The Impact of Consumer Skepticism on Blockchain-Enabled Sustainability Disclosure in a Supply Chain

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Abstract:

The growing recognition of sustainable supply chain practices is indisputable. Nevertheless, consumer skepticism regarding the credibility of product sustainability information, which includes environmental impact and social responsibility, poses a significant challenge. Blockchain-enabled disclosure has surfaced as a promising approach to address this skepticism. In this paper, a game-theoretical model is developed to investigate the investment strategy in blockchain-enabled disclosure within a supply chain composed of one retailer and two manufacturers, each selling products with varying levels of sustainability. Considering consumer skepticism, we assume that consumers who trust sustainability information are willing to pay a premium for sustainable products, while skeptical consumers are not. Our analysis suggests that blockchain-enabled disclosure can effectively increase consumer trust in sustainability information and promote sustainable practices. However, our findings reveal a potential pitfall: intensified market competition between manufacturers, leading to reduced profits for both, while the retailer persistently benefits from blockchain-enabled disclosure. Furthermore, we find non-monotonic effects of consumer skepticism on retailer and manufacturer profits, with certain conditions resulting in a decreased likelihood of investing in blockchain-enabled disclosure as skepticism increases. Lastly, we examine the government-mandated disclosure policy, illustrating that such policy can generate a win-win situation for society and the environment by improving social welfare and environmental performance.

Keywords: supply chain management; sustainability; blockchain-enabled disclosure; consumer skepticism; game theory

1. Introduction

Sustainability encompasses economic, environmental, and social responsibility dimensions, known as the triple bottom line (TBL) view (Elkington & Rowlands, 1999). A global study by IBM found that sustainability is gaining importance among consumers, with 50% willing to pay an average premium of 59% for eco-friendly products (IBM, 2022). In countries such as Germany, the US, the UK, and Australia, a majority of grocery shoppers (60%, 58%, 57%, and 53% respectively) are willing to pay a premium for such products (YouGov., 2021). However, despite the high level of interest, only a small fraction of consumers who express a desire to purchase sustainable products actually do so, highlighting the well-known intention-behavior gap (White et al., 2019; Haller, 2022). Unlike tangible quality attributes, sustainability claims are credence claims that ordinary consumers cannot verify before or after purchase. As a result, 56% of consumers now doubt green product information, and only 25% of consumers view labeling a product as responsibly sourced or manufactured indicates sustainability (Cho & Taylor, 2020; Deloitte, 2022). Although traditional traceability technologies have been adopted widely, such as barcodes or radio frequency identification (RFID), they are not trusted by consumers because product information can be intentionally altered. As a solution, blockchain traceability systems have been adopted to eliminate consumer skepticism regarding a product's sustainable attributes (Behnke & Janssen, 2020; Harrison & Leopold, 2021).

Blockchain technology uses block structure which is encrypted to verify and store data while utilizing distributed ledger consensus algorithm to generate and update data, making supply chains more transparent, secure, ethical, efficient, and stable. Due to the unchangeable nature of blockchain, strangers who are using the same blockchain can trust each other, in other words, blockchain technology is trust free. This feature may reduce consumer skepticism, which could reduce the intention-behavior gap. The United Nations Conference on Trade and Development (UNCTAD) encourages governments and businesses to leverage blockchain to expedite sustainable development. Prominent manufacturers, including Nestlé and Dole Food Company, have adopted IBM's Food Trust™, a blockchain-based food traceability system, to offer consumers real-time access to food supply chain data and prevent fraudulent labeling (IBM, 2019). This instills confidence in consumers that the product is sustainable, leading them to be more willing to pay a premium (Kshetri, 2019; Spanaki et al., 2022). Furthermore, blockchain-based solutions are expected to be primarily used in the retail industry's supply chain market (Businesswire, 2021). For example, Carrefour, as the pioneering retailer adopting blockchain for organic products, ensures consumer trust through transparent product provenance and production methods (Carrefour, 2022). By scanning a QR code on the label, customers can access the product's origin, pathway, quality, and organic certification. Carrefour also uses blockchain for tracing textile products, providing consumers to access extensive sustainability information, such as the method of cotton cultivation and environmental certifications. Walmart has mandated that suppliers of fresh organic greens use blockchain technology to trace their products along the supply chain back to the farm, along with sharing ingredient sourcing information and sustainability practices to consumers (Walmart, 2018). Other retailers like JD.com, Amazon, Alibaba and De Beers have also invested in blockchain for building consumer confidence in sustainable products (Hou et al., 2023). These cases highlight the growing trend of retailers actively promoting blockchain-enabled sustainability disclosure to enhance consumer trust and purchasing decisions.

The adoption of reliable blockchain-enabled sustainability disclosure in the supply chain can potentially increase consumers' willingness to pay for these products, which appears to be good news for sustainable manufacturers and retailers seeking to eliminate consumer skepticism. However, the response from traditional product manufacturers needs to be considered. These manufacturers may resort to aggressive pricing strategies in the face of increased pressure due to the disclosure. Then more consumers are likely to consider low price over sustainability to purchase products from the traditional manufacturer, making the sustainable supply chain does not benefit from investing in blockchain-enabled disclosure. As a result, the implications of blockchain-enabled sustainability disclosure are not straightforward, and little is known about its effects on the supply chain in the presence of consumer skepticism. Therefore, this paper aims to investigate three research questions:

(1) Under what circumstances will both the sustainable manufacturer and retailer invest in blockchain-enabled sustainability disclosure?

(2) What are the impacts of consumer skepticism on blockchain-enabled sustainability disclosure?

(3) Under what conditions should the government support the supply chain in implementing blockchain-enabled disclosure?

To answer the above questions, this paper formulates a supply chain consisting of one retailer and two manufacturers - one sustainable and the other traditional. The sustainable manufacturer focuses on environmental protection and social responsibility, resulting in a higher production cost due to eco-friendly practices and materials. Conversely, the traditional manufacturer prioritizes cost reduction and short-term profitability, thus producing a traditional counterpart at a lower cost. Without blockchain-enabled disclosure, skeptical consumers' willingness-to-pay is the same for both sustainable and traditional products. However, with the introduction of blockchain-enabled disclosure, consumers gain access to complete information about a product and would like to pay a premium for sustainable products. The decision to invest in blockchain-enabled disclosure is made by the sustainable manufacturer or the retailer, and the supply chain will implement it when both parties invest. By comparing the profits of supply chain members with and without blockchain-enabled disclosure, this study aims to identify the conditions under which supply chains invest in blockchain-enabled sustainability disclosure and the impact of consumer skepticism on the investment decision.

The study offers analytical results that help explain the differences in attitudes toward investment decisions of blockchain-enabled sustainability disclosure between retailers and manufacturers in practice. Unlike the findings revealed by previous studies, such as Fan et al. (2020) and Xu et al. (2021a), which suggest that blockchain-enabled disclosure can enhance consumers' willingness to pay for products and benefit the manufacturer, our study demonstrates that the economic consequences are more nuanced. In particular, we find that even for the sustainable manufacturer, the investment of blockchain-enabled disclosure is not always advantageous due to the intensified competition it triggers, resulting in a lose-lose situation for both manufacturers when the sustainable manufacturer has a cost disadvantage. Moreover, our results indicate that an increase in consumer skepticism does not necessarily make the supply chain (comprising both the sustainable manufacturer and retailer) more inclined to invest in blockchain-enabled disclosure. When consumer skepticism is low, intensified competition resulting from blockchain-enabled disclosure has a more negative impact as consumer skepticism increases. Lastly, our study shows that blockchain-enabled disclosure may result in negative environmental implications. This is because increased competition can lower prices for both sustainable and traditional products, boosting consumer surplus and social welfare but harming the environment through the increased sales quantities. Nevertheless, a government-mandated disclosure policy can lead to a win-win outcome for both society and the environment.

The present study makes several contributions to the literature on blockchain-enabled sustainability disclosure in supply chains. Firstly, the study investigates the investment decision of the supply chain members concerning blockchain-enabled sustainability disclosure in the context of consumer skepticism, an area that has remained unexplored in prior research. Secondly, our model incorporates two types of consumers to analyze the impacts of consumer skepticism on blockchain investment decisions in a supply chain. Skeptical consumers are only willing to pay a higher price for sustainable products when blockchain-enabled disclosure is implemented, while common consumers trust sustainability information and are willing to pay the premium regardless of blockchain-enabled disclosure. Finally, the study analyzes the impact of blockchain-enabled disclosure on both social welfare and the environment. In doing so, our findings provide valuable insights for policymakers seeking to guide firms in making informed blockchain investment decisions that enhance social welfare and promote environmental stewardship.

The rest of the paper is organized as follows. Section 2 briefly reviews the relevant literature and positions the paper within the existing research. Section 3 develops the model used in the analysis. In Section 4, the study investigates equilibriums of the supply chain with and without blockchain-enabled sustainability disclosure. Then in Section 5, the study identifies the optimal investment strategy of blockchain-enabled disclosure for the sustainable manufacturer and the retailer. The study also examines the impacts of consumer skepticism and blockchain-enabled disclosure's influences on other stakeholders. Finally, Section 6 provides a summary of the findings and discusses managerial insights and potential avenues for future research. Proofs of all results are presented in the appendices.

2. Literature

Our study is related to three literature streams: sustainable supply chain management, blockchain technology in supply chain management and consumer skepticism.

2.1 Sustainable supply chain management

The topic of sustainability has gained a lot of attention from both academic and business communities in the past decade. Those interested in reviewing the sustainability literature may consult the works of Brandenburg et al. (2014), Sodhia and Tang (2018), Agrawal et al. (2019) and Feng et al. (2022). To fully integrate sustainability into a supply chain, it is optimal to start at the product life cycle design stage. Several supply chain models incorporating green process innovation or green product development have been proposed, such as those by Hong et al. (2019), Dai and Zhang (2017), Agi and Yan (2020), Zhu and He (2017) and Shen et al. (2021). In this study, we build upon this literature but focus on the assumption that sustainable products have already been developed, thereby bypassing the design stage.

Many studies have focused on the coordination mechanism, including Zhang et al. (2015), Panda et al. (2015) and Heydari et al. (2019). Manufacturers can use sustainability as a competitive strategy by producing sustainable products, which have been extensively studied in the literature, such as Galbreth and Ghosh (2013), Lee et al. (2018), and Tian et al. (2019). Sustainable supply chain models have also investigated competition issues. Wang et al. (2022) consider competition between retailers or manufacturers in a green supply chain to find the optimal hedging strategy. Liu et al. (2012) discover that manufacturers of products with inferior environmental friendliness benefit from intensified downstream retail competition, while Yun et al. (2021) explore contract strategies for promoting supply chain sustainability when two competing retailers have asymmetric demand information. In the context of two competing sustainable supply chains, Yang et al. (2017) employ revenue-sharing contracts to improve emission reduction rates by competing on the product greening level. Orsdemir et al. (2019) identify the conditions under which environmental concerns would lead to vertical integration in two competing supply chains, while Wang et al. (2019) investigate a closed-loop supply chain in which a manufacturer and a remanufacturer, acting as competing collectors, sell new and remanufactured products, respectively, through a retailer.

Building on this strand of research, our study investigates the issue of competition between two manufacturers in a sustainable supply chain model, where their products differ in terms of sustainability, and a single retailer is present. However, our work significantly diverges from previous studies as we account for a unique feature of the sustainability market: the presence of skeptical consumers who are hesitant to pay extra for sustainable products. Within this context, we explore the optimal blockchain-enabled disclosure strategy for the sustainable manufacturer or the retailer.

2.2 Blockchain technology in sustainable supply chain management

Recently years witnessed the growing interest of Blockchain technology in various domains, including healthcare (Hussien et al., 2021), financial services (Zachariadis et al., 2019; Choi, 2020; Dolgui et al., 2020), environmental and social sustainability (Cole et al., 2019; Chaudhuri et al., 2021; Papadopoulos et al., 2022), third-party logistics (Zhang, et al. 2023), remanufacturing supply chain (Niu, et al. 2022). A growing body of literature highlights the potential for blockchain technology to transform business practices and enhance trust, transparency, and traceability in sustainable supply chains. For instance, within the agri-food supply chain, researchers such as Feng (2016), Nayal et al. (2021), and Yadav et al. (2021) have investigated the use of blockchain-enabled traceability systems to ensure food safety and product quality, as well as enable consumers to verify such attributes. Zhou et al. (2023) develop a game model to study the value of blockchain enabled supply chain traceability under competition. Similarly, Chen et al. (2023) research the traceability strategy choice in competing supply chains based on blockchain technology. Besides track and trace function, blockchain has also been utilized to detect counterfeit products in the pharmaceutical and fashion supply chains as well as retail platforms, with increased efficiency (Chan et al., 2020; Wang et al., 2020; Zhou, et al. 2022). Blockchain can also enhance sustainability by providing consumers with information on product origin (Friedman & Ormiston, 2022; Saberi et al., 2019) and track upstream behavior to promote labor rights and safe working conditions in global supply chains (Venkatesh et al., 2020; Zhou et al., 2023). These studies primarily focus on the qualitative or empirical investigation of blockchain's implementation and identifying its benefits and barriers in sustainable supply chains.

