduction of nanofoods. However, the price decrease of the high quality food sector is not greater than that of the conventional food sector; this conclusion is consistent with the fact that the indirect effect cannot be greater than the direct effect of the introduction of

---

[12] The results also hold when market power in the high quality and conventional food sectors decreases after the introduction of the nanofood.

[13] $P_n \leq P_c + V < P_h + V$ since $P_c < P_h$.

[14] The " =" sign occurs when $\theta_i = 0$, i.e., under perfect competition. $(i = c, h, n)$

nanofoods.

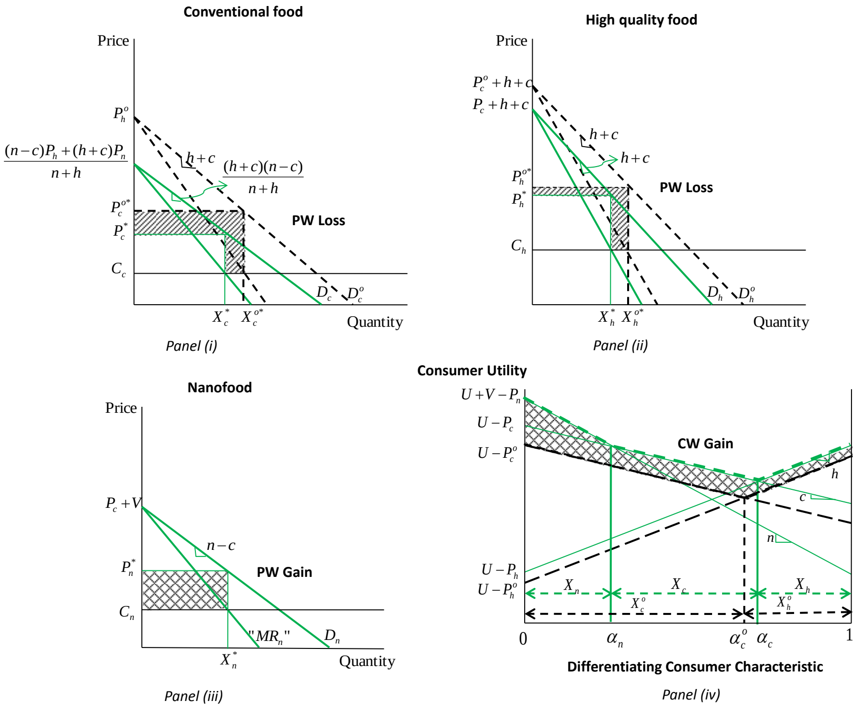

Figure 6: *Market equilibrium and welfare impacts of food nanotechnology under scenario A ($n > c$) when the nanofood innovation is non-drastic.*

▷ Proof of Proposition 1b:

After the introduction of the food nanotechnology innovation the market share of the conventional food is affected in the following ways: (1) market share is lost to the nanofood sector, and (2) market share is captured from the high quality food sector as some of the high quality food consumers switch their consumption to the conventional food due to the greater price decrease in the latter (See Figure 7). Therefore, to prove that the market share of the conventional food decreases after the introduction of nanofoods, we need to show that the gain in market share from the high quality food sector does not suffice to offset the loss in the market share to the nanofood sector (that is, $\alpha_c - \alpha_c^o \leq \alpha_n$).

The coexistence condition when $n > c$ dictates that $P_n \geq P_c + V - \frac{n-c}{h+c}(P_h - P_c)$, which can be alternatively expressed as $\frac{P_h-P_c}{h+c} \geq \frac{P_c-P_n+V}{n-c}$. Then, $\alpha_c - \alpha_c^o \leq \alpha_n$ implies

$\frac{P_h - P_c}{h+c} - \frac{P_h^o - P_c^o}{h+c} \leq \frac{P_c - P_n + V}{n-c} \leq \frac{P_h - P_c}{h+c}$, which holds true as $P_h^o - P_c^o \geq 0$.

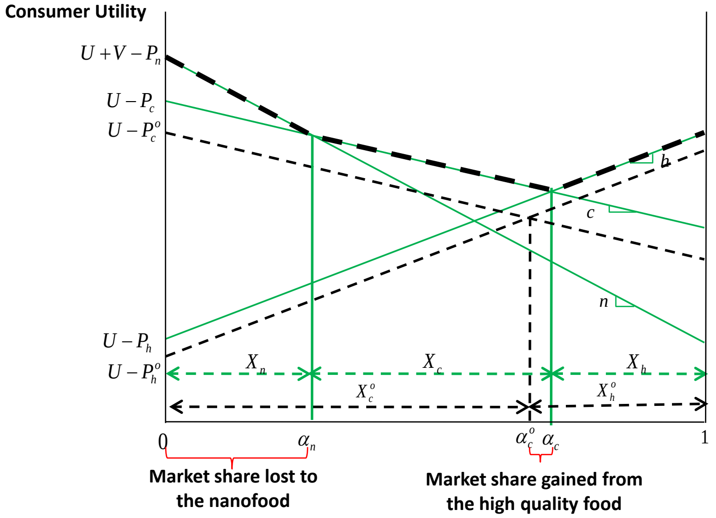

Figure 7: *The reduction in the market share of the conventional food under scenario A ($n > c$).*

Proposition 2: When consumers are more averse to nanotechnology than conventional food technology, the introduction of a food nanotechnology innovation decreases the welfare of conventional and high quality food producers, increase the welfare of nanofood producers, and increase the welfare of all consumers - with the greatest welfare gains captured by those consumers switching to nanofoods.

▷ Proof:

As prices and quantities demanded of the conventional and high quality food decline, welfare for producers of these respective products is reduced, where PW_c loss $= (P_c^{o*} - P_c^*)(X_c^{o*} - X_c^*)$ and PW_h loss $= (P_h^{o*} - P_h^*)(X_h^{o*} - X_h^*)$. Nanofood producers, on the other hand, experience welfare gains by the amount PW_n gain $= (P_n^* - C_n)X_n^*$.

While the effect of the introduction of food nanotechnology on aggregate producer welfare is inconclusive all consumers experience welfare gains given by:

$$
\begin{aligned}
CW_n \text{ gain} &= \int_0^{\alpha_n} \Big(U_n(\alpha) - U_c^o(\alpha)\Big) d(\alpha) = \int_0^{\alpha_n} \Big(V - P_n^* + P_c^{o*} - (n-c)\alpha\Big) d(\alpha) \\
CW_c \text{ gain} &= \int_{\alpha_n}^{\alpha_c^o} \Big(U_c(\alpha) - U_c^o(\alpha)\Big) d(\alpha) + \int_{\alpha_c^o}^{\alpha_c} \Big(U_c(\alpha) - U_h^o(\alpha)\Big) d(\alpha) \\
&= \int_{\alpha_n}^{\alpha_c^o} \Big(P_c^{o*} - P_c^*\Big) d(\alpha) + \int_{\alpha_c^o}^{\alpha_c} \Big(P_h^{o*} - P_c^* - (c+h)\alpha\Big) d(\alpha) \\
CW_h \text{ gain} &= \int_{\alpha_c}^{1} \Big(U_h(\alpha) - U_h^o(\alpha)\Big) d(\alpha) = \int_{\alpha_c}^{1} \Big(P_h^{o*} - P_h^*\Big) d(\alpha)
\end{aligned}
$$

where $\alpha_c^o = X_c^{o*}, \alpha_n = X_n^*$, and $\alpha_c = X_n^* + X_c^*$.

Consumer welfare gains are depicted graphically in Figure 6, panel (iv) where it is easy to see that welfare gains are not the same across consumers. Indeed, the greatest welfare gain is experienced by the consumers who find it optimal to switch their consumption to nanofoods. These are the consumers with relatively low values of the differentiating characteristic α, who are either indifferent to ($\alpha = 0$) or are relatively less averse to interventions in the production process; thus, more likely to switch to nanofoods and gain additional utility from the enhanced attributes enabled by food nanotechnology notwithstanding their greater aversion to nanotechnology than to conventional food technology ($n > c$). Consumes who continue to consume the conventional or the high quality food product experience welfare gains due to the reduction in food prices.

Proposition 3: When consumers are more averse to nanotechnology than conventional food technology, the greater (smaller) are the adoption costs of nanofoods, the smaller (greater) are the reductions in the market prices and quantities of existing food substitutes.

▷ Proof:

It is straightforward to show that:[15]

$$\frac{d(\Delta P_c^*)}{dC_n} = \frac{-(c+h)\theta_c(1+\theta_h)}{c\theta_c(\theta_h-\theta_n)+n(1+\theta_c+\theta_h)(1+\theta_n)+h(1+\theta_h)(1+\theta_c+\theta_n)} \leq 0$$

$$\frac{d(\Delta P_h^*)}{dC_n} = \frac{-(c+h)\theta_c\theta_h}{c\theta_c(\theta_h-\theta_n)+n(1+\theta_c+\theta_h)(1+\theta_n)+h(1+\theta_h)(1+\theta_c+\theta_n)} \leq 0$$

The intuition behind Proposition 3 is that relatively low adoption costs for nanofood producers result in relatively lower market prices for the nanofood product, which in turns attracts more consumers away from the conventional food sector. This decrease in the demand for the conventional food induces further reduction in the conventional food prices. The high quality sector is also indirectly affected in such a way that its prices end up being lower than before. Once again, we notice that the magnitude of additional price reduction in the conventional food product (direct effect) is greater than in the high quality food product (indirect effect) (i.e., $\left|\frac{d(\Delta P_c^*)}{dC_n}\right| > \left|\frac{d(\Delta P_h^*)}{dC_n}\right|$).

Likewise, the greater (smaller) are the adoption costs of nanofoods, the smaller (greater) are the reductions in the market quantities of existing food substitutes since:

$$\frac{d(\Delta X_c^*)}{dC_n} = \frac{-(h+n)(1+\theta_h)}{(n-c)[c\theta_c(\theta_h-\theta_n)+n(1+\theta_c+\theta_h)(1+\theta_n)+h(1+\theta_h)(1+\theta_c+\theta_n)]} < 0$$

$$\frac{d(\Delta X_h^*)}{dC_n} = \frac{-\theta_c}{c\theta_c(\theta_h-\theta_n)+n(1+\theta_c+\theta_h)(1+\theta_n)+h(1+\theta_h)(1+\theta_c+\theta_n)} \leq 0$$

The three propositions put forward in the non-drastic innovation case also demonstrate the main findings in the *drastic* innovation case where the food nanotechnology innovation drives its conventional counterpart out of market. Note that since in this case the conventional food product is out of the market, all corresponding analyses after the introduction of food nanotechnology exclude the conventional food product. In the drastic innovation case, the market equilibrium quantities and prices of

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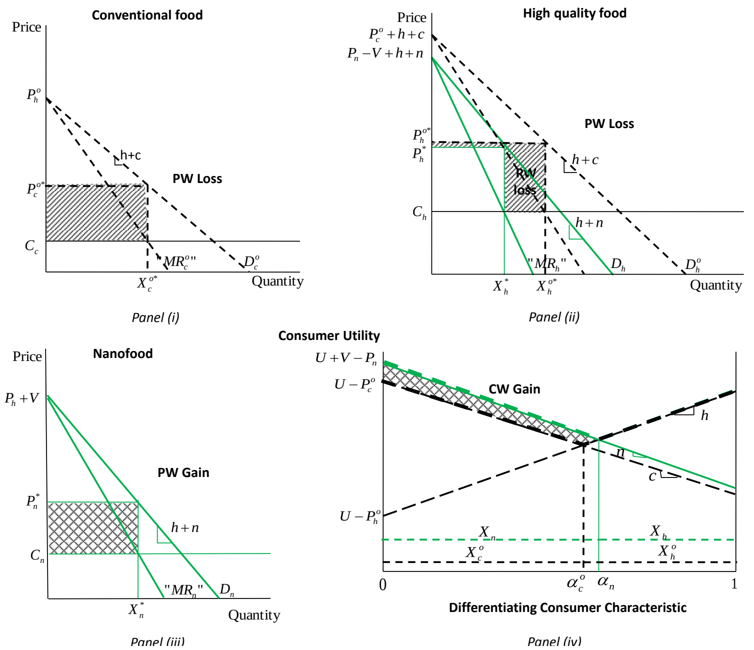
[15] See Appendix A for the expressions of ΔP_c^* and ΔP_h^*.