Some studies measure the adoption of blockchain in operations and sustainable supply chain management from a game theory perspective. Choi and Luo (2019) explore the way of blockchain to improve data quality and forecasting accuracy in sustainable fashion supply chain. Choi (2019) compare blockchain-enabled and traditional jewelry retail and conclude that blockchain reduces the need for consumers to verify diamond authenticity, thus reducing the risk of fake records. Manupati et al. (2020) propose to use blockchain approach to monitor supply chain performance, reduce operational costs, and optimize emissions in a three-stage production allocation model. Bai and Sarkis (2020) construct an appraisal model for blockchain technology that enhances supply chain transparency and mitigates sustainability risks. Chod et al. (2020) formulate a signaling model to investigate the effects of blockchain-enabled supply chain transparency, which facilitates firms to communicate private information (i.e. their operational capabilities) to lenders more efficiently. Niu et al. (2021) explore the incentives for using blockchain to track medicine quality in a medical supply chain with two manufacturers and a retailer. Cao and Shen (2022) propose to adopt blockchain technology to block the entrance of less sustainable products in global trade. They identify a blockchain adoption cost threshold, above which the entry of less sustainable products can be blocked. Chen et al. (2023) study the traceability strategy choices in a supply chain consisting of two competing manufacturers selling online through retail or direct channels. They compare two strategies including building traceability system or joining third-party blockchain platforms and identify the conditions for different strategies. Cui et al. (2023) use game theory to analyze traceability-driven blockchains in different supply chain structures, finding that traceability can enhance product quality and profits in serial supply chains, but may reduce product quality in parallel supply chains. However, game-theoretical models in the literature do not consider the effects of consumer behavior on blockchain adoption strategy and blockchain-enabled information disclosure.

Considering that blockchain can improve trust of consumers on product quality, Wu and Wang (2023) examine platform-led blockchain adoption strategy in a supply chain with heterogeneous suppliers, Biswas et al. (2023) analyze the trade-offs between traceability and sustainability in blockchain technology for supply chains, and Shen et al. (2022) study the adoption of blockchain technology to combat copycats in a supply chain. But we shift the focus to the impact of blockchain technology on eliminating consumer skepticism by disclosing product sustainability information. Different from Fan et al. (2020), who examine the adoption conditions of blockchain when all customers have traceability awareness in a three-stage supply chain, and Xu et al. (2021b), who study supply chain coordination problem with all consumers having a stronger environmental awareness for green products under blockchain, we model two types of consumers. Specifically, only skeptical consumers whose willingness to pay for sustainable products can be improved by the use of blockchain technology. Our model demonstrates how the use of blockchain-enabled disclosure can increase the amount of consumers' willing to pay more for sustainable products, and examines the investment strategy of sustainable manufacturers or retailers in blockchain and its subsequent impact on social welfare and the environment. Our study also differs from Shen et al. (2022) in the problems investigated. Shen et al. (2022) mainly focus on the copycat combating problem, while our paper aims to study the impact of consumer skepticism on blockchain-enabled sustainability disclosure.

2.3 Consumer skepticism

Consumer skepticism has attracted considerable interest from researchers in marketing and consumer behavior fields. It is defined as the doubt or disbelief that consumers have about marketing claims, advertising messages, and brand promises (Obermiller & Spangenberg, 1998; Mohr et al., 1998). Attribution theory has been commonly used to explore the antecedents of consumer skepticism and to elucidate how people interpret corporate social involvement as well as how this perception influences their subsequent behavior (Leonidou & Skarmeas, 2017; Dalal, 2020; Skarmeas & Leonidou, 2013; Ginder et al., 2021).

Previous studies have focused on the influencing factors of consumer skepticism towards corporate social responsibility (CSR) or environmental concerns (Mohr et al., 1998; Leonidou & Skarmeas, 2017). Researchers have identified company-cause fit as a key factor that influences consumer skepticism, as shown in studies by Becker-Olsen et al. (2006) and DeMotta et al. (2023). Low congruence between a firm and its sustainable activities in a given communication can prompt consumers skeptical about CSR and environmental performance of the company. D'souza and Taghian (2005) and Mitra et al. (2019) find that consumers who are more knowledgeable about environmental issues or are environmentally concerned are more likely to consider the company's green practices or claims unconvincing. In contrast, Matthes and Wonneberger (2014) show that green consumers are less skeptical of firms' green claims than non-green consumers. Connors et al. (2017) also highlight that message concreteness influences the level of consumer skepticism.

Consumer skepticism can lead to negative consequences for firms, such as poor purchase intentions, negative brand positioning, negative evaluations, and a bad reputation (Leonidou & Skarmeas, 2017). To overcome this skepticism, Atkinson and Rosenthal (2014) and Ganz and Grimes (2018) find that specific messages can increase consumers' trust in eco-labels or green claims.

At present, there is a dearth of research examining the influence of consumer skepticism on the decision-making processes of supply chain actors. Our contribution to this field of study lies in the inaugural investigation of the effectiveness of blockchain-enabled sustainability disclosure as a strategy for mitigating consumer skepticism. Our findings have the potential to inform supply chain stakeholders about the circumstances under which blockchain should be employed to alleviate consumer skepticism and promote sustainability within the supply chain.

3. Model for blockchain-enabled sustainability disclosure

We study a supply chain with two competing manufacturers and one common retailer. The manufacturers exhibit asymmetric characteristics with respect to their social and environmental responsibility, as well as associated production costs. Specifically, Manufacturer S (sustainable manufacturer) produces sustainable products at a high unit production cost c, whereas Manufacturer T (traditional manufacturer) produces traditional products at a low unit production cost that is normalized to 0 for analytical tractability.

The present investigation centers on an industry where the verification of final product sustainability poses a challenge, like organic food or clothing sectors. By leveraging this technology, information concerning the sustainability of the product can be tracked and recorded on a tamper-proof ledger in real time throughout the production and transportation processes. Although other technologies may also be able to achieve the track and trace function with blockchain technology, the information recorded by other technologies could be manipulated on purpose. Therefore, they are not trust free. The unchangeable nature of blockchain make it a trust free technology. People who are using the same blockchain can trust each other without knowing their identities. Therefore, the information in blockchain is reliable and moral hazard problems could be avoided. Manufacturer S and the retailer can invest in blockchain-enabled disclosure mechanisms to communicate information on product sustainability.

The market size is normalized to 1. We assume that consumers' willingness to pay for the traditional product is heterogeneous and uniformly distributed over the interval $[0,1]$. The heterogeneity of consumers' willingness to pay is not uncommon in practice and widely used in the literature, see, e.g., Mussa and Rosen (1978), Ferguson and Toktay (2006), and Aviv et al. (2019). Consumers are generally willing to pay sustainable products a premium, but not all of them are able to distinguish between traditional products and sustainable products (Gao et al., 2017). Therefore, we assume that a proportion $\phi \in (0,1)$ of consumers in the market are informed and not skeptical about product information of sustainability, e.g., in the case of Walmart, some consumers trust environmental information provided by the producer and can identify pollution-free or organic vegetables (sustainable products). Each common consumer with willingness-to-pay for the traditional product v, is willing to pay $(1+\alpha)v$ for the sustainable product. However, other consumers are skeptical, i.e., they do not trust the limited information on sustainable source and production on the packaging of supermarket vegetables or labels of clothing (Deloitte, 2022), and not willing to pay the premium α. We limit to $0<\alpha<1$, to ensure that the premium that common consumers are willing to pay for the sustainable product is no greater than the price they are willing to pay for the traditional product. The size of the skeptical consumer group is $1-\phi$ and represents the level of consumer skepticism in the market.

Let q_S (q_T) denote the selling quantity of sustainable (traditional) products, and p_S (p_T) the market clearing price of sustainable (traditional) products. The purchasing behavior of consumers is modeled such that each consumer buys the product that maximizes their net utility, subject to the constraint that they only purchase one product. The inverse demand functions are derived based on the consumer utility functions (the detailed derivation is presented in Appendix B):

$$p_S = \begin{cases} \dfrac{(1+\alpha)(\phi - q_S)}{\phi}, & \text{if } q_T < \dfrac{1-\phi}{\phi} q_S, \\ \dfrac{\alpha(\phi - q_S) + \phi(1 - q_S - q_T)}{\phi}, & \text{if } q_T \geq \dfrac{1-\phi}{\phi} q_S. \end{cases} \tag{1}$$

$$p_T = \begin{cases} \dfrac{1-\phi-q_T}{1-\phi}, & \text{if } q_T < \dfrac{1-\phi}{\phi} q_S, \\ 1 - q_S - q_T, & \text{if } q_T \geq \dfrac{1-\phi}{\phi} q_S. \end{cases} \tag{2}$$

Note that the market-clearing price of sustainable products is consistently higher than that of traditional products since common consumers are generally willing to pay a premium for sustainable products. However, skeptical consumers, who do not share this willingness, choose not to purchase sustainable products.

The kinked inverse demand functions, Equations (1) and (2), indicate that if the selling quantity of traditional products is sufficiently small, i.e., $q_T < (1-\phi) q_S / \phi$, and the market clearing price of traditional products is sufficiently high, then common consumers do not buy traditional products. In this case, the sustainable product dominates the market segment of informed consumers, while the traditional product dominates the market segment of skeptical consumers. However, if the quantity of traditional products being sold is not negligible, informed consumers may also opt to purchase traditional products. In such a case, sustainable and traditional products compete for informed consumers.

The adoption of blockchain technology facilitates a veracious disclosure of the sustainable product's information by Manufacturer S. Notably, leading food retailers such as Walmart and Carrefour deploy the IBM Food Trust blockchain to eliminate consumers' skepticism concerning food quality and freshness. Here, we use Equations (1) and (2) with $\phi = 1$ to represent consumer demand within the context of blockchain-enabled sustainability disclosure, which demonstrates that skeptical consumers become willing to pay more for the sustainable products. The game model in this study is a four-stage Stackelberg game involving a retailer and two competing manufacturers. The game proceeds as follows:

- First, either Manufacturer S or the retailer decides on whether to invest in blockchain-enabled sustainability disclosure. If blockchain technology is adopted, all consumers will be non-skeptical regarding products' sustainability information, i.e., $\phi = 1$.
- Second, based on the observed blockchain-enabled disclosure strategy of Manufacturer S or the retailer, both Manufacturer S and Manufacturer T independently and simultaneously determine the wholesale prices of their respective products.
- Third, the retailer determines the quantities of sustainable and traditional products to sell.
- Forth, demand is realized by consumers making their purchase decisions, and firms get their profits.

The game is sequential, and all players have complete information and act rationally. The retailer's profit is as follows:

$$\pi_R\left(q_S, q_T\right) = \left(p_S - w_S\right)q_S + \left(p_T - w_T\right)q_T. \tag{3}$$

Manufacturer S's profit function is

$$\pi_S\left(w_S\right) = \left(w_S - c\right)q_S, \tag{4}$$

and Manufacturer T's profit function is

$$\pi_T\left(w_T\right) = w_T q_T. \tag{5}$$

4. Equilibrium Analysis

In this section, we first examine the scenario where Manufacturer S does not invest in blockchain-enabled disclosure of its product sustainability information, i.e., a proportion

$(1-\phi)$ of consumers in the market are skeptical about the product's sustainability information. We derive the optimal decisions and associated profits for each player. Note that the scenario with blockchain-enabled disclosure can be seen as a special case of the scenario without blockchain-enabled disclosure when $\phi = 1$.

4.1 Case with no blockchain-enabled disclosure

In this subsection, we consider the case with no blockchain-enabled disclosure of product sustainability information, denoted by the superscript n. The game between the retailer and two competing manufacturers is analyzed using backward induction. At the last stage, taking the wholesale prices w_S^n and w_T^n as given, we derive the retailer's optimal quantity response functions as follows.

LEMMA 1. *In the case of no blockchain-enabled disclosure, the retailer's optimal quantity responses are*

(i) if $w_S^n - w_T^n \ge \alpha$, $q_S^{n*} = 0$, *and* $q_T^{n*} = \frac{1}{2}\left(1 - w_T^n\right)$*;*

(ii) if $\alpha w_T^n \le w_S^n - w_T^n < \alpha$, $q_S^{n*} = \dfrac{\phi\left(\alpha - w_S^n + w_T^n\right)}{2\alpha}$, *and*

$$q_T^{n*} = \frac{\alpha - \alpha\phi + \phi w_S^n - \left(\alpha + \phi\right) w_T^n}{2\alpha};$$

(iii) otherwise, $q_S^{n*} = \dfrac{\phi\left(1 + \alpha - w_S^n\right)}{2\left(1 + \alpha\right)}$, *and* $q_T^{n*} = \frac{1}{2}\left(1 - \phi\right)\left(1 - w_T^n\right)$.

The retailer's quantity decisions are affected by the wholesale prices set by the two competing manufacturers. Specifically, the relative magnitudes of these prices influence the optimal quantities of traditional and sustainable products that the retailer chooses to sell. If the wholesale price of Manufacturer S is prohibitively high, the retailer will only sell traditional products, resulting in the elimination of sustainable products from the market. Conversely, if the wholesale price of Manufacturer S is sufficiently low, the retailer will sell both traditional and sustainable products, catering to the preferences of both skeptical and common consumers. Notably, traditional products retain a cost advantage over sustainable products and therefore will always remain in the market.