the high quality food and the nanofood product are given by equation (2.26) and illustrated in Figure 8.

$$
\begin{aligned}
X_h^* &= \frac{(1+\theta_n)(h+n) + C_n - V - C_h}{(h+n)(1+\theta_n+\theta_h)} \\
X_n^* &= \frac{\theta_h(h+n) + C_h + V - C_n}{(h+n)(1+\theta_n+\theta_h)} \\
P_h^* &= \frac{\theta_h[(1+\theta_n)(h+n) + C_n - V] + (1+\theta_n)C_h}{1+\theta_n+\theta_h} \\
P_n^* &= \frac{\theta_n[\theta_h(h+n) + C_h + V] + (1+\theta_h)C_n}{1+\theta_n+\theta_h}
\end{aligned}
\tag{2.26}
$$



Panel (i) *Panel (ii)*

Panel (iii) *Panel (iv)*

Figure 8: *Market equilibrium and welfare impacts of food nanotechnology under scenario A ($n > c$) when the nanofood innovation is drastic.*

2.3.2 Market equilibrium and welfare under scenario B ($n = c$)

Recall that scenario B occurs when consumers are either indifferent between food nanotechnology and the conventional food technology or unaware of the existence of food nanotechnology.[16] Under this scenario, the market and welfare impacts of food nanotechnology under the *ineffective* and *drastic* innovation cases are qualitatively the same as under scenario A where consumers are more averse to food nanotechnology than conventional food technology. In fact, if we look at equations (2.10) and (2.26) which characterize the equilibrium results in the ineffective and drastic innovation cases, either c or n but not both, enter the equations.

Under the *non-drastic* case, the coexistence of the available food products implies that the condition $P_n = P_c + V$ is satisfied. This case is depicted in Figure 9, panel (iv) where the utility schedules U_n and U_c coincide. The consumer with a

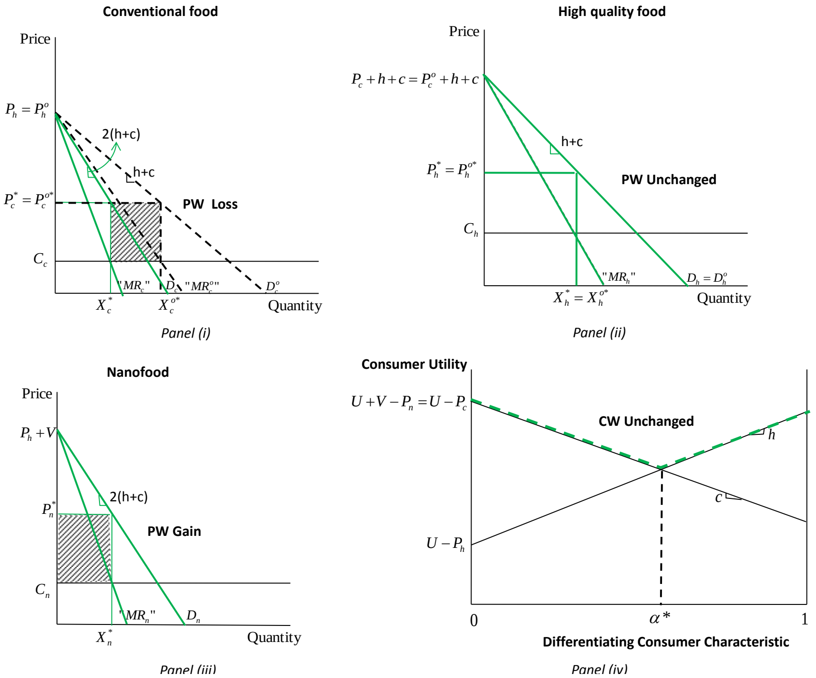


Figure 9: *Market and welfare impacts of food nanotechnology under scenario B ($n = c$) when the nanofood innovation is non-drastic.*

differentiating characteristic $\alpha_* = \dfrac{P_h - P_c}{h + c}$ such that $U_c(\alpha_*) = U_h(\alpha_*)$ or $U_n(\alpha_*) = U_h(\alpha_*)$ is indifferent between the high quality and the conventional food product or

---

[16] This scenario captures the situation in many countries (e.g., the US) where the majority of the public is unaware that hundreds of nanofoods and food packaging applications are already in the market (IFIC 2012; PEN 2010).

between the high quality and the nanofood product. Given the above, the consumer with an α value such that $\alpha \in [0, \alpha_*]$ chooses either the conventional food or the nanofood product while the consumer with an α value such that $\alpha \in (\alpha_*, 1]$ chooses the high quality food product.

The market share for the nanofood, conventional food and high quality food product is, respectively, given by $X_n = X_c = 0.5\alpha_*$ and $X_h = 1 - \alpha_*$. The inverse demand functions are derived in equation (2.27).

$$\begin{aligned} P_c(X_c) &= P_h - 2(h+c)X_c \\ P_n(X_n) &= P_h + V - 2(h+c)X_n \\ P_h(X_h) &= P_c + h + c - (h+c)X_h \end{aligned} \tag{2.27}$$

Simultaneously solving the FOCs in (2.25), where $P_c(X_c), P_n(X_n)$ and $P_h(X_h)$ are characterized by (2.27), yields the market equilibrium quantities and prices:

$$\begin{aligned} X_c^* &= \frac{C_h + \theta_h(c+h) - C_c}{2(c+h)(1+\theta_c+\theta_h)} \\ X_n^* &= \frac{C_h(1+\theta_c) + \theta_h[C_c + (c+h)(1+\theta_c)] - C_n(1+\theta_c+\theta_h)}{2(c+h)(1+\theta_c+\theta_h)(1+\theta_n)} \\ X_h^* &= \frac{C_c + (c+h)(1+\theta_c) - C_h}{(c+h)(1+\theta_c+\theta_h)} \\ P_c^* &= \frac{\theta_c\left[\theta_h(h+c) + C_h\right] + (1+\theta_h)C_c}{1+\theta_c+\theta_h} \\ P_n^* &= \frac{(Cn+V)(1+\theta_c+\theta_h) + \theta_n\{(C_n+V)(1+\theta_c) + \theta_h[(c+h)(1+\theta_c) + C_c + V]\}}{(1+\theta_c+\theta_h)(1+\theta_n)} \\ P_h^* &= \frac{\theta_h\left[(1+\theta_c)(h+c) + C_c\right] + (1+\theta_c)C_h}{1+\theta_c+\theta_h} \end{aligned} \tag{2.28}$$

A comparison of the market equilibrium prices of the conventional and high quality food products in (2.28) with (2.10) shows that they remain the same after the introduction of food nanotechnology. In addition, while the market demand facing the conventional food sector before the introduction of the nanofood is split between the nanofood and the conventional food when nanofoods enter the market, the market demand of the high quality food product remains unchanged. As a result, welfare for the conventional food producers decreases after the introduction of nanofoods while welfare for the high quality food producers stays the same (see Figure 9, panels (i), (ii) and (iii)). Consumer welfare remains unchanged (see Figure 9, panel (iv)).