Both competing manufacturers determine their wholesale prices simultaneously to maximize their respective profits. This optimization process leads to the derivation of the best response functions for each manufacturer:

$$w_S^n\left(w_T^n\right)=\begin{cases}\frac{1}{2}\left(1+\alpha+c\right), & \mathit{if}\ w_T^n>\frac{1+\alpha+c}{2\left(1+\alpha\right)},\\ \left(1+\alpha\right)w_T^n, & \mathit{if}\ \frac{\alpha+c}{1+2\alpha}<w_T^n\le\frac{1+\alpha+c}{2\left(1+\alpha\right)},\\ \frac{1}{2}\left(\alpha+c+w_T^n\right), & \mathit{if}\ c-\alpha<w_T^n\le\frac{\alpha+c}{1+2\alpha},\\ c, & \mathit{if}\ w_T^n\le c-\alpha.\end{cases}$$

$$w_T^n\left(w_S^n\right)=\begin{cases}\frac{1}{2}, & \mathit{if}\ w_S^n\ge\frac{1}{2}+\alpha,\\ w_S^n-\alpha, & \mathit{if}\ \max\left\{\frac{1}{2}+\alpha-\frac{1}{2}\sqrt{\phi},\frac{\alpha\left(1+2\alpha+\phi\right)}{2\alpha+\phi}\right\}\le w_S^n<\frac{1}{2}+\alpha,\\ \frac{\alpha-\alpha\phi+\phi w_S^n}{2\left(\alpha+\phi\right)}, & \mathit{if}\ \frac{\sqrt{\alpha\left(\alpha+\phi\right)\left(1-\phi\right)}-\alpha\left(1-\phi\right)}{\phi}\le w_S^n<\frac{\alpha\left(1+2\alpha+\phi\right)}{2\alpha+\phi},\\ \frac{1}{2}, & \mathit{if}\ w_S^n\le\min\left\{\frac{\alpha\left(1+2\alpha+\phi\right)}{2\alpha+\phi},\frac{\sqrt{\alpha\left(\alpha+\phi\right)\left(1-\phi\right)}-\alpha\left(1-\phi\right)}{\phi}\right\}\\ & \mathit{or}\ \frac{\alpha\left(1+2\alpha+\phi\right)}{2\alpha+\phi}\le w_S^n<\frac{1}{2}+\alpha-\frac{1}{2}\sqrt{\phi}.\end{cases}$$

The intuition behind these response functions is explained as follows. If the wholesale price of Manufacturer T is prohibitively high, i.e., $w_T^n>\frac{1+\alpha+c}{2\left(1+\alpha\right)}$, Manufacturer S can monopolize the market segment of common consumers since the retailer does not sell traditional products to this group. Otherwise, Manufacturer S competes with Manufacturer T in the market segment of common consumers. However, if w_T^n is sufficiently high, i.e., $\frac{\alpha+c}{1+2\alpha}<w_T^n\le\frac{1+\alpha+c}{2\left(1+\alpha\right)}$, Manufacturer S can lower his wholesale price and drive traditional products out of the market segment of common consumers. In

contrast, if w_T^n is sufficiently low, i.e., $w_T^n \le c-\alpha$, sustainable products will be driven out of the market.

The same intuition shapes Manufacturer T's response function. Note that, if the wholesale price of Manufacturer S is prohibitively high or prohibitively low, i.e., $w_S^n > \frac{1}{2}+\alpha$ or $w_S^n \le \min\left\{\frac{\alpha(1+2\alpha+\phi)}{2\alpha+\phi}, \frac{\sqrt{\alpha(\alpha+\phi)(1-\phi)}-\alpha(1-\phi)}{\phi}\right\}$, Manufacturer T's optimal response is $w_T^n(w_S^n)=\frac{1}{2}$. In the former case, Manufacturer S monopolizes the whole market, whereas in the latter case, Manufacturer S monopolizes the market segment of skeptical consumers.

Combining the optimal response functions of the two manufacturers, we obtain the following equilibrium outcomes.

PROPOSITION 1. *In the case with no blockchain-enabled disclosure, there exist two thresholds,* $t_1^n = \frac{\alpha(2\alpha+\phi+1)}{2\alpha+\phi}$, *and* $t_2^n = \frac{1+2\alpha}{2}$, *such that in equilibrium the optimal wholesale prices of Manufacturer S and Manufacturer T are*

(i) if $c < t_1^n$, $w_S^{n*} = \frac{2\alpha^2+(2c+\phi+1)\alpha+2c\phi}{4\alpha+3\phi}$ *and* $w_T^{n*} = \frac{(2-\phi)\alpha+c\phi}{4\alpha+3\phi}$;

(ii) if $t_1^n \le c < t_2^n$, $w_S^{n*}=c$ *and* $w_T^{n*}=c-\alpha$;

(iii) otherwise, $w_S^{n*}=c$ *and* $w_T^{n*}=\frac{1}{2}$.

The three equilibrium scenarios for the optimal wholesale prices of the two manufacturers are illustrated in Figure 1. It is observed that, due to its cost advantage, Manufacturer T is always inclined to compete with Manufacturer S in determining the wholesale price. Therefore, the wholesale price of Manufacturer T would never be prohibitively high in equilibrium. Consequently, even if the sustainable product is highly competitive, i.e., c is low and α is large (see the area of scenario (i) in Figure 1), the two manufacturers compete within the market segment of common consumers. Otherwise, Manufacturer T can drive sustainable products out of the market. Specifically, if the sustainable product is uncompetitive, i.e., c is high and α is small (see the area of scenario (iii) in Figure 1), Manufacturer T can ignore the competition from Manufacturer S and operate as a monopolistic manufacturer.

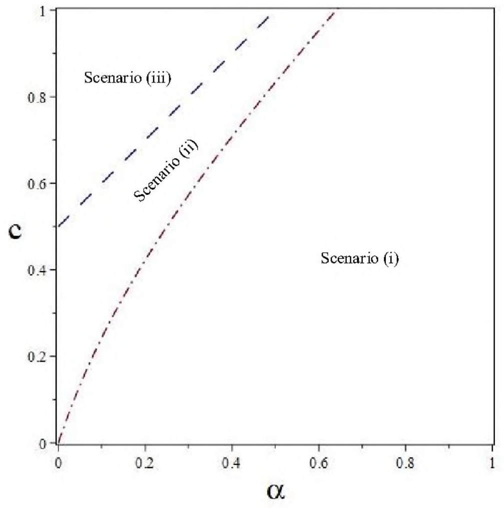

Figure 1. Illustrations of these three scenarios in Proposition 1

By substituting the manufacturers' optimal wholesale prices into the quantity response functions of the retailer, we can obtain the optimal selling quantities in the absence of blockchain-enabled disclosure, as presented below.

(i) if $c < t_1^n$, $q_S^{n*} = \dfrac{\left(2\alpha^2 + (1+\phi)\alpha - (2\alpha+\phi)c\right)\phi}{2\alpha(\alpha+3\phi)}$ and

$$q_T^{n*} = \frac{(\alpha+\phi)\left((2-\phi)\alpha + c\phi\right)}{2\alpha(4\alpha+3\phi)};$$

(ii) if $t_1^n \le c < t_2^n$, $q_S^{n*} = 0$ and $q_T^{n*} = \dfrac{1+\alpha-c}{2}$;

(iii) otherwise, $q_S^{n*} = 0$ and $q_T^{n*} = \dfrac{1}{4}$.

4.2 *Case with blockchain-enabled disclosure*

In this subsection, we analyze the case where sustainability information is disclosed through blockchain technology (denoted by the superscript d), with either the retailer or Manufacturer S would invest in blockchain-enabled sustainability disclosure. In this scenario, all consumers no longer hold any skepticism towards the sustainability information of sustainable products. By substituting $\phi = 1$ into the results from the case without blockchain-enabled disclosure, we can derive the equilibrium outcomes as follows.

There exist thresholds, $t_1^d = \dfrac{2\alpha(\alpha+1)}{2\alpha+1}$ and $t_2^n = \dfrac{1+2\alpha}{2}$ (defined in Proposition 1) such that the two manufacturer's optimal wholesale prices are

(i) if $c < t_1^d$, $w_S^{d*} = \dfrac{2(\alpha^2+(1+c)\alpha+c)}{3+4\alpha}$ and $w_T^{d*} = \dfrac{\alpha+c}{3+4\alpha}$;

(ii) if $t_1^d \le c < t_2^n$, $w_S^{d*} = c$ and $w_T^{d*} = c-\alpha$;

(iii) otherwise, $w_S^{d*} = c$ and $w_T^{d*} = \dfrac{1}{2}$.

The retailer's optimal selling quantities in the case with blockchain-enabled disclosure are

(i) if $c < t_1^d$, $q_S^{d*} = \dfrac{2\alpha(1+\alpha)-(1+2\alpha)c}{2\alpha(3+4\alpha)}$, and $q_T^{d*} = \dfrac{(1+\alpha)(\alpha+c)}{2\alpha(3+4\alpha)}$;

(ii) if $t_1^d \le c < t_2^n$, $q_S^{d*} = 0$ and $q_T^{d*} = \dfrac{1+\alpha-c}{2}$;

(iii) otherwise, $q_S^{d*} = 0$ and $q_T^{d*} = \dfrac{1}{4}$.

4.3 Comparison analysis

We compare the equilibrium outcomes in cases with and without blockchain-enabled disclosure, and have the following findings.

First, the two cases are identical if $c > t_1^n$. Note that $t_1^n > t_1^d$ always holds. Here, if the unit cost of the sustainable product is high enough, Manufacturer S will be driven out of the market, regardless of Manufacturer S's or the retailer's blockchain-enabled disclosure strategy. Therefore, the blockchain-enabled disclosure strategy has no impact on the results in equilibrium. Otherwise, the blockchain-enabled disclosure strategy can make a difference, which is presented in the following proposition.

PROPOSITION 2. *For $c \le t_1^n$, there exist two thresholds,*

$T_1 = \dfrac{\alpha(4\alpha^2+2\alpha(1+2\phi)+3\phi)}{4\alpha^2+4\alpha(1+\phi)+3\phi}$ *and* $T_2 = \dfrac{\alpha(8\alpha^2+4\alpha(2+\phi)+3\phi)}{8\alpha^2+4\alpha(1+\phi)+3\phi}$, *such that*

blockchain-enabled sustainability disclosure makes

(i) both manufacturers' wholesale prices lowered.

(ii) the selling quantity of traditional products reduced if and only if $c < T_1$;

(iii) the selling quantity of sustainable products reduced if and only if $c > T_2$.

T_1 *increases with* ϕ*, and* T_2 *or* t_1^n *increases with* ϕ.

The comparative analysis demonstrates that blockchain-enabled sustainability disclosure always induces both manufacturers to lower their own wholesale prices. We explain the economic rationale behind it as follows. If c is low enough, i.e., $c < t_1^d$, regardless of blockchain-enabled disclosure strategy, the two manufacturers compete in the market. With blockchain-enabled disclosure, all consumers have access to accurate information distinguishing sustainable and traditional products. Consequently, Manufacturer T becomes less appealing to skeptical consumers. Therefore, to safeguard its market share within this consumer segment, Manufacturer T adopts a strategic pricing policy by lowering its wholesale price. This, in turn, makes Manufacturer S less attractive to common consumers, who are aware of the verifiable information regarding sustainable products. To counteract this, Manufacturer S also strategically lowers its wholesale price to defend its market share among common consumers.

The preceding discussion suggests that the use of blockchain-enabled sustainability disclosure leads to heightened competition between the two manufacturers. In the absence of blockchain-enabled disclosure, Manufacturer T can predominantly target skeptical consumers to market traditional products, while Manufacturer S can target common consumers to market sustainable products. However, with the advent of blockchain-enabled disclosure, both manufacturers are incentivized to compete for the entire market, resulting in intense competition. Given the cost advantage of Manufacturer T, Manufacturer S is more likely to be edged out of the market in scenarios featuring blockchain-enabled disclosure. Specifically, if c is intermediate, i.e., $t_1^d \le c < t_1^n$, Manufacturer S is expected to be driven out of the market in the case with blockchain-enabled disclosure, whereas in the case with no blockchain-enabled disclosure, it is not subject to the same outcome.

Proposition 2 also illustrates how the impacts of blockchain-enabled disclosure on the retailer's selling quantities are influenced by different levels of consumer skepticism $(1-\phi)$. We observe that the higher the consumer skepticism, i.e., ϕ is smaller, the less likely blockchain-enabled disclosure could reduce the sales quantity of the traditional product and sustainable product, i.e., $\partial T_1/\partial\phi > 0$ and $\partial T_2/\partial\phi < 0$. This is because blockchain-enabled disclosure, with no consumer skepticism ($\phi = 1$), induces both manufacturers to engage in fierce price competition, and this effect is significant when more consumer skepticism is removed. We also observe that when more consumers are skeptical, Manufacturer T has less incentive to target common consumers to sell traditional products and drive Manufacturer S out of the market, i.e., $\partial t_1^n / \partial \phi < 0$. Thus, the higher the consumer skepticism, the greater challenge to the sale of the sustainable product due to blockchain-enabled disclosure.

In Figure 2, ↑ indicates an increase and ↓ indicates a decrease, then we first observe scenarios (ii) and (iii) of proposition 2. In the case of blockchain-enabled disclosure, both manufacturers lower their wholesale prices, generally leading to an increase in the retailer's selling quantities of both the traditional product and the sustainable product. However, if c is prohibitively low, i.e., $c < T_1$, Manufacturer T's cost advantage is not significant enough, then a lower wholesale price cannot successfully maintain its market share. Consequently, the selling quantity of the traditional product decreases. Conversely, if c is sufficiently high, i.e., $c > T_2$, Manufacturer S' cost disadvantage becomes significant, leading to a reduction in the sustainable product's selling quantity. Specifically, blockchain-enabled disclosure might make Manufacturer S to be driven out of the market, resulting in the selling quantity of the sustainable product is reduced to 0

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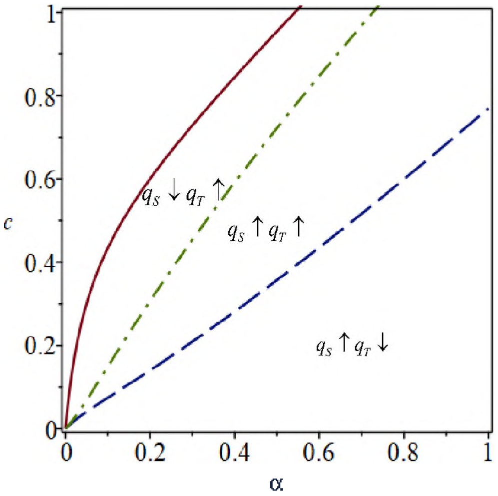

Figure 2. Impacts of blockchain-enabled disclosure on selling quantities

Figure 2 also reveals that when c remains constant, as α increases, common consumers are willing to pay more for the sustainable product, then blockchain-enabled disclosure first decreases (increases) and then increases (decreases) the selling quantity of sustainable (traditional) products. This is because the competitiveness of Manufacturer S can be enhanced by blockchain-enabled disclosure when α is large.