2.3.3 Market equilibrium and welfare under scenario C ($n < c$)

Under this scenario, consumers are less averse to food nanotechnology than conventional food technology.[17] Unlike scenario A, the consumers who are more likely to switch to nanofoods under this scenario are those who are relatively more averse to interventions in the production process. This situation is depicted in Figure 10 where the slope of the utility curve of the conventional food product is steeper than the slope of the utility curve of the nanofood product.[18]

Once again, the choices available to consumers are given in equation (2.15). We denote by α_c the consumer who obtains the same utility from the consumptions of the conventional food and the nanofood, $\alpha_c = \dfrac{P_c - P_n + V}{h + n}$ and by α_n the consumer who obtains the same utility from the consumptions of the nanofood and the high quality food, $\alpha_n = \dfrac{P_h - P_n + V}{h + n}$. Given the above, the consumer with a differentiating characteristic α such that $\alpha \in [0, \alpha_c]$, $\alpha \in (\alpha_c, \alpha_n]$ and $\alpha \in (\alpha_n, 1]$ would consume the conventional, nanofood, and high quality food product, respectively.

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[17] An example of a situation where this scenario may emerge is the use of nanosensors that could lead to a reduction in the amount of, and/or more efficient use of, chemicals and fertilizers in the production process (Chaudhry and Castle 2011).

[18] While only the non-drastic case is explicitly considered in scenario C, the analytical results under the drastic and ineffective cases are qualitatively the same as under scenario A (see arguments in section 2.3.2.)

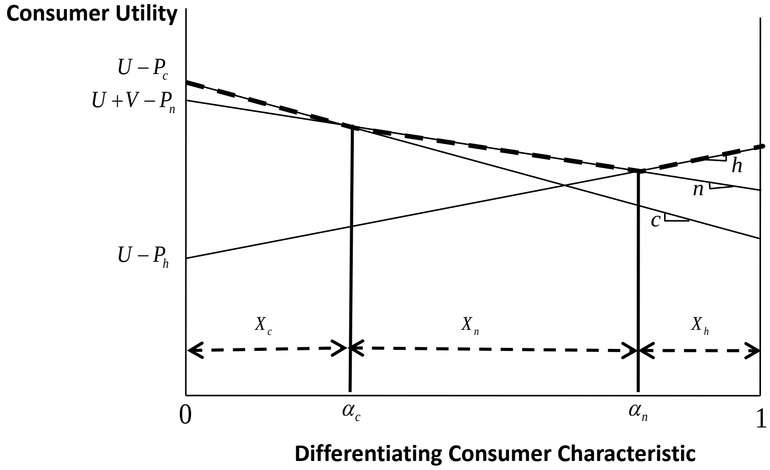

Figure 10: *Consumption decisions and market shares under scenario C ($n < c$) when the nanofood innovation is non-drastic.*

The inverse demand functions are given by

$$\begin{aligned} P_c(X_c) &= P_n - V - (c-n)X_c \\ P_n(X_n) &= \frac{(c-n)P_h + (h+n)P_c - (h+c)P_n + (h+c)V}{(c-n)(h+n)} \\ P_h(X_h) &= P_n + h + n - V - (h+n)X_h \end{aligned} \tag{2.29}$$

The market equilibrium quantities and prices of the conventional food, nanofood and high quality food product are obtained by simultaneously solving the FOCs in (2.25), where $P_c(X_c), P_n(X_n)$ and $P_h(X_h)$ are characterized by (2.29), as follows:

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

$$\begin{aligned} X_n^* = {} & \frac{(c+h)\{(h+n)(1+\theta_h)C_c + (c-n)(1+\theta_c)[C_h + (h+n)\theta_h]\}}{(c-n)(h+n)(1+\theta_n)\{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta-h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]\}} \\ & - \frac{V(c+h)\{c+h+(2c+h-n)\theta_h + \theta_c[c+2h+n+2(c+h)\theta_h]\}}{(c-n)(h+n)(1+\theta_n)\{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta-h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]\}} \\ & + \frac{\theta_n(c+h)\{(h+n)(1+\theta_h)C_c + (c-n)(1+\theta_c)C_h + \theta_n(h+n)[(c-n)(1+\theta_c) - V]\}}{(c-n)(h+n)(1+\theta_n)\{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta-h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]\}} \\ & - \frac{C_n(c+h)(1+\theta_n)[c+h+(c-n)\theta_c + (h+n)\theta_h]}{(c-n)(h+n)(1+\theta_n)\{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta-h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]\}} \end{aligned}$$

$$\begin{aligned} X_h^* = {} & \frac{(c+h)(1+\theta_c)(h+n-V+C_n) + [c+h+C_c+(c-n)\theta_c](h+n)\theta_n}{(c+h)\{(h+n)(1+\theta_h)(1+\theta_n) + \theta_c[h+n+(c+h)\theta_h + (n-c)\theta_n]\}} \\ & - \frac{C_h[(c+h)(1+\theta_c) + (h+n)\theta_n]}{(h+n)\{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta_h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]\}} \end{aligned}$$

$$\begin{aligned} P_c^* = {} & \frac{C_c\{(c+h)(1+\theta_n) + \theta_h[c+h+(h+n)\theta_n]\}}{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta_h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]} \\ & + \frac{\theta_c\{(c+h)(1+\theta_h)(C_n - V) + (c-n)[C_h + \theta_h(h+n)]\theta_n\}}{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta_h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]} \end{aligned}$$