These observations generate an interesting but important managerial insight: when blockchain-enabled disclosure is adopted in the supply chain, and no consumers are skeptical, the retailer should exercise caution in attempting to sell more sustainable products. Moreover, if Manufacturer S is unable to compete effectively, the retailer should reduce the selling quantity of sustainable products, which corresponds to the case of $c > T_2$ in proposition 2.

5. Optimal investment strategy of blockchain-enabled disclosure

In this section, we compare the profits of Manufacturer S and the retailer under both scenarios to identify the optimal investment strategy for blockchain-enabled disclosure and examine the impact of consumer skepticism. Furthermore, we explore the strategic implications of blockchain-enabled disclosure from the perspectives of Manufacturer T, the government, and the environment.

It is important to note that if Manufacturer S's unit production cost is prohibitively high, i.e., $c \geq t_1^n$, regardless of the blockchain-enabled disclosure strategy, Manufacturer S will be driven out of the market. Neither competition nor blockchain-enabled disclosure will occur. To avoid trivial outcomes, in the following analysis, we exclude the scenario $c \geq t_1^n$.

Recall that t_1^n and T_2 are defined in Proposition 1 and Proposition 2 respectively. We define a threshold as follows:

$$T_D = \frac{\alpha\left(2\alpha(1+2\alpha)\left(16\alpha(1+\alpha)+(15+16\alpha)\phi\right)-(3+4\alpha)(4\alpha+3\phi)\phi^{1/2}+(3+4\alpha)^2\phi^2\right)}{16\alpha^2(1+2\alpha)^2+4\alpha\left(6+19\alpha+16\alpha^2\right)\phi+(3+4\alpha)^2\phi^2},$$

we always have $T_D < T_2$.

***PROPOSITION* 3.** *(i) Manufacturer S should invest in blockchain-enabled sustainability disclosure if and only if* $c < T_D$ *; (ii) The retailer should invest in blockchain-enabled sustainability disclosure if and only if* $c < t_1^n$ *.*

When $\phi < \frac{4\alpha\left(3+8\alpha+4\sqrt{(3+4\alpha)\alpha}\right)}{9}$*,* T_D *decreases with* ϕ *, otherwise* T_D *increases with* ϕ *.*

Interestingly, the analysis reveals that Manufacturer S may not always find it optimal to invest in blockchain-enabled sustainability disclosure, even when disregarding the cost associated with the adoption of the blockchain technology. On the one hand, the blockchain-enabled disclosure increases skeptical consumers' willingness to pay for the sustainable product, thus directly benefiting Manufacturer S. On the other hand, it intensifies competition between the asymmetric manufacturers, leading to an indirect negative impact. When c is sufficiently high, the negative impact of intensified competition dominates, reducing Manufacturer S's selling quantity. As a result, Manufacturer S could be hurt by the blockchain-enabled disclosure.

Proposition 3 (ii) shows that blockchain-enabled disclosure always improves the profits of the retailer if Manufacturer S is not driven out of the market i.e., $c < t_1^n$. This is because the blockchain-enabled sustainability disclosure increases consumers' willingness to pay for Manufacturer S's products and intensifies the competition between the two manufacturers. Both effects are positive for the retailer, so the retailer is always willing to invest in blockchain-enabled disclosure as long as Manufacturer S is not driven out of the market. Proposition 3 (i) and (ii) jointly generate an important insight: note that $T_D < t_1^n$, the retailer is more willing to invest in blockchain-enabled disclosure than Manufacturer S. Therefore, Manufacturer S may not want the retailer to invest in blockchain-enabled disclosure, which implies that only when the cost is not sufficiently high, i.e., $c < T_D$, can the supply chain achieve blockchain-enabled disclosure (both the Manufacturer S and retailer invest in blockchain-enabled disclosure), as observed in Figure 3.

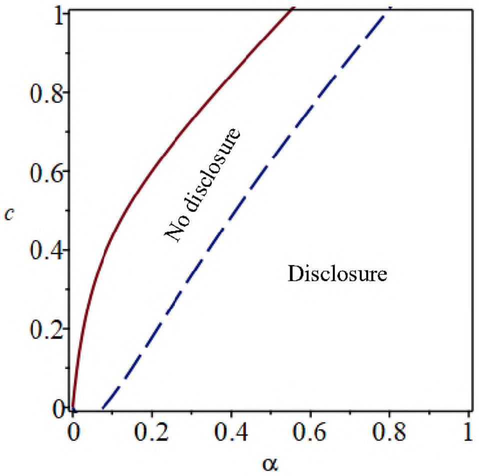

Figure 3. Optimal blockchain-enabled disclosure strategy

Next, we explore the impacts of consumer skepticism $(1-\phi)$ on the blockchain-enabled disclosure strategy of the supply chain. An interesting finding is that the supply chain is not always more likely to achieve blockchain-enabled disclosure as consumer skepticism increases, i.e., as ϕ decreases. The willingness of the retailer and Manufacturer S to invest in blockchain differs as consumer skepticism rises. Higher consumer skepticism always increases the retailer's willingness to invest in blockchain-enabled disclosure, that is $\partial t_1^n / \partial \phi < 0$. In contrast, when consumer skepticism is sufficiently low, blockchain-enabled disclosure would highlight the negative impact of intensified competition and Manufacturer S would benefit less from more skeptical consumers who become willing to pay more for the sustainable product, thus the incentive for Manufacturer S to invest in blockchain-enabled disclosure decreases as customer skepticism increases, that is $\partial T_D / \partial \phi > 0$. Therefore, Manufacturer S may not want the retailer to invest in blockchain technology as consumer skepticism increases, which also makes the supply chain less likely to achieve blockchain-enabled disclosure.

5.1 Effects of blockchain-enabled disclosure

In this subsection, we analyze the strategic effects of blockchain-enabled disclosure from various stakeholders' perspectives.

PROPOSITION 4. *The blockchain-enabled sustainability disclosure always hurts Manufacturer T.*

The analysis presented in Proposition 2 has demonstrated that the adoption of blockchain-enabled sustainability disclosure has two distinct effects on the competition between the two manufacturers. Firstly, it increases the willingness to pay of consumers for Manufacturer S's sustainable products. Secondly, it intensifies the competition between the two manufacturers. As expected, both of these effects have negative implications for Manufacturer T, ultimately leading to a reduction in its profit when blockchain-enabled disclosure is adopted.

Next, we discuss the impact of blockchain-enabled disclosure from the angles of consumer surplus and social welfare.

PROPOSITION 5. *Blockchain-enabled sustainability disclosure always improves consumer surplus and social welfare.*

The intensified competition between the two manufacturers, brought on by the disclosure, leads to a decrease in market clearing prices of both sustainable and traditional products, as both manufacturers lower their wholesale prices. This decrease, however, results in an increase in consumer surplus. Hence, blockchain-enabled sustainability disclosure always enhances consumer welfare. Moreover, the retailer's profit and consumer surplus always increase, and Manufacturer S's profit may increase as well. In contrast, only Manufacturer T's profit decreases in the presence of blockchain-enabled disclosure. Overall, the impact of blockchain-enabled disclosure on social welfare is consistently positive.

Finally, we examine the effect of blockchain-enabled disclosure on the environment. Following Agrawal et al. (2012), Yan et al. (2015) and Reimann et al. (2019), we use a weighted sales quantity, $q_T + \gamma q_E$, as a proxy for the sustainable supply chain's environmental impact. It implies that the negative impact of consuming one unit of a traditional product is normalized to 1, while the negative environmental impact of consuming one unit of sustainable products is $\gamma \in [0,1]$.

Define a threshold $T_E = \dfrac{\left(4(2\gamma-1)\alpha^2 + 2\left((4\gamma-1) - 2(1-\gamma)\phi\right)\alpha - 3(1-\gamma)\phi\right)\alpha}{4(2\gamma-1)\alpha^2 - \left(4(1+\phi)\alpha + 3\phi\right)(1-\gamma)}$.

PROPOSITION 6. *The blockchain-enabled sustainability disclosure benefits the environment if and only if* $c < T_E$ *and* $\gamma < \dfrac{4\alpha^2 + 2(1+2\phi)\alpha + 3\phi}{8\alpha^2 + 4(2+\phi)\alpha + 3\phi}$.

T_E is increasing in ϕ. In this study, a unit of product has a negative environmental impact during the consumption stage, though the impact of a sustainable product is less significant. This is because the blockchain-enabled disclosure intensifies the competition between the two manufacturers, the total sales quantity, in general, increases in the case of blockchain-enabled disclosure. However, it is straightforward to find that for the same sales quantity, a smaller γ, indicating the better environmental performance of the sustainable product, always benefits the environment. Thus, for a small γ, if the blockchain-enabled disclosure can make fewer traditional products consumed, the environment can be better off, even though more sustainable products might be consumed. Proposition 2 and Figure 2 have shown the sales quantity of traditional products is reduced in the case of blockchain-enabled disclosure if and only if c is sufficiently low, where, intuitively, the blockchain-enabled disclosure is more likely to benefit the environment.

The two thresholds in Proposition 3 and Proposition 6 are depicted in Figure 4 where the blue dotted line is T_D, the green dashed line is T_E, and the region of $c < t_1^n$ is divided into four parts by the two lines. Furthermore, Table 1 presents an overview of the four regions in Figure 4.

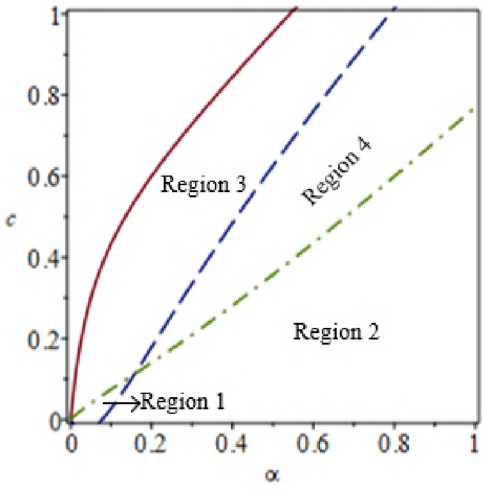

Figure 4. Illustration of three thresholds

Table 1 Overview of the four regions in Figure 4

	Impacts of blockchain-enabled disclosure

	Blockchain-enabled disclosure	*Environment*	*Social welfare*
Region 1	No	Positive	Positive
Region 2	Yes	Positive	Positive
Region 3	No	Negative	Positive
Region 4	Yes	Negative	Positive

In Regions 1 and 2, blockchain-enabled disclosure is beneficial to society and the environment, but there is no incentive for the supply chain to invest in blockchain-enabled disclosure in Region 1. Although the retailer's profit is improved by adopting blockchain-enabled disclosure, Manufacturer S' profit only increases after the disclosure in Regions 2 and 4. Therefore, in Region 1, i.e., if c is low enough and α is sufficiently small, blockchain-enabled disclosure cannot be achieved in the supply chain. To achieve a win-win situation for both society and the environment, it is necessary for the government to issue a mandatory disclosure policy or for the retailer to offer incentives to Manufacturer S to adopt a blockchain-enabled disclosure strategy. In Region 3, where the supply chain does not invest in blockchain-enabled disclosure, such disclosure can create tension between society and the environment, resulting in benefits for society but harm for the environment. Thus, whether to provide support for blockchain-enabled disclosure in Region 3 depends on the government's primary objective. If the government prioritizes economic performance, then a blockchain-enabled sustainability disclosure strategy should be supported.

Proposition 6 also illustrates that as consumer skepticism $(1-\phi)$ increases, blockchain-enabled disclosure can make the environment less easy to be better off, that is $\partial T_E / \partial \phi > 0$. This is because blockchain-enabled disclosure reduces consumer skepticism, as demonstrated in Proposition 2. This reduction in skepticism is likely to result in an increase in sales quantity for both traditional and sustainable products, which can have negative implications for the environment.

6. Conclusions

In recent years, leading firms have increasingly invested in improving the social and environmental sustainability of their products. While many consumers would like to pay a premium for such benefits, they are often deterred by a lack of clear or trustworthy sustainability information. Blockchain-enabled sustainability disclosure can potentially address this problem by reducing consumer skepticism and increasing their willingness to pay, thereby boosting the profitability of sustainable manufacturers. However, due to market competition between traditional and sustainable products, as well as supply chain dynamics, the implications of blockchain-enabled sustainability disclosure are not straightforward. To address this issue, we build a game-theoretical model to investigate the optimal blockchain-backed sustainability disclosure investment strategy of the supply chain, as well as its impacts on multiple stakeholders. We investigate the effects of consumer skepticism on blockchain-enabled disclosure and characterize the optimal decisions of the sustainable manufacturer, the traditional manufacturer, and the common retailer in cases with and without blockchain-enabled disclosure.

To begin with, comparative analysis reveals that while blockchain-enabled sustainability disclosure leads to an increase in consumers' willingness to pay for sustainable products, it does not always increase the optimal sales quantity of sustainable products. This is because the blockchain-enabled disclosure intensifies competition between manufacturers, which may adversely impact the sustainable manufacturer when investing in blockchain-enabled disclosure. However, the intensified competition benefits the retailer, albeit at the expense of both manufacturers' profits, leading to the retailer's increased willingness to invest in blockchain-enabled disclosure. Secondly, the optimal investment strategy of the sustainable supply chain in blockchain-enabled disclosure is significantly related to consumer skepticism. When consumer skepticism is low, the negative effects of intensified competition would dominate, making blockchain-enabled disclosure less attractive for the sustainable manufacturer to invest in as customer skepticism increases. Finally, while blockchain-enabled sustainability disclosure always improves consumer surplus and social welfare, it may have adverse effects on the environment. This is because intensified competition leads to lower market clearing prices of both sustainable and traditional products, resulting in increased selling quantities that are detrimental to the environment. In cases where the sustainable manufacturer is unwilling to invest in blockchain-enabled disclosure, a mandatory disclosure policy or support from the government can result in a win-win outcome for both society and the environment.