$$\begin{aligned} P_n^* = {} & \frac{C_n(c+h)(1+\theta_h)(1+\theta_c)}{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta_h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]} \\ & + \frac{\theta_n\{[c+h+(c-n)\theta_c + (h+n)\theta_h]V + (c-n)(1+\theta_c)[\theta_h(h+n) + C_h] + (h+n)(1+\theta_h)C_c\}}{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta_h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]} \end{aligned}$$

$$\begin{aligned} P_h^* = {} & \frac{C_h\{(c+h)(1+\theta_n) + \theta_c[c+h+(c-n)\theta_n]\}}{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta_h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]} \\ & + \frac{\theta_h\{(c+h)(1+\theta_c)(C_n - V + h + n) + [c+h+C_c+\theta_c(c-n)](h+n)\theta_n\}}{(c+h)(1+\theta_n) + \theta_c[(c+h)(1+\theta_h) + (c-n)\theta_n] + \theta_h[c+h+(h+n)\theta_n]} \end{aligned}$$

Propositions $1, 2$, and 3 also hold true when consumers are less averse to food nanotechnology than conventional food technology. However, under this scenario, the introduction of food nanotechnology has a direct effect on both existing sectors. The reduction in the demand of the high quality food is not a result of the lower conventional food price as in scenario A, but caused by the change in consumption decisions of some high quality food consumers who switch their consumption to nanofoods due to the benefits offered by food nanotechnology. Besides, the change in consumer attitudes from being more to less averse to the use of food nanotechnology compared to conventional food technology results in the change in the distributional effects of food nanotechnology on consumer welfare. Specifically, the group of consumers who experience the greatest welfare gains are those with relatively moderate aversion towards food nanotechnology. Figure 11 depicts the market equilibrium and welfare impacts of food nanotechnology under scenario C.

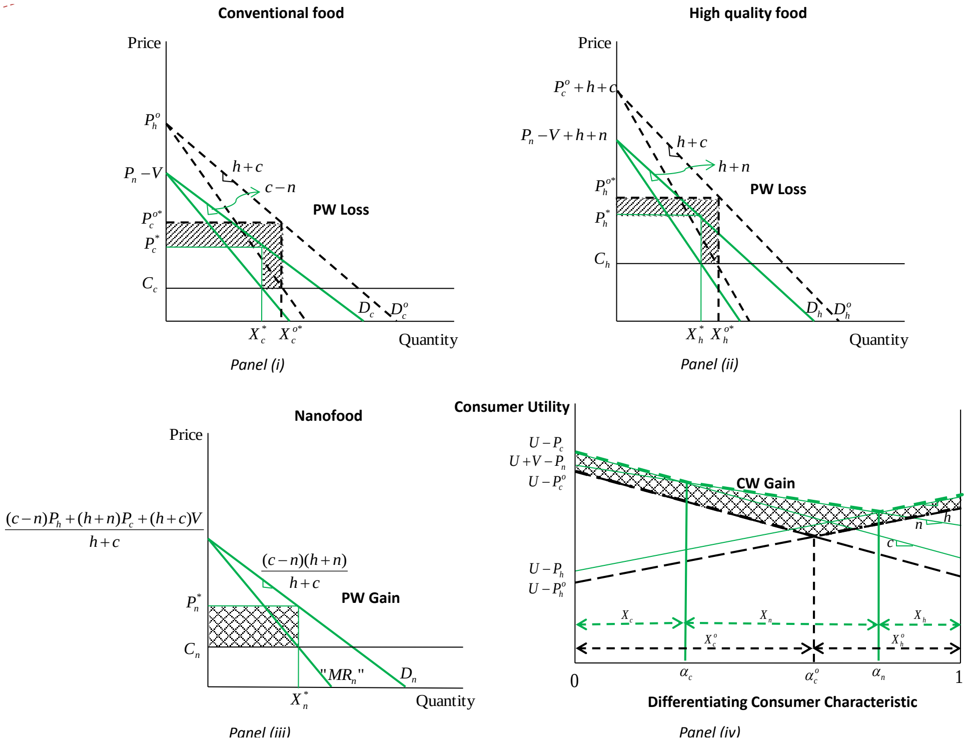

Figure 11: *Market equilibrium and welfare impacts of food nanotechnology under scenario C ($n < c$) when the nanofood innovation is non-drastic.*

3 Welfare implications of a labeling regime for food nanotechnology

Under current regulations, mandatory labeling of food nanotechnology is not required. However, several efforts are under way to implement labeling regulations, either mandatory or voluntary, in a number of countries. In the EU the Food Information to Consumers Regulation mandates the text "nano" to be placed on the product's label next to the nanomaterials or nano-ingredients used in food production. This regulation will take effect in December 2014 (NanoTrust Dossier 2012). Taiwan is the first country to carry out a certification system, the Nano-Mark, for nanofood products that meet specific standards as a means of promoting safe and high quality nanoproducts (Chau et al. 2007).

Unlike the above countries, there are no plans currently under way in the US to implement mandatory labeling of the use of nanotechnology, even though the US has the greatest number of commercialized consumer products (Chau et al. 2007). Proponents of labeling regulation point to the need to protect 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. Critics, on the other hand, warn 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. Fears concerning consumer response to nanofood labeling might hinder the adoption of food nanotechnology by producers and/or processors under a mandatory labeling regime and might deter voluntary labeling when labeling is not mandated. Consumer opposition may impede the advancement of food nanotechnology therefore regulators should take into account the welfare implications of labeling of food nanotechnology for consumers and producers in determining the optimal regulatory framework for food nanotechnology.

In what follows we analyze the welfare implications of mandatory labeling of food nanotechnology. Under the status quo, where nanofood labeling is not imposed, consumers assign a probability δ to a food product being nanofood as its nature is not known with certainty (e.g., the production technology used is a credence attribute under no labeling). The utility discount factor capturing this uncertainty can be expressed as:

$$n^{nl} = \delta n + (1 - \delta)c \tag{3.1}$$

where δ is the probability that the non-labeled food is nanofood ($0 \leq \delta \leq 1$) and thus $1 - \delta$ is the probability that it is conventional food. Following this setup, if consumers are unaware of the existence of food nanotechnology (i.e., $\delta = 0$) in the absence of labeling, they will view nanofood as conventional food. By contrast, if consumers can make a perfect inference that the food is nanofood (i.e., $\delta = 1$) by, for example, observing the enhanced attributes enabled by food nanotechnology (which would not be credence in this case), their utility of consuming a unit of nanofood would be correctly discounted even without product labels.