Our results have significant implications for various stakeholders in the sustainable supply chain. Firstly, investing in blockchain-enabled sustainability disclosure may not always be a profitable strategy for sustainable manufacturers, even when ignoring the implementation costs of blockchain technology. The decision to invest in blockchain-enabled disclosure depends on the market structure, consumer skepticism, and cost structure. Blindly investing in blockchain-enabled sustainability disclosure may lead to a price war, reducing profits for both sustainable and competing traditional manufacturers. To avoid direct competition, manufacturers with asymmetric market power should aim to monopolize a market segment for products with notable sustainable or environmental features that consumers are willing to pay a high premium for.

Secondly, blockchain-enabled sustainability disclosure can increase consumers' willingness to pay and intensify competition between manufacturers, which is advantageous for the retailer. Hence, retailers should encourage and support sustainable manufacturers to invest in blockchain-enabled sustainability disclosure. One way to do so is by initiating a blockchain disclosure project, providing financial incentives to manufacturers, or mandating manufacturers to participate in it, such as Amazon or JD.com (Agi & Yan, 2020). Governments can also promote blockchain-enabled disclosure, but the environmental performance of the supply chain does not necessarily improve. Policymakers should consider two conditions: first, for products with inconspicuous sustainable features, like organic cotton clothing, sustainably sourced seafood or fair-trade coffee, where consumers are willing to pay only a low premium for the environment, a supportive disclosure policy may be necessary. Second, the blockchain-enabled disclosure policy can only lead to a win-win outcome for society and the environment if the production cost of sustainable products is low.

Our paper is not without limitations like any other research, which will lead to future research. First, we assume that the information disclosure is perfect, i.e., all the supply chain partners disclose their sustainability information fully to the customer. This situation could be ideal in practice since supply chain players may decide to partly disclose their information for their own purposes. Therefore, further studies could examine the robustness of our results under imperfect blockchain-enabled sustainability disclosure, assuming that it may not perfectly inform consumers about the sustainability of products. Second, we ignore the cost of adopting blockchain technology in the supply chain. Although this is a fixed cost, which may not impact the qualitative conclusions, it may impact the incentive of participating in the supply chain. Therefore, incorporating the cost of blockchain-enabled sustainability disclosure would be a valuable topic for future research, such as identifying optimal cost-sharing mechanisms in the sustainable supply chain. Finally, our model takes the environmental friendliness of products as exogenous. In practice, however, the environmental impact of a product could be decided during the product design stage. The product design decision may also interact with the blockchain technology adoption decision. Thus, following research could study how the blockchain-enabled disclosure strategy interacts with the environmental innovation strategy.

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Appendix

Appendix A: Proof

Proof of Lemma 1

We first consider the scenario $q_T^n \geq (1-\phi) q_S^n / \phi$. The retailer's profit function is

$$\pi_R^n = \left(\frac{\alpha(\phi - q_S^n) + \phi(1 - q_S^n - q_T^n)}{\phi} - w_E^n \right) q_S^n + (1 - q_S^n - q_T^n - w_T^n) q_T^n, \text{ subject to}$$

$q_T^n \geq (1-\phi) q_E^n / \phi$. The Lagrangian and the KKT optimality conditions for the retailer's optimization problem are

$$L_R^n = \left(\frac{\alpha(\phi - q_S^n) + \phi(1 - q_S^n - q_T^n)}{\phi} - w_S^n \right) q_S^n + (1 - q_S^n - q_T^n - w_T^n) q_T^n + \lambda \left(q_T^n - \frac{1-\phi}{\phi} q_S^n \right), \tag{1}$$

$$1 + \alpha - w_S^n - 2q_T^n - \frac{2(\phi + \alpha) q_S^n}{\phi} - \frac{1-\phi}{\phi} \lambda = 0, \tag{2}$$

$$1 - 2q_T^n - 2q_S^n - w_T^n + \lambda = 0, \tag{3}$$

$$\lambda \left(q_T^n - \frac{1-\phi}{\phi} q_S^n \right) = 0. \tag{4}$$

The Lagrangian multiplier λ is either zero or positive, resulting in two scenarios for analysis.

Scenario (i): $\lambda = 0$, $q_S^{n*} = \dfrac{\phi(\alpha + w_T^n - w_S^n)}{2\alpha}$ and $q_T^{n*} = \dfrac{\alpha(1-\phi) + \phi w_S^n - (\alpha + \phi) w_T^n}{2\alpha}$. Substituting λ, q_S^{n*}, q_T^{n*} into Equation (2), (3) and (4), we have $(1+\alpha) w_T^n \leq w_S^n$. Due to $q_S^n > 0$, the quantity constraint requires $w_S^n < w_T^n + \alpha$. When $w_S^n \geq w_T^n + \alpha$, $q_S^{n*} = 0$ and $q_T^{n*} = \dfrac{1 - w_T^n}{2}$.

Scenario (ii): $\lambda > 0$, $q_T^n = \frac{1-\phi}{\phi} q_S^n$, we have $q_S^{n*} = \frac{\phi\left(1+\alpha\phi+(1-\phi)w_T^n-\phi w_S^n\right)}{2(1+\alpha\phi)}$ and $q_T^{n*} = \frac{(1-\phi)\left(1+\alpha\phi-(1-\phi)w_T^n-\phi w_S^n\right)}{2(1+\alpha\phi)}$. The multiplier $\lambda > 0$ requires $w_S^n < (1+\alpha)w_T^n$.

Second, we consider $q_T^n < (1-\phi)q_S^n/\phi$. The retailer's profit function is $\pi_R^n = \left(\frac{(1+\alpha)(\phi-q_S^n)}{\phi} - w_S^n\right)q_S^n + \left(\frac{1-\phi-q_T^n}{1-\phi} - w_T^n\right)q_T^n$, subject to $q_T^n < (1-\phi)q_S^n/\phi$. From the first-order condition, we have $q_E^{n*} = \frac{\phi\left(1+\alpha-w_E^n\right)}{2(1+\alpha)}$ and $q_T^{n*} = \frac{1}{2}(1-\phi)\left(1-w_T^n\right)$. The quantity constraint requires $w_S^n < (1+\alpha)w_T^n$.

By examining the retailer's profitability, when $w_S^n < (1+\alpha)w_T^n$, the pricing strategy $q_S^{n*} = \frac{\phi\left(1+\alpha-w_S^n\right)}{2(1+\alpha)}$ and $q_T^{n*} = \frac{1}{2}(1-\phi)\left(1-w_T^n\right)$ is preferred over the pricing strategy $q_S^{n*} = \frac{\phi\left(1+\alpha\phi+(1-\phi)w_T^n-\phi w_S^n\right)}{2(1+\alpha\phi)}$ and $q_T^{n*} = \frac{(1-\phi)\left(1+\alpha\phi-(1-\phi)w_T^n-\phi w_S^n\right)}{2(1+\alpha\phi)}$.

Combining these optimal solutions and their conditions in all scenarios gives Lemma 1.

Proof of Proposition 1

According to the retailer's response function, Manufacturer S and Manufacturer T decide optimal wholesale prices simultaneously.

At first, we consider the case of $w_S^n \geq w_T^n + \alpha$. If w_T^n is sufficiently low, there is no scope for Manufacturer S to enhance the market demand for the sustainable product by reducing the price, i.e., $w_S^n\left(w_T^n\right) = c$ if $w_T^n \leq c - \alpha$. Simultaneously, Manufacturer T's optimization problem is $\max\limits_{w_T} \pi_T^n = \frac{\left(1-w_T^n\right)w_T^n}{2}$, subject to $w_S^n \geq w_T^n + \alpha$. We easily obtain the optimal solution $w_T^n\left(w_S^n\right) = \frac{1}{2}$ if $w_S^n \geq \frac{1}{2} + \alpha$.

Second, Manufacturer S's and Manufacturer T's optimization problems are $\pi_S^n = \frac{\left(w_S^n - c\right)\left(\alpha + w_T^n - w_S^n\right)\phi}{2\alpha}$ and $\pi_T^n = \frac{\left(\alpha\left(1-\phi\right) + \phi w_S^n - \left(\alpha+\phi\right) w_T^n\right) w_T^n}{2\alpha}$ respectively, subject to $\left(1+\alpha\right) w_T^n \le w_S^n < w_T^n + \alpha$. For Manufacturer S, the unconstrained solution is $w_S^n\left(w_T^n\right) = \frac{1}{2}\left(w_T^n + \alpha + c\right)$, which satisfies the constraints if and only if $c - \alpha < w_T^n \le \frac{\alpha + c}{1+2\alpha}$. If $w_T^n > \frac{\alpha+c}{1+2\alpha}$, then the optimal solution is $w_S^n\left(w_T^n\right) = \left(1+\alpha\right) w_T^n$. If $w_T^n \le c - \alpha$, then the optimal solution is infinitely approaching $w_S^n\left(w_T^n\right) = w_T^n + \alpha$. Similarly, for Manufacturer T, we obtain $w_T^n\left(w_S^n\right) = \frac{\alpha\left(1-\phi\right) + \phi w_S^n}{2\left(\alpha+\phi\right)}$, which satisfies the constraints if and only if $\frac{\alpha\left(1-\phi\right)\left(1+\alpha\right)}{2\alpha+\phi-\alpha\phi} \le w_S^n < \frac{\alpha\left(1+2\alpha+\phi\right)}{2\alpha+\phi}$. If $w_S^n < \frac{\alpha\left(1-\phi\right)\left(1+\alpha\right)}{2\alpha+\phi-\alpha\phi}$, then the optimal solution is $w_T^n\left(w_E^n\right) = \frac{w_E^n}{1+\alpha}$. If $w_S^n \ge \frac{\alpha\left(1+2\alpha+\phi\right)}{2\alpha+\phi}$, the optimal solution is infinitely approaching $w_T^n\left(w_S^n\right) = w_S^n - \alpha$.

Thirdly, two manufacturers' optimization problems are $\pi_S^n = \frac{\left(w_S^n - c\right)\left(1+\alpha - w_S^n\right)\phi}{2\left(1+\alpha\right)}$ and $\pi_T^n = \frac{1}{2}\left(1-\phi\right)\left(1-w_T^n\right) w_T^n$ respectively, subject to $w_S^n < \left(1+\alpha\right) w_T^n$. For Manufacturer S, the unconstrained solution is $w_S^n\left(w_T^n\right) = \frac{1}{2}\left(1+\alpha+c\right)$ which satisfies the constraints if and only if $w_T^n > \frac{1+\alpha+c}{2\left(1+\alpha\right)}$. Otherwise, the optimal solution is infinitely approaching $w_S^n\left(w_T^n\right) = \left(1+\alpha\right) w_T^n$. Similarly, for Manufacturer T, $w_T^n\left(w_S^n\right) = \frac{1}{2}$, which satisfies the constraints if and only if $w_S^n < \frac{1+\alpha}{2}$. Otherwise, the optimal solution is infinitely approaching $w_T^n\left(w_S^n\right) = \frac{w_S^n}{1+\alpha}$.

We identify the Manufacturer T's optimal pricing decision by examining its profitability. The solution $w_T^n\left(w_S^n\right) = \frac{w_S^n}{1+\alpha}$ is always dominated by the third solution $w_T^n\left(w_S^n\right) = \frac{1}{2}$, which implies $w_T^n\left(w_S^n\right) = \frac{1}{2}$ is the dominant strategy if

$w_S^n < \frac{\alpha(1-\phi)(1+\alpha)}{2\alpha+\phi-\alpha\phi}$. With $w_T^n\left(w_S^n\right) = \frac{1}{2}$, Manufacturer T's profit in the third strategy is $\pi_T^n = \frac{1}{8}(1-\phi)$. With $w_T^n\left(w_S^n\right) = \frac{\alpha(1-\phi)+\phi w_S^n}{2(\alpha+\phi)}$, Manufacturer T's profit in the second strategy is $\pi_T^n = \frac{\left(\phi w_S^n + \alpha(1-\phi)\right)^2}{8\alpha(\alpha+\phi)}$. Letting $\frac{1}{8}(1-\phi) = \frac{\left(\phi w_S^n + \alpha(1-\phi)\right)^2}{8\alpha(\alpha+\phi)}$, we have $w_S^n = \frac{\sqrt{\alpha(\alpha+\phi)(1-\phi)}-\alpha(1-\phi)}{\phi}$, which falls into the interval $\left[\frac{\alpha(1-\phi)(1+\alpha)}{2\alpha+\phi-\alpha\phi}, \min\left\{\frac{1+\alpha}{2}, \frac{\alpha(1+2\alpha+\phi)}{2\alpha+\phi}\right\}\right)$. Therefore, $w_T^n\left(w_S^n\right) = \frac{1}{2}$ is the dominant solution if $\frac{\alpha(1-\phi)(1+\alpha)}{2\alpha+\phi-\alpha\phi} \le w_S^n < \min\left\{\frac{\alpha(1+2\alpha+\phi)}{2\alpha+\phi}, \frac{\sqrt{\alpha(\alpha+\phi)(1-\phi)}-\alpha(1-\phi)}{\phi}\right\}$.

The solution $w_T^n\left(w_S^n\right) = \frac{w_S^n}{1+\alpha}$ is always dominated by the solution $w_T^n\left(w_E^n\right) = \frac{\alpha(1-\phi)+\phi w_E^n}{2(\alpha+\phi)}$. Thus, the $w_T^n\left(w_E^n\right) = \frac{\alpha(1-\phi)+\phi w_E^n}{2(\alpha+\phi)}$ is the dominant solution if $\frac{\sqrt{\alpha(\alpha+\phi)(1-\phi)}-\alpha(1-\phi)}{\phi} \le w_S^n < \frac{\alpha(1+2\alpha+\phi)}{2\alpha+\phi}$. Similarly, it is easy to prove the dominant solution is $w_T^n\left(w_S^n\right) = w_S^n - \alpha$ if $\max\left\{\frac{1}{2}+\alpha-\frac{1}{2}\sqrt{\phi}, \frac{\alpha(1+2\alpha+\phi)}{2\alpha+\phi}\right\} \le w_S^n < \frac{1}{2}+\alpha$, and $w_T^n\left(w_S^n\right) = \frac{1}{2}$ is the dominant solution if $\frac{\alpha(1+2\alpha+\phi)}{2\alpha+\phi} \le w_S^n < \frac{1}{2}+\alpha-\frac{1}{2}\sqrt{\phi}$.

We have three candidates for the equilibrium solution:

(i) $w_S^1 = c$ and $w_T^1 = \frac{1}{2}$;

(ii) $w_S^2 = \frac{2\alpha^2+(2c+\phi+1)\alpha+2c\phi}{4\alpha+3\phi}$ and $w_T^2 = \frac{(2-\phi)\alpha+c\phi}{4\alpha+3\phi}$;

(iii) $w_S^3 = \frac{1}{2}(1+\alpha+c)$ and $w_T^3 = \frac{1}{2}$.

Scenario (i), i.e., w_i^1 implies that Manufacturer S has been driven out of the market; scenario (ii), i.e., w_i^2 implies that two manufacturers compete in the market segment of common consumers; scenario (iii), i.e., w_i^3 implies that Manufacturer S targets only the common consumers and Manufacturer T targets only the skeptical consumers.

(1) The conditions for $\left(w_S^1, w_T^1\right)$ to become an equilibrium solution

We investigate whether Manufacturer S (Manufacturer T) deviates from $\left(w_S^1, w_T^1\right)$. First, we consider that Manufacturer S turns to targeting the whole market. Given that $w_T^{n*} = w_T^1 = \frac{1}{2}$ and $\pi_S^n = \frac{\left(w_S^n - c\right)\left(\alpha + w_T^1 - w_S^n\right)\phi}{2\alpha}$, Manufacturer S's optimal wholesale price response is $w_S^{12} = \frac{1}{2}\left(\frac{1}{2} + \alpha + c\right)$. If $w_S^{12} \ge w_T^1 + \alpha$, i.e., $c \ge \frac{1}{2} + \alpha$, it is optimal for Manufacturer S to be driven out of the market, i.e., not to deviate from w_E^1. If $w_T^1\left(1+\alpha\right) \le w_S^{12} < w_T^1 + \alpha$, i.e., $\frac{1}{2} < c \le \frac{1}{2} + \alpha$, we have $\pi_S^{n*}\left(w_S^{12}, w_T^1\right) > \pi_S^{n*}\left(w_S^1, w_T^1\right)$, then Manufacturer S will turn to w_S^{12}. Here, $\pi_S^{n*}\left(w_S^{12}, w_T^1\right) = \frac{\left(1 + 2\alpha - 2c\right)^2 \phi}{32\alpha}$. Similarly, given that $w_S^{n*} = w_S^1 = c$ and $\pi_T^n = \frac{\left(\alpha\left(1-\phi\right) + \phi w_E^1 - \left(\alpha + \phi\right) w_T^n\right) w_T^n}{2\alpha}$, Manufacturer T's optimal wholesale price response is $w_T^{12} = \frac{\alpha + \left(c - \alpha\right)\phi}{2\left(\alpha + \phi\right)}$. If $w_T^{12} \le w_S^1 - \alpha$, i.e., $c \ge \frac{\alpha\left(2\alpha + \phi + 1\right)}{2\alpha + \phi}$, Manufacturer T won't deviate from w_T^{*1}. If $w_S^1 - \alpha < w_T^{12} \le \frac{w_S^1}{1+\alpha}$, i.e., $\frac{\alpha\left(1+\alpha\right)\left(1-\phi\right)}{2\alpha + \phi - \alpha\phi} \le c < \frac{\alpha\left(2\alpha + \phi + 1\right)}{2\alpha + \phi}$, we have $\pi_T^{n*}\left(w_S^1, w_T^{12}\right) \le \pi_T^{n*}\left(w_S^1, w_T^1\right)$, then Manufacturer T obtains a smaller profit after deviating, and hence Manufacturer T will also not deviate from w_T^1.

Next, we consider that Manufacturer S switches to target only the common consumers. Given $w_T^{n*} = w_T^1 = \frac{1}{2}$, Manufacturer S's optimal wholesale price response is $w_S^{13} = \frac{1}{2}\left(1 + \alpha + c\right)$. If $w_E^{13} \ge w_T^1 + \alpha$, i.e., $c \ge \alpha$, Manufacturer S will not deviate from

w_S^1. If $w_T^1(1+\alpha) \le w_S^{13} < w_T^1+\alpha$, i.e., $c < \alpha$, we have $\pi_S^{n^*}\left(w_S^{13}, w_T^1\right) > \pi_S^{n^*}\left(w_S^1, w_T^1\right)$, then Manufacturer S will turn to w_S^{13}. Here, $\pi_S^{n^*}\left(w_S^{13}, w_T^1\right) = \frac{(1+\alpha-c)^2\phi}{8(1+\alpha)}$. Similarly, given that $w_S^{n^*} = w_S^1 = c$, Manufacturer T's optimal wholesale price response is $w_T^{13} = \frac{1}{2}$. If $w_T^{13} \le w_S^1 - \alpha$, i.e., $c \ge \frac{1}{2} + \alpha$, Manufacturer T will not deviate from w_T^1. If $w_S^1 - \alpha < w_T^{13} \le \frac{w_S^1}{1+\alpha}$, i.e., $\frac{1}{2}(1+\alpha) \le c < \frac{1}{2} + \alpha$, we have $\pi_T^{n^*}\left(w_S^1, w_T^{13}\right) \le \pi_L^{n^*}\left(w_S^1, w_T^1\right)$, then Manufacturer T will also not deviate from w_T^1. Here, $\pi_T^{n^*}\left(w_S^1, w_T^{13}\right) = \frac{1}{8}(1-\phi)$.

Combining the above conditions, we obtain $\left(w_E^1, w_T^1\right)$ is an equilibrium if and only if $c \ge \frac{1}{2} + \alpha$.

(2) The conditions for $\left(w_S^2, w_T^2\right)$ to become an equilibrium solution

We investigate whether Manufacturer S (Manufacturer T) deviates from $\left(w_S^2, w_T^2\right)$. By examining $w_T^2(1+\alpha) \le w_S^2 < w_T^2+\alpha$, we obtain $\frac{\alpha(1-\alpha\phi-2\phi)}{(2\alpha+\phi-\alpha\phi)} \le c < \frac{(1+2\alpha+\phi)}{2\alpha+\phi}$. First, if Manufacturer S turns to being driven out of the market, given $w_T^{n^*} = w_T^2 = \frac{(2-\phi)\alpha + c\phi}{4\alpha+3\phi}$, the optimal wholesale price response is $w_S^{21} = c$. If $w_T^2(1+\alpha) \le w_S^{21} < w_T^2+\alpha$, i.e., $\frac{\alpha(1+\alpha)(2-\phi)}{4\alpha+2\phi-\alpha\phi} \le c < \frac{(1+2\alpha+\phi)}{2\alpha+\phi}$, Manufacturer S will not deviate from w_S^2. If $w_S^{21} \ge w_T^2+\alpha$, i.e., $c \ge \frac{(1+2\alpha+\phi)}{2\alpha+\phi}$, we have $\pi_S^{n^*}\left(w_S^{21}, w_T^2\right) \le \pi_S^{n^*}\left(w_S^2, w_T^2\right)$. Then Manufacturer S will also not deviate from w_S^2. Given $w_S^{n^*} = w_S^2 = \frac{2\alpha^2 + (2c+\phi+1)\alpha + 2c\phi}{4\alpha+3\phi}$, if Manufacturer T turns to target the whole market, the optimal wholesale price response is $w_T^{21} = \frac{1}{2}$. If $w_S^2 - \alpha < w_T^{21} \le \frac{w_S^2}{1+\alpha}$, i.e., $\frac{(2+\phi)\alpha+3\phi}{4(\alpha+\phi)} \le c < \frac{4\alpha^2 + (2+4\phi)\alpha + 3\phi}{4(\alpha+\phi)}$, Manufacturer T will not deviate from w_T^2. If

$w_T^{21} \ge w_S^2 - \alpha$, i.e., $c \ge \frac{4\alpha^2 + (2+4\phi)\alpha + 3\phi}{4(\alpha+\phi)}$ and $\pi_T^{n*}\left(w_S^2, w_T^{21}\right) \le \pi_T^{n*}\left(w_S^2, w_T^2\right)$, then Manufacturer T will also not deviate from w_T^2.

Next, if Manufacturer S turns to target only the common consumers, given $w_T^{n*} = w_T^2 = \frac{(2-\phi)\alpha + c\phi}{4\alpha+3\phi}$, the optimal wholesale price response is $w_S^{23} = \frac{1}{2}(1+\alpha+c)$. If $w_T^2(1+\alpha) \le w_S^{23} < w_T^2 + \alpha$, i.e., $c < \frac{4\alpha^2 + \alpha\phi - 3\phi}{4\alpha+\phi}$, Manufacturer S will not deviate from w_S^2. $w_S^{23} < w_T^2(1+\alpha)$ doesn't exist. Given $w_S^{n*} = w_S^2 = \frac{2\alpha^2 + (2c+\phi+1)\alpha + 2c\phi}{4\alpha+3\phi}$, if Manufacturer T turns to target only the skeptical consumers, the optimal wholesale price response is $w_T^{23} = \frac{1}{2}$. If $w_S^2 - \alpha < w_T^{23} \le \frac{w_S^2}{1+\alpha}$, i.e., $\frac{(2+\phi)\alpha + 3\phi}{4(\alpha+\phi)} \le c < \frac{4\alpha^2 + (2+4\phi)\alpha + 3\phi}{4(\alpha+\phi)}$, Manufacturer T will not deviate from w_T^2. If $w_T^{23} > \frac{w_S^2}{1+\alpha}$, i.e., $c < \frac{(2+\phi)\alpha + 3\phi}{4(\alpha+\phi)}$ and $\pi_T^{n*}\left(w_E^2, w_T^{23}\right) \le \pi_T^{n*}\left(w_E^2, w_T^2\right)$, then Manufacturer T will not deviate from w_T^{*2}.

Combining the above conditions, we obtain $\left(w_S^2, w_T^2\right)$ is an equilibrium if and only if $\frac{\alpha(1-\alpha\phi-2\phi)}{(2\alpha+\phi-\alpha\phi)} \le c < \frac{(1+2\alpha+\phi)}{2\alpha+\phi}$.

(3) The conditions for $\left(w_S^3, w_T^3\right)$ to become an equilibrium solution

We investigate the conditions under which $\left(w_S^3, w_T^3\right)$ is an equilibrium. If Manufacturer S turns to be driven out of the market, given $w_T^n = w_T^3 = \frac{1}{2}$, the optimal wholesale price response is $w_S^{31} = c$. If $w_S^{31} \le w_T^3(1+\alpha)$, i.e., $c \le \frac{1}{2}(1+\alpha)$, Manufacturer S will not deviate from w_S^3. If $w_S^{31} > w_L^3 + \alpha$, i.e., $c > \frac{1}{2} + \alpha$, we have $\pi_S^{n*}\left(w_S^{31}, w_T^3\right) \le \pi_S^{n*}\left(w_S^3, w_T^3\right)$, then Manufacturer S will also not deviate from w_S^3. Given $w_S^{n*} = w_S^{*3} = \frac{1}{2}(1+\alpha+c)$, if Manufacturer T turns to target the whole market, the optimal wholesale price response is $w_T^{31} = \frac{1}{2}$. We have $w_T^{31} < \frac{w_E^3}{1+\alpha}$ and $\pi_T^{n*}\left(w_S^3, w_T^{31}\right) > \pi_T^{n*}\left(w_S^3, w_T^3\right)$, which implies that Manufacturer T always obtains higher profit after turning to w_T^{31}. So $\left(w_S^3, w_T^3\right)$ cannot be an equilibrium solution.

(4) Comparison of the conditions

Obviously, the conditions for $\left(w_S^1, w_T^1\right)$ and $\left(w_S^2, w_T^2\right)$ to be an equilibrium solution cannot cover all the values of c. According to the above analysis, if $c < \frac{\alpha(1-\alpha\phi-2\phi)}{(2\alpha+\phi-\alpha\phi)}$, we find no equilibrium solution. If the best response functions for Manufacturer S and Manufacturer T are $w_S^n\left(w_T^n\right) = c$ and $w_T^n\left(w_S^n\right) = c-\alpha$ respectively, we have $\frac{(1+2\alpha+\phi)}{2\alpha+\phi} \le c < \frac{1}{2}+\alpha$. Thus, $w_S^{n*} = c$ and $w_T^{n*} = c-\alpha$ become an equilibrium solution if and only if $\frac{(1+2\alpha+\phi)}{2\alpha+\phi} \le c < \frac{1}{2}+\alpha$.

Combining these optimal solutions and their conditions in all scenarios gives proposition 1.

Proof of Proposition 2

By comparing the wholesale prices under cases with and without blockchain-enabled disclosure, we have two results. Define a threshold $\underline{c} = \frac{\alpha(1-\alpha\phi-2\phi)}{(2\alpha+\phi-\alpha\phi)}$.

(1) Comparison of wholesale prices

In the case of $\underline{c} \le c < t_1^d$, we have $w_S^{n*} = \frac{2\alpha^2+(2c+\phi+1)\alpha+2c\phi}{4\alpha+3\phi}$ and $w_S^{d*} = \frac{2\left(\alpha^2+(1+c)\alpha+c\right)}{3+4\alpha}$, then $w_S^{n*} - w_S^{d*} = \frac{\alpha(1-\phi)(3+2\alpha-2c)}{(3+4\alpha)(3\phi+4\alpha)} > 0$. Similarly, we have $w_T^{n*} - w_T^{d*} = \frac{2\alpha(1-\phi)(3+2\alpha-2c)}{(3+4\alpha)(3\phi+4\alpha)} > 0$.