The uncertainty consumers face under a no labeling regime can be reduced by introducing labeling regulation. Indeed, the presence of nanofood labels would inform consumers of the true nature of the products and, therefore, allow them to correctly discount their utility from consuming the nanofood ($i.e., n^{nl} = n$). Moreover, in situations where consumers view labeling as a warningl, and, thus, become more averse to food nanotechnology under labeling than under no labeling with perfect inference, product labels amplify perceived risks (i.e., $n^{nl} = n'$ where $n' > n$). We call these effects of labeling on consumer preferences/attitudes *the preference effect(s)*. Besides, the imposition of labeling might result in additional production costs for nanofood producers *(the cost effect)*. For simplicity, we assume that labeling regulation for nanofoods affects the cost structure of the nanofood sector only.[19] Moreover, related administrative costs of the regulation are assumed to be fixed and borne by nanofood producers.

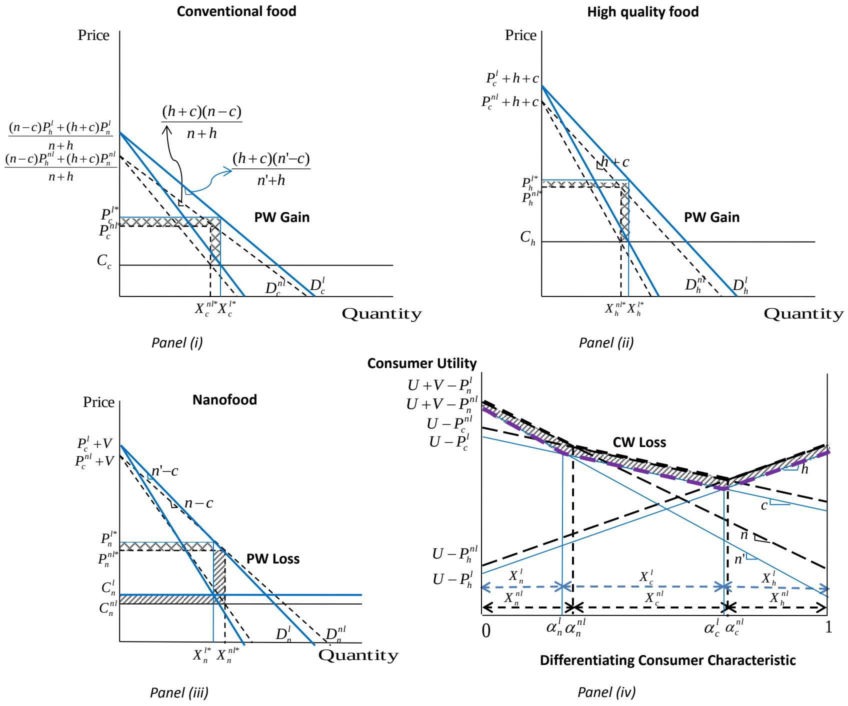

Figure 12: *The effects of nanofood labeling (from $n > c$ to $n' > c$ and $n' > n$).*

Figure 12 illustrates the preference and cost effects of labeling when consumers are *more averse* to food nanotechnology than conventional food technology under no labeling and their aversion increases under the labeling regime. Both preference and cost effects work in the same direction since the production cost and the consumer

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[19] 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 high quality food incur 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.

disutility towards nanofoods increase following labeling regulation. The quantity of nanofood demanded declines, increasing the nanofood price. As the nanofood price increases, demand for conventional food increases in response and thus the conventional food price also increases. The increase in the price of conventional food now affects the market demand for both the high quality food and the nanofood. On the supply side, labeling is found to be welfare-enhancing for conventional and high quality food producers whereas welfare-decreasing for nanofood producers (see Figure 12, panels (i), (ii) and (iii)).[20] On the consumer side, the increases in existing non-nano food prices reduce consumer utility from the consumption of these products and eventually consumer welfare (see Figure 12, panel (iv)). 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 and producer welfare. Furthermore, the greater is consumer valuation of the enhanced attributes of nanofoods, the smaller is the loss in consumer welfare.

The imposition of labeling regulation on food nanotechnology is not always associated with the decrease in consumer welfare, however. When, in the absence of labeling, consumers are equally averse to food nanotechnology as to conventional production technology ($n = c$) and their aversion to food nanotechnology increases under labeling, it is highly likely that labeling leads to a gain in consumer welfare. This case is depicted in Figure 13, panel (iv). Under this case, when labeling is imposed, consumers correctly discount their utility which is greater than the utility discount for the conventional food (i.e., $n^{nl} = n > c$). Producers of nanofoods need to adjust their pricing strategy to account for the changes in consumer attitudes towards their product. For coexistence of the nanofood with the conventional and high quality

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[20] See Appendix B for Simulation Result on the effect of labeling on the welfare of nanofood producers.

substitute product under labeling the nanofood price will be lower than under no labeling. For this reason, consumer utility increases and so does consumer welfare. However, nanofood producers incur a welfare loss due to lower market quantities and prices but higher adoption costs. On the other hand, conventional food producers gain greater market share as more consumers prefer conventional food to nanofood; the change in their welfare equals $(P_c^{nl} - P_c^l)(X_c^{nl} - X_c^l)$. The conventional food price falls, causing a decrease in the market demand for and price of the high quality food. Consequentially, welfare of high quality food producers decreases.