In the case of $\max\left\{\underline{c}, t_1^d\right\} \le c < t_1^n$, $w_S^{n*} - w_S^{d*} = \frac{(1+2\alpha+\phi)\alpha-(2\alpha+\phi)c}{4\alpha+3\phi} > 0$,

$w_T^{n*} - w_T^{d*} = \frac{2\left((1+2\alpha+\phi)\alpha-(2\alpha+\phi)c\right)}{4\alpha+3\phi} > 0$.

Therefore, we obtain Proposition 2 (i), i.e., blockchain-enabled disclosure makes both manufacturers' wholesale prices lowered.

(2) Comparison of the sales quantities

We define $\Delta q_S = q_S^{n*} - q_S^{d*}$ and $\Delta q_T = q_T^{n*} - q_T^{d*}$.

In the case of $\underline{c} \le c < t_1^d$, we have

$\Delta q_S = \frac{\left(\left(8\alpha^2+4(1+\phi)\alpha+3\phi\right)c-\left(8\alpha^2+4(2+\phi)\alpha+3\phi\right)\alpha\right)(1-\phi)}{2\alpha(3+4\alpha)(4\alpha+3\phi)}$. Substituting $c=\underline{c}$ and $c=t_1^d$ into Δq_S, we obtain $\Delta q_S\big|_{c=\underline{c}} = \frac{\left(4\alpha^2+2(1+2\phi)\alpha+3\phi-1\right)(1-\phi)}{2(3+4\alpha)(\alpha\phi-2\alpha-\phi)} < 0$ and

$\Delta q_S\big|_{c=t_1^d} = \frac{(1-\phi)\phi}{2(1+2\alpha)(4\alpha+3\phi)} > 0$. Letting $\Delta q_S = 0$, we have

$c = \frac{\alpha\left(8\alpha^2+4\alpha(2+\phi)+3\phi\right)}{8\alpha^2+4\alpha(1+\phi)+3\phi} = T_2$. Clearly, if $c > T_2$, the sales quantity of the sustainable product would be reduced with blockchain-enabled disclosure, i.e., $\Delta q_S > 0$. And we can determine the first-order derivative of T_2 with respect to consumer skepticism $\frac{\partial T_2}{\partial \phi} = -\frac{4\alpha^2(4\alpha+3)}{\left(4\alpha(1+2\alpha+\phi)+3\phi\right)^2} < 0$. Similarly, we have

$\Delta q_T = \frac{\left(\left(4\alpha^2+(2+4\phi)\alpha+3\phi\right)\alpha-\left(4\alpha^2+4(1+\phi)\alpha+3\phi\right)c\right)(1-\phi)}{2\alpha(3+4\alpha)(4\alpha+3\phi)}$. Substituting $c=\underline{c}$ and $c=t_1^d$ into Δq_T, we obtain $\Delta q_T\big|_{c=\underline{c}} = \frac{\left(2\alpha^2+4\alpha\phi+3\phi-1\right)(1-\phi)}{2(3+4\alpha)(2\alpha+\phi-\alpha\phi)} > 0$ and

$\Delta q_T\big|_{c=t_1^d} = \frac{(\phi-1)\phi}{2(1+2\alpha)(4\alpha+3\phi)} < 0$. Letting $\Delta q_T = 0$, we have

$c = \frac{\alpha\left(4\alpha^2+2\alpha(1+2\phi)+3\phi\right)}{4\alpha^2+4\alpha(1+\phi)+3\phi} = T_1$. Clearly, if $c < T_1$, the sales quantity of the traditional product would be reduced with blockchain-enabled disclosure, i.e., $\Delta q_T > 0$. And we can determine the first-order derivative of T_1 with respect to consumer skepticism

$$\frac{\partial T_1}{\partial \phi}=\frac{2\alpha^2(4\alpha+3)}{\left(4\alpha(1+\alpha+\phi)+3\phi\right)^2}>0.$$

In the case of $\max\{\underline{c},t_1^d\}\le c<t_1^n$, we have $q_S^{d*}=0$, then $\Delta q_S=q_S^{n*}>0$.

$\Delta q_T=\dfrac{2\alpha(1+2\alpha+\phi)-2(2\alpha+\phi)c}{(4\alpha+3\phi)}$. Letting $\Delta q_T=0$, we have $c=\dfrac{(1+2\alpha+\phi)\alpha}{2\alpha+\phi}=t_1^n$.

Thus, we obtain $\Delta q_T>0$ in this case, and $\dfrac{\partial t_1^n}{\partial \phi}=-\dfrac{\alpha}{(2\alpha+\phi)^2}>0$.

Combining the above results, we obtain Proposition 2 (ii) and (iii).

Proof of Proposition 3

Define $\Delta\pi_S=\pi_S^{n*}-\pi_S^{d*}$. We compare Manufacturer S's profits with and without blockchain-enabled disclosure.

In the case of $\underline{c}\le c<t_1^d$,

$\Delta\pi_S=\dfrac{\left((2\alpha+\phi)c-(1+2\alpha)\alpha-\alpha\phi\right)^2\phi}{2(4\alpha+3\phi)^2\alpha}-\dfrac{\left((1+2\alpha)c-2(1+\alpha)\alpha\right)^2}{2(3+4\alpha)^2\alpha}$. We have $\dfrac{\partial^2\Delta\pi_S}{\partial c^2}<0$ in this case. Substituting $c=\underline{c}$ and $c=t_1^d$ into $\Delta\pi_E$, we obtain

$$\Delta\pi_S\Big|_{c=\underline{c}}=\frac{\left(\left(16\alpha^2+24\alpha+9\right)\phi^2+\left(32\alpha^3+39\alpha^2+2\alpha-7\right)\phi+\left(4\alpha^2+2\alpha-1\right)^2\right)(\phi-1)\alpha}{2(3+4\alpha)^2(\alpha\phi-\phi-2\alpha)^2}<0$$

and $\Delta\pi_S\Big|_{c=t_1^d}=\dfrac{(1-\phi)^2\alpha\phi}{2(1+2\alpha)^2(4\alpha+3\phi)^2}>0$. Letting $\Delta\pi_S=0$, we have

$$c=\frac{\alpha\left(2\alpha(1+2\alpha)\left(16\alpha(1+\alpha)+(15+16\alpha)\phi\right)-(3+4\alpha)(4\alpha+3\phi)\phi^{1/2}+(3+4\alpha)^2\phi^2\right)}{16\alpha^2(1+2\alpha)^2+4\alpha\left(6+19\alpha+16\alpha^2\right)\phi+(3+4\alpha)^2\phi^2}=T_D$$

in this case. Thus, we have $\Delta\pi_S<0$ if and only if $c<T_D$. In addition, we have

$$T_2-T_D=\frac{3(3+4\alpha)\phi^{5/2}+8(3+5\alpha)\alpha\phi^{3/2}+16(1+2\alpha)\alpha^2\phi^{1/2}+2(4\alpha+3\phi)\alpha\phi}{\left((3+4\alpha)^2\phi^2+4\left(16\alpha^2+19\alpha+6\right)\alpha\phi+16(1+2\alpha)^2\alpha^2\right)\left(8\alpha^2+(1+\phi)\alpha+3\phi\right)}>0$$

. We also determine the first-order derivative of T_D with respect to consumer skepticism

$$\frac{\partial T_D}{\partial \phi}=\frac{\begin{pmatrix} 3(3+4\alpha)^2\phi^3+4(3+5\alpha)(3\phi-4\alpha(1+4\alpha))\alpha\phi-64\alpha^3(1+2\alpha)^2 \\ -32(3+4\alpha)\left(32\alpha^3+16(1+2\phi)\alpha^2+16(2+\phi)\alpha\phi+3\phi^2\right)\alpha\phi^{1/2} \end{pmatrix}(3+4\alpha)^2(4\alpha+3\phi)\alpha}{16\left((3+4\alpha)^2\phi^2+4\left(16\alpha^2+19\alpha+6\right)\alpha\phi+16(1+2\alpha)^2\alpha^2\right)^2(3+4\alpha)(4\alpha+3\phi)\phi^{1/2}}$$

. Let $A=\begin{pmatrix} 3(3+4\alpha)^2\phi^3+4(3+5\alpha)(3\phi-4\alpha(1+4\alpha))\alpha\phi-64\alpha^3(1+2\alpha)^2 \\ -32(3+4\alpha)\left(32\alpha^3+16(1+2\phi)\alpha^2+16(2+\phi)\alpha\phi+3\phi^2\right)\alpha\phi^{1/2} \end{pmatrix}$,

$A_1=3(3+4\alpha)^2\phi^3+12(3+5\alpha)\phi^2\alpha$ and

$$A_2=16\alpha^2(3+5\alpha)(1+4\alpha)\phi+64\alpha^3(1+2\alpha)^2+32(3+4\alpha)\begin{pmatrix} 32\alpha^3+16(1+2\phi)\alpha^2 \\ +((3+16\alpha)\phi+32\alpha)\phi \end{pmatrix}\alpha\phi^{1/2}$$

, we have $A=A_1-A_2$. Since $\frac{\partial\left(A_1{}^2-A_2{}^2\right)}{\partial\phi}>0$, letting $A_1{}^2-A_2{}^2=0$, we have $\phi=\frac{4\alpha\left(3+8\alpha+4\sqrt{(3+4\alpha)\alpha}\right)}{9}$. Since $A<0$ ($A\geq 0$) equals to $\frac{\partial T_D}{\partial\phi}<0$ ($\frac{\partial T_D}{\partial\phi}\geq 0$), it is easy to obtain if $\phi<\frac{4\alpha\left(3+8\alpha+4\sqrt{(3+4\alpha)\alpha}\right)}{9}$, $\frac{\partial T_D}{\partial\phi}<0$, otherwise $\frac{\partial T_D}{\partial\phi}\geq 0$.

In the case of $\max\{\underline{c},t_1^d\}\leq c<t_1^n$, $\pi_S^{d*}=0$, then $\Delta\pi_S=\pi_S^{n*}>0$.

Define $\Delta\pi_R=\pi_R^{n*}-\pi_R^{d*}$. We compare the retailer's profits with and without blockchain-enabled disclosure.

In the case of $\underline{c}\leq c<t_1^d$, we have

$$\Delta\pi_R=\frac{\left((4\alpha+\phi)\phi c^2-\alpha\left(2(4+4\alpha+\phi)\phi c+4\phi\alpha^2+\left(4+8\phi+\phi^2\right)\alpha+9\phi\right)\right)(\alpha+\phi)}{4\alpha(4\alpha+3\phi)^2}-\frac{\left((1+4\alpha)c^2-2(4\alpha+5)\alpha c+\left(4\alpha^2+13\alpha+9\right)\alpha\right)(1+\alpha)}{4\alpha(4\alpha+3\phi)^2}.$$

$\Delta\pi_R$ is concave in c. Because of $\Delta=-\left(12\alpha^2+12(1+\phi)\alpha+11\phi\right)(3+4\alpha)^2(4\alpha+3\phi)^2<0$, we have $\Delta\pi_R<0$.

In the case of $\max\left\{\underline{c}, t_1^d\right\} \le c < t_1^n$,

$$\Delta\pi_R = \frac{\left((4\alpha+\phi)\phi c^2 - \alpha\left(2(4+4\alpha+\phi)\phi c + 4\phi\alpha^2 + \left(4+8\phi+\phi^2\right)\alpha + 9\phi\right)\right)(\alpha+\phi)}{4\alpha(4\alpha+3\phi)^2} - \frac{(1+\alpha-c)^2}{4}$$

. Letting $\Delta\pi_R = 0$, we have $c = t_1^n$ and $c = \frac{\left(8\alpha^2 + 6(2+\phi)\alpha + (11-\phi)\phi\right)\alpha}{8\alpha^2 + 6\alpha\phi - \phi^2}$. Clearly, if $8\alpha^2 + 6\alpha\phi - \phi^2 = 0$, $\Delta\pi_R < 0$. If $8\alpha^2 + 6\alpha\phi - \phi^2 > 0$, $\Delta\pi_R$ is concave in c and $t_1^n < \frac{\left(8\alpha^2 + 6(2+\phi)\alpha + (11-\phi)\phi\right)\alpha}{8\alpha^2 + 6\alpha\phi - \phi^2}$, so we have $\Delta\pi_R < 0$. If $8\alpha^2 + 6\alpha\phi - \phi^2 < 0$, $\Delta\pi_R$ is convex in c and $t_1^n > \frac{\left(8\alpha^2 + 6(2+\phi)\alpha + (11-\phi)\phi\right)\alpha}{8\alpha^2 + 6\alpha\phi - \phi^2}$. Substituting $c = \underline{c}$ and $c = t_1^d$ into $\Delta\pi_R$, we obtain $\Delta\pi_R\big|_{c=\underline{c}} = \frac{\alpha(\phi - 4\alpha - 4)(\alpha+\phi)^2}{4(\alpha\phi - \phi - 2\alpha)^2} < 0$ and

$$\Delta\pi_R\Big|_{c=t_1^d} = \frac{\alpha\left(16\alpha^2 + 4(3+4\phi)\alpha + (11+\phi)\phi\right)(\phi-1)}{4(1+2\alpha)^2(4\alpha+3\phi)^2} < 0$$

. Thus, we also have $\Delta\pi_R < 0$.

Therefore, Manufacturer S prefers to invest in blockchain-enabled disclosure if and only if $c < T_D$. And the retailer' prefers to invest in blockchain-enabled disclosure if $c < t_1^n$.

Proof of Proposition 4

Define $\Delta\pi_T = \pi_T^{n*} - \pi_T^{d*}$. We compare Manufacturer T's profits with and without blockchain-enabled disclosure.