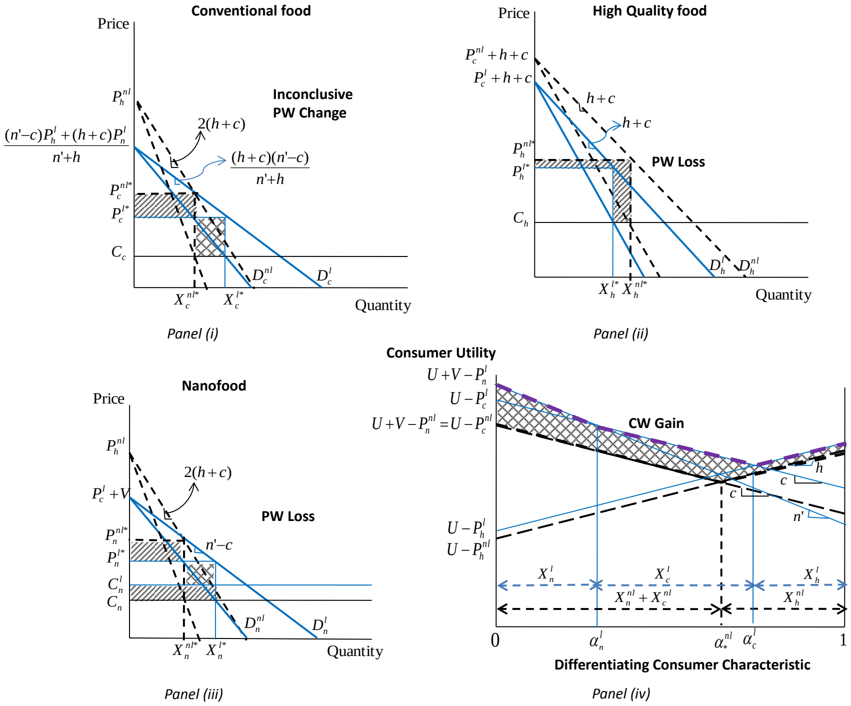
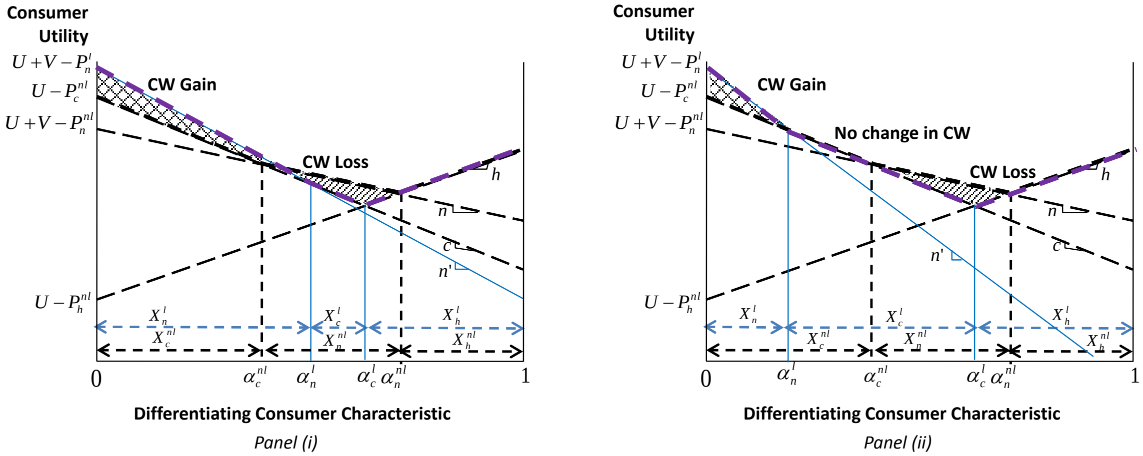


Figure 13: *The effects of nanofood labeling (from $n = c$ to $n' > c$).*

When, under the no labeling regime, consumers are less averse to food nanotechnology than to conventional food technology ($n < c$) but the labeling regulation changes their attitudes to becoming more averse ($n' > c$), similar to the above case, we find that, to maintain the coexistence of nanofoods with alternative food products, nanofood producers ought to decrease their food price. However, whether the market share for the nanofood product is lower than before depends on the magnitude of the reduction in the nanofood price and/or the degree of consumer aversion to food nanotechnology following the labeling regulation. The greater is the price reduction and/or the lower is the degree of consumer aversion to the use of food nanotechnology, the higher is the likelihood that the market share for the nanofood increases when the labeling regulation is imposed (Figure 14).



Panel (i) *Panel (ii)*

Figure 14: *The effects of nanofood labeling on consumer welfare (from* $n < c$ *to* $n' > c$*). The increase and decrease in the market share of nanofood are shown in panels (i) and (ii), respectively.*

Intuitively, when labeling causes consumers to become more averse to food nanotechnology, nanofood consumers would alter their consumption choice either to the conventional food or to the high quality food. Recall that under this case those are the consumers with relatively moderate aversion to interventions in the production process. However, with the lower price, the nanofood sector is attracting new consumers who are relatively low averse to interventions in the production process. The market share of the nanofood, therefore, might increase (see Figure 14, panel (i)) or decrease (see Figure 14, panel (ii)). For this reason, the effects of labeling on producer welfare are inconclusive. Although the aggregate consumer welfare effects are also inconclusive, it is, to some extent, clear as to who are the losers and winners in this case. Consumers who continue or switch their consumption to the nanofood under labeling are shown to gain welfare while those who switch their consumption from the nanofood to the conventional food or the high quality food product experience welfare losses.

4 Conclusions

An analytical framework of heterogeneous consumers and imperfectly competitive producers is developed to investigate the market and welfare impacts of introducing nanotechnology into the food system under different labeling regimes. Different scenarios regarding consumer attitudes towards food nanotechnology are considered and the exact conditions under which a food nanotechnology innovation might end up being ineffective, non-drastic, or drastic are derived. Results show that moderate prices levels, consumer attitudes towards food nanotechnology, and consumer valuations of the enhanced attributes offered by food nanotechnology are more likely to result in a non-drastic nanofood innovation. An interesting finding is that high consumer valuations of the enhanced attributes of nanofoods can lead to consumer acceptance of nanofoods even when consumers are averse to nanotechnology. Moreover, a change in consumer attitudes from more to less averse to food nanotechnology compared to conventional food technology might result in a switch from an ineffective food nanotechnology innovation to a non-drastic one.

In most cases, the introduction of food nanotechnology causes a reduction in the quantities and prices of existing food alternatives with the quantity and price decreases being greater when adoption costs are low. As a result, welfare is lower for non-adopting producers yet greater for nanofood adopters and all consumers. Results are different when consumers are equally averse to food nanotechnology as to conventional technology. Under this scenario, neither do high quality food producers incur welfare loss nor does consumer welfare increase since the entry of nanofoods does not affect the prices of the available food alternatives. Conventional food producers, on the other hand, experience welfare losses solely from the decline in the market demand.