In the case of $\underline{c} \le c < t_1^d$, we have

$$\Delta\pi_T = \frac{\left(c\phi + (2-\phi)\alpha\right)^2(\alpha+\phi)}{2(4\alpha+3\phi)^2\alpha} - \frac{(c+\alpha)^2(1+\alpha)}{2(3+4\alpha)^2\alpha}$$

. $\Delta\pi_T$ is concave in c, and $\frac{\partial^2\Delta\pi_T}{\partial c^2} < 0$

. Because of $\Delta\pi_T\big|_{c=\underline{c}} = \frac{\left(12\alpha^3 + 16(1+\phi)\alpha^2 + 4(1+6\phi)\alpha + 9\phi - 1\right)(1-\phi)^2\alpha}{2(3+4\alpha)^2(\alpha\phi - \phi - 2\alpha)^2} > 0$ and

$$\Delta\pi_T\Big|_{c=t_1^d} = \frac{\left(4\alpha + (4-\phi)\phi\right)(1-\phi)\alpha\phi}{2(1+2\alpha)^2(4\alpha+3\phi)^2} > 0$$

, we have $\Delta\pi_T > 0$.

In the case of $\max\left\{\underline{c}, t_1^d\right\} \le c < t_1^n$, we have

$$\Delta\pi_T = \frac{\left(c\phi + (2-\phi)\alpha\right)^2 (\alpha+\phi)}{2(4\alpha+3\phi)^2 \alpha} - \frac{(c-\alpha)(1+\alpha-c)}{2}$$. $\Delta\pi_T$ is convex in c. Letting $\Delta\pi_T = 0$, we have $c = t_1^n$ and $c = \frac{\left(8\alpha^2 + 4(1+2\phi)\alpha + (4+\phi)\phi\right)\alpha}{8\alpha^2 + 8\alpha\phi + \phi^2}$. Because of

$$\frac{\left(8\alpha^2 + 4(1+2\phi)\alpha + (4+\phi)\phi\right)\alpha}{8\alpha^2 + 8\alpha\phi + \phi^2} - t_1^n = \frac{(3\phi+4\alpha)\alpha\phi}{(2\alpha+\phi)\left(8\alpha^2+8\alpha\phi+\phi^2\right)} > 0$$, we have $\Delta\pi_T > 0$.

Therefore, in the presence of blockchain-enabled disclosure, Manufacturer T's profit always decreases.

Proof of Proposition 5

Social welfare is equal to the sum of the retailer's and the two manufacturers' profits and consumer surplus. We use cs and sw to represent consumer surplus and social welfare, and define $\Delta cs = cs^n - cs^d$ and $\Delta sw = sw^n - sw^d$.

By comparing consumer surplus with and without blockchain-enabled disclosure, we have

$$\Delta cs = \frac{1}{2}\left(1+\alpha-p_E^{n*}\right)q_E^{n*} + \frac{1}{2}\left(1-p_T^{n*}\right)q_T^{n*} - \left(\frac{1}{2}\left(1+\alpha-p_E^{d*}\right)q_E^{d*} + \frac{1}{2}\left(1-p_T^{d*}\right)q_T^{d*}\right)$$. In the case of $\underline{c} \le c < t_1^d$,

$$\Delta cs = \frac{\left(4\phi\alpha^3 + \left(4+\phi^2+8(1-c)\phi\right)\alpha^2 + \left(9+4c^2-2(4+\phi)c\right)\phi\alpha + c^2\phi\right)(\alpha+\phi)}{8(4\alpha+3\phi)^2\alpha} - \frac{\left(4\alpha^3 + (13-8c)\alpha^2 + \left(9+4c^2-10c\right)\alpha + c^2\right)(1+\alpha)}{8(3+4\alpha)^2\alpha}$$. We have $\frac{\partial^2 \Delta cs}{\partial c^2} < 0$ and $\Delta = -\left(12\alpha^2 + 12(1+\phi)\alpha + 11\phi\right)(4\alpha+3\phi)^2(3+4\alpha)^2 < 0$. Thus, $\Delta cs < 0$ in this case. In the case of $\max\left\{\underline{c}, t_1^d\right\} \le c < t_1^n$,

$$\Delta cs = \frac{\left(8\alpha^3 + 2(6+3\phi-4c)\alpha^2 + (11-\phi-6c)\alpha\phi + c\phi^2\right)\left(c\phi - 2\alpha^2 - (1-\phi-2c)\alpha\right)}{8(4\alpha+3\phi)^2\alpha}.$$

Letting $\Delta cs = 0$, we have $c = t_1^n$ and $c = \frac{\left(8\alpha^2 + 6(2+\phi)\alpha + (11-\phi)\phi\right)\alpha}{8\alpha^2 + 6\alpha\phi - \phi^2}$. Clearly, if

$8\alpha^2+6\alpha\phi-\phi^2=0$, $\Delta cs<0$. If $8\alpha^2+6\alpha\phi-\phi^2>0$, Δcs is concave in c and $t_1^n<\frac{\left(8\alpha^2+6(2+\phi)\alpha+(11-\phi)\phi\right)\alpha}{8\alpha^2+6\alpha\phi-\phi^2}$, then we have $\Delta cs<0$. If $8\alpha^2+6\alpha\phi-\phi^2<0$, Δcs is convex in c and $t_1^n>\frac{\left(8\alpha^2+6(2+\phi)\alpha+(11-\phi)\phi\right)\alpha}{8\alpha^2+6\alpha\phi-\phi^2}$. Substituting $c=\underline{c}$ and $c=t_1^d$ into Δcs, we obtain $\Delta cs\big|_{c=\underline{c}}=\frac{(\phi-4\alpha-4)(\alpha+\phi)^2\alpha}{8(\alpha\phi-\phi-2\alpha)^2}<0$ and $\Delta cs\big|_{c=t_1^d}=\frac{\left(16\alpha^2+4(3+4\phi)\alpha+(11+\phi)\phi\right)(\phi-1)\alpha}{8(1+2\alpha)^2(4\alpha+3\phi)^2}<0$. Thus, we also have $\Delta cs<0$.

Similarly, we compare social welfare with and without blockchain-enabled disclosure. Let $\Delta sw=\Delta\pi_S+\Delta\pi_T+\Delta\pi_R+\Delta cs$. In the case of $\underline{c}\le c<t_1^d$, we have $\frac{\partial^2\Delta sw}{\partial c^2}<0$ and $\Delta<0$. In the case of $\max\left\{\underline{c},t_1^d\right\}\le c<t_1^n$, $\frac{\partial^2\Delta sw}{\partial c^2}>0$. Letting $\Delta sw=0$, we have $c=t_1^n$ and $c=\frac{\left(8\alpha^2-2(10-11\phi)\alpha-(13-11\phi)\phi\right)\alpha}{8\alpha^2+22\alpha\phi+11\phi^2}$, $t_1^n>\frac{\left(8\alpha^2-2(10-11\phi)\alpha-(13-11\phi)\phi\right)\alpha}{8\alpha^2+22\alpha\phi+11\phi^2}$. And $\Delta sw\big|_{c=\underline{c}}=\frac{\left(4\alpha^2-(12-19\phi)\alpha-(8-11\phi)\phi\right)(\alpha+\phi)\alpha}{8(\alpha\phi-\phi-2\alpha)^2}<0$, $\Delta sw\big|_{c=t_1^d}=\frac{\left(48\alpha^2+4(5+12\phi)\alpha+(13+11\phi)\phi\right)(\phi-1)\alpha}{8(1+2\alpha)^2(4\alpha+3\phi)^2}<0$. Therefore, we obtain $\Delta sw<0$ in both cases.

Proof of Proposition 6

We analyze the impact of blockchain-enabled disclosure on the environment in the region of $c<t_1^n$. By comparing the sales quantities with and without blockchain-enabled disclosure, we have $\Delta E=q_T^{n*}+\gamma q_S^{n*}-\left(q_T^{d*}+\gamma q_S^{d*}\right)$. In the case of $\underline{c}\le c<t_1^d$, if $\frac{\partial\Delta E}{\partial c}>0$, we have $\Delta E\big|_{c=t_1^d}=\frac{\left(2\alpha+(1-\gamma)\phi\right)(\phi-1)\alpha}{2(1+2\alpha)(4\alpha+3\phi)}<0$, $\Delta E<0$. If $\frac{\partial\Delta E}{\partial c}\le 0$ and

$\min\left\{\Delta E\big|_{c=\underline{c}}, \Delta E\big|_{c=0}\right\} > 0$, we have

$$c < \frac{\left(4(2\gamma-1)\alpha^2 + 2\left((4\gamma-1) - 2(1-\gamma)\phi\right)\alpha - 3(1-\gamma)\phi\right)\alpha}{4(2\gamma-1)\alpha^2 - \left(4(1+\phi)\alpha + 3\phi\right)(1-\gamma)} = T_E \text{ and}$$

$\gamma < \dfrac{4\alpha^2 + 2(1+2\phi)\alpha + 3\phi}{8\alpha^2 + 4(2+\phi)\alpha + 3\phi}$. Thus, $\Delta E > 0$. In the case of $\max\left\{\underline{c}, t_1^d\right\} \le c < t_1^n$, $\dfrac{\partial \Delta E}{\partial c} > 0$ and $\Delta E\Big|_{c=t_1^n} = 0$, then we have $\Delta E < 0$. We also obtain

$$\frac{\partial T_E}{\partial \phi} = \frac{2\alpha^2(3+4\alpha)(1+2\gamma)(1-\gamma)}{\left(4(1-2\gamma)\alpha^2 + \left(4(1+\phi)\alpha + 3\phi\right)(1-\gamma)\right)^2} > 0.$$

$\Delta E > 0$ means that the blockchain-enabled sustainability disclosure can benefit the environment.

Appendix B: Derivation of inversed demand functions

The market size is normalized to 1. We assume that there are two types of consumers in the market. The proportion of common consumers is ϕ. Other consumers are skeptical about the product's sustainability information. In the case of blockchain-enabled disclosure, there are no skeptical consumers, that is $\phi = 1$. We use subscripts I and U to denote common and skeptical consumers respectively. The common (skeptical) consumers who purchase a sustainable product obtain the net utility $U_{IS} = (1+\alpha)v - p_S$ ($U_{US} = v - p_S$). The common/skeptical consumers who purchase a traditional product obtain the net utility $U_{IT} = U_{UT} = v - p_T$. All consumers' willingness to pay for the traditional product v is uniformly distributed over $[0,1]$.

In our analysis, we consider cases where the sustainable manufacturer prices the sustainable product higher than the traditional product (i.e., $p_S > p_T$) due to its production cost disadvantages, and it is in line with the relevant case in practice (Yenipazarli & Vakharia, 2015). Intuitively, if $p_S > p_T$, all skeptical consumers buy traditional products. Assume a skeptical consumer who is indifferent between buying the traditional product and being inactive is located at v_U, then $v_U = p_T$. Thus, the demand for the traditional product from skeptical consumers is $(1-\phi)(1-v_U)$. Each common consumer has three options: (i) buy a sustainable product; (ii) buy a traditional product; or (iii) be inactive. Assume a common consumer who is indifferent between buying a sustainable product and a traditional product is located at v_{I1}, then $(1+\alpha)v_{I1}-p_S=v_{I1}-p_T$, which leads to $v_{I1}=(p_S-p_T)/\alpha$. Similarly, assume that a common consumer who is indifferent between buying a traditional product and being inactive is located at v_{I2}, then $v_{I2}-p_T=0$, which leads to $v_{I2}=p_T$.

Therefore, if $v_{I1}\geq v_{I2}$, that is $p_S\geq(1+\alpha)p_T$, all of the three strategies are observed in equilibrium. Then the common consumers who follow strategy (i) value the product more than the common consumers who follow strategy (ii), and the common consumers who follow strategy (ii) value the product more than the common consumers who follow strategy (iii). The demand for the traditional product from common consumers is $\phi(v_{I1}-v_{I2})$. Obviously, all skeptical consumers would buy the traditional product, so the demand for the traditional product from skeptical consumers is $(1-\phi)(1-v_U)$. Therefore, the total demand for the traditional product is $\phi(v_{I1}-v_{I2})+(1-\phi)(1-v_U)$ and $q_T=\phi(v_{I1}-v_{I2})+(1-\phi)(1-v_U)=\phi((p_S-p_T)/\alpha-p_T)+(1-\phi)(1-p_T)$. The demand for sustainable products comes only from common consumers, that is $\phi(1-v_{I1})$. Therefore, $q_S=\phi(1-v_{I1})=\phi(1-(p_S-p_T)/\alpha)$. Solving for p_S and p_T, we obtain if $p_S\geq(1+\alpha)p_T$ which is equivalent to $q_T\geq((1-\phi)q_S)/\phi$, $p_S=(\alpha(\phi-q_S)+\phi(1-q_S-q_T))/\phi$ and $p_T=1-q_S-q_T$.

If $v_{I1}<v_{I2}$, that is $p_S<(1+\alpha)p_T$, which is equivalent to $q_T\leq((1-\phi)q_S)/\phi$, strategy (i) and strategy (iii) of common consumers are observed in equilibrium. In other words, all common consumers will not consider buying traditional products. Assume that the common consumer who is indifferent between buying a sustainable product and being inactive is located at v_I. Then $(1+\alpha)v_{I1}-p_S=0$, which leads to $v_I=p_S/(1+\alpha)$. The demand for sustainable products from common consumers is $\phi(1-v_I)$. And the demand for the traditional product comes only from skeptical consumers, that is $(1-\phi)(1-v_U)$. Therefore, $q_S=\phi(1-p_S/(1+\alpha))$ and

$q_T = (1-\phi)(1-p_T)$. Solving for p_S and p_T, we obtain $p_S = ((1+\alpha)(\phi - q_S))/\phi$ and $p_T = (1-\phi-q_T)/(1-\phi)$.

Combining the above results gives the inverse demand functions, as shown in Equations (1) and (2).

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