Analytical results show that in most cases the main beneficiaries of the introduction of food nanotechnology are consumers who switch their consumption to nanofoods. In particular, when consumers perceive food nanotechnology as more invasive than conventional food nanotechnology ($n > c$), the consumers that experience the greatest welfare gains are those with relatively low aversion to interventions in the production process. Conversely, when food nanotechnology is perceived as less invasive ($n < c$), this is the group of consumers with relatively moderate levels of aversion.

Finally, the welfare impacts of labeling food nanotechnology depend on consumer attitudes towards food nanotechnology and the magnitude of labeling costs. Specifically, the labeling regulation negatively affects consumer welfare if consumers are averse to food nanotechnology and/or view labeling as a warning signal. If labeling costs are only applied to the nanofood sector, the regulation benefits the non-adopting sectors which experience gains in producer welfare. 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 and producer welfare. Surprisingly, when consumers are equally averse to food nanotechnology as to conventional technology under the no labeling regime, consumer welfare increases even if consumers become more averse under a labeling system. The welfare impacts are less clear cut when consumers perceive food nanotechnology as less invasive under the no labeling system. In this case, the welfare effects depend on the magnitude of the reduction of the nanofood price and/or the level of aversion towards food nanotechnology under labeling. Welfare gains could be realized by those consumers switching their consumption to the nanofood while welfare losses might be borne by those consumers switching to conventional food.

The above results are based on a number of assumptions the relaxing of which is likely to change the results. Specifically, a uniform distribution of consumers along their differentiating characteristic and a homogeneous consumer valuation of the enhanced attributes of food nanotechnology were assumed. Another important assumption is that only the nanofood sector will incur labeling cost and segregation costs will not be incurred by the conventional and high quality product sectors. If the fears regarding the potential of nanomaterials to contaminate are substantiated, labeling, segregation and identity preservation costs for the other product sectors ought to be incorporated into the labeling analysis. The relaxing of the above assumptions is the focus of future research.

Appendices

A The differences/reductions in the market equilibrium prices and quantities of existing substitute foods ($n > c$)

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

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

$$\Delta X_c^* = X_c^{o*} - X_c^*$$
$$= \frac{(n-c)\theta_c\theta_h(C_h + c\theta_h) + h(n-c)\theta_c\theta_h^2 + (h+n)(V-C_n)(1+\theta_h)(1+\theta_c+\theta_h)}{(n-c)(1+\theta_c+\theta_h)[c\theta_c(\theta_h-\ \theta_n) + n(1+\theta_c+\theta_h)(1+\theta_n) + h(1+\theta_h)(1+\theta_c+\theta_n)]}$$

$$+ \frac{-(n-c)\theta_c\theta_n[C_h + (c+h)\theta_h] + C_c\{h(1+\theta_h)(1+\theta_c+\theta_h) + c\theta_c(\theta_h-\theta_n) + n[(1+\theta_h)^2 + \theta_c(1+\theta_n)]\}}{(n-c)(1+\theta_c+\theta_h)[c\theta_c(\theta_h-\ \theta_n) + n(1+\theta_c+\theta_h)(1+\theta_n) + h(1+\theta_h)(1+\theta_c+\theta_n)]}$$

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

B Simulations

For $n > c$, the profit of nanofood producers is given by:

$$\Pi_n = \frac{\theta_n\{(V-C_n)\big[(h+n)(1+\theta_h) + (n-c)\theta_c\big] + C_c(h+n)(1+\theta_h) + \big[C_h + (c+h)\theta_h\big](n-c)\theta_c\}^2}{(n-c)\big[c\theta_c(\theta_h-\theta_n) + h(\theta_h+1)(\theta_c+\theta_n+1) + n(\theta_n+1)(\theta_c+\theta_h+1)\big]^2}$$

The simulation to verify the preference impact of labeling is conducted using Mathematica. Figure 15 depicts the changes of the profits of nanofood producers for $n \in [2, 10]$. 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.

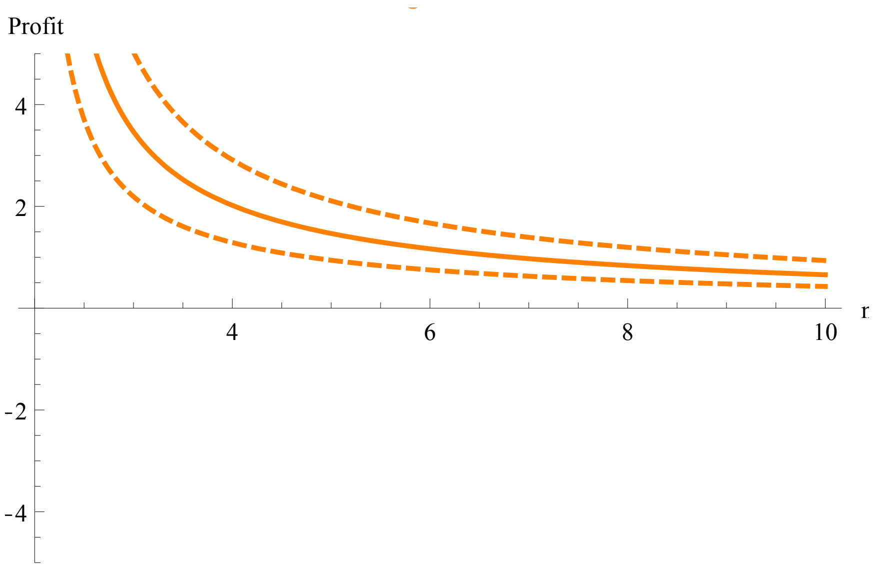


Figure 15: *The profits of nanofood producers* when consumers are more averse to food nanotechnology than conventional technology under the no labeling regime and consumer aversions are intensified under the labeling regime (Case: $n > c$). **Input Values:** $V = 5$; $C_n = 2$; $C_c = 1.7$; $C_h = 2.4$; $\theta_n = 0.54$; $\theta_c = 0.44$; $\theta_h = 0.7$; $c = 1.91$; $h = 1.2$. The three curves represent the profits of nanofoods producers when the production costs run from 1 to 3 with the dashed curves being the upper bound and lower bound.

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