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Research Article

Strategic Analysis of the Recycler considering Consumer Behavior Based on E-Platform Recycling

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Internet + platform recycling is a new model of recycling that provides more ways to recycle WEEE. Considering consumers' preference for channels, we construct a single-channel reverse supply chain model (Model-S) and two dual-channel reverse supply chain models (Model-DU and Model-DD) consisting of a recycler and an e-platform and consider the unified pricing and differentiated pricing strategies in the dual-channel models. By solving the optimal decisions of members using game theory, we innovatively investigate the influence of channel competition and consumer behavior on e-platform recycling and provide a theoretical basis for recyclers to develop pricing strategies in different situations. We find that it is beneficial for the recycler to build its own channel and adopt the differentiated price strategy (Model-DD); more WEEE also can be recycled in this model. However, the e-platform prefers Model-S or Model-DU, which depends on the consumers' preference and the disposal revenue of WEEE. In addition, consumers' preference for e-platform is good for them but harmful for the recycler and has a negative impact on recycling quantities. These results aim to provide a theoretical basis for channel management and pricing strategies in the reverse supply chain and further enrich the managerial insights.

1. Introduction

Waste Electrical and Electronic Equipment (WEEE) are discarded devices and appliances that use electricity, such as computers, mobile phones, and refrigerators [1]. With the acceleration of the replacement of electronic products, the amount of WEEE has shown rapid growth in general. In 2016, the global amount of electronic waste (e-waste) was approximately 44.7 million metric tons (Mt) and is expected to grow to 52.2 million Mt in 2021. The annual growth rate has reached 3% to 4%, but less than 20% can be effectively recovered [2]. Randomly discarded e-waste will cause serious environmental pollution (on air, dust, soil, sediments, plants, and so on), which poses a threat to human health [3, 4]. The recycling of e-waste is essential to the sustainable development of the electronics industry as a secondary source of critical metals, and it will contain greater recycling value with improvement in science and technology [5–7]. Under the dual effects of resource sustainability and environmental hazards, the recycling and reuse of WEEE should be taken into account.

However, as the top e-waste producer in the world, less than 20% of the WEEE generated in China has been documented to be recycled in recent years [2]. According to a survey conducted in Zhuhai, more than 50% of the residents tended to store wasted mobile phones at home rather than recycling; price and convenience were found to be the primary factors that affected residents' willingness to participate in recycling [8]. The "Internet + recycling" model has the advantages of eliminating information asymmetry, reducing transaction costs, and expanding the scope and scale of recycling; it is more convenient than traditional methods. To promote the innovation of recycling models and explore the "Internet + recycling" model, China has also issued a series of policy guidelines, such as the 2015 Circular

Economy Promotion Plan, which accelerates the process of Internet + recycling in China [9].

With the development of big data and Internet technology, e-platforms have arisen in a new stage of rapid development and provide new ideas for WEEE recycling [10]. With the opening of the e-platform to third-party merchants, many recyclers have begun to enter the e-platform for recycling. For example, a specialized recycling business sector, Paipai, is opened on JD Mall (https://www.jd.com/), served by Aihuishou, Yifeng.com, and so on. In uSell (https://www.usell.com/), sellers can publish second-hand electronic products on the website, and qualified buyer agencies will bid on the e-platform. This is a way of ordering online and recycling offline. Firstly, users place their orders online and describe the condition of the electronic product on the e-platform. Then the recycler gives the price evaluation based on the description. After consumers accept the price and submit used products, they will be paid by the recycler in the form of third-party payment, and the e-platform earns the commission from each order for providing trading service, as shown in Figure 1.

In addition to recycling through the e-platform, recyclers can also open a direct online recycling channel, which has certain requirements for technology and capital. A self-built recycling channel is direct to customers without paying other third-party fees. For example, as China's largest recycler of second-hand 3C electronic products, Aihuishou not only has direct recycling channels but also cooperates with JD Mall and Huawei Mall to boost its recycling business. However, the addition of a direct recycling channel will inevitably lead to competition between channels. It is also an issue for the recycler to set recycling prices when there are multiple recycling channels. Generally speaking, recyclers usually pay consumers based on the residual value of used products. For example, Aihuishou will set the same recycling price on its official website and on the Paipai for products of the same quality. On the other hand, recyclers will also weigh the costs of different channels to set the price. For example, online recycling prices are usually higher than offline stores. Under the background of the coexistence of various recycling forms, the fundamental challenge faced by recyclers is how to manage recycling channels and formulate scientific price strategies, to achieve economic and environmental sustainability. Should recyclers build direct recycling channels? And if so, how should they set recycling prices for different channels? Answering these questions is critical to the development of the recycling industry.

In the dual-channel reverse supply chain, consumers' preference for recycling channels affects the decision-making of recyclers and the supply chain performance. When dual recycling channels exist, the e-platform can attract consumers by providing better recycling services, allowing consumers to inquire about past transactions before placing an order and making correct decisions [11, 12]. In the research, we introduce consumers' preferences for channels and construct three reverse supply chains to focus on the recycler's channel selection and pricing strategies using game theory. The following questions are attempted to be answered: (1) which recycling model is superior for enterprises and the supply chain? (2) How do consumers' preferences and channel competition affect the decision-making of the recycler and e-platform, as well as the supply chain performance? (3) Which recycling pricing strategy is better in the dual-channel reverse supply chain?

The primary contributions of this article are summarized as follows:

(i) In the context of e-platform recycling, we build a single-channel reverse supply chain model and two dual-channel reverse supply chain models and examine the impact of channel conflict on pricing strategy, extending previous research.

(ii) There are few studies on whether price discrimination in the reverse supply chain is effective. This article considers the pricing strategy of the recycler for different recycling channels to provide a basis for recyclers to formulate unified or differentiated prices strategy.

The rest of article is organized as follows. A related literature review is provided in Section 2. Section 3 gives the problem statement, assumptions, and notation, and three reverse supply chain models are constructed and solved using the Stackelberg game. Section 4 analyzes and compares equilibrium solutions and further discusses in terms of consumer surplus, environmental benefits, and corporate profits. Based on the results, managerial insights and practical implications are given in Section 5. Finally, conclusions and outlook are given.

2. Literature Review

In this section, we mainly focus on three streams of the related literature: reverse supply chain channel management, reverse supply chain pricing strategy, and consumer behavior.

2.1. Reverse Supply Chain Channel Management. Effective recycling channels for consumers to return WEEE are the key to improving recycling rates. So, some research has focused on the collection models under different situations. Savaskan et al. [13] and Ma et al. [14] studied closed-loop supply chain models with different single reverse channels. They showed that the retailer (agent) was the most effective undertaker of recycling. Chuang et al. [15] extended the research of Savaskan et al. [13] and found that the cost of recycling will affect the manufacturer's best recycling channel choice. Tirkolaee et al. [16] designed a sustainable mask closed-loop supply chain network during the COVID-19 pandemic and found that the costs of supply chain can be reduced by using recycling operations. Lotfi et al. [17] proposed medical waste chain network design that considers resiliency and sustainability. Gu et al. [18] explored that the manufacturer is more willing to recycle directly instead of entrusting others if processed by itself. And increasingly, studies have expanded from single recycling channels to dual recycling channel situation. Whether a dual recycling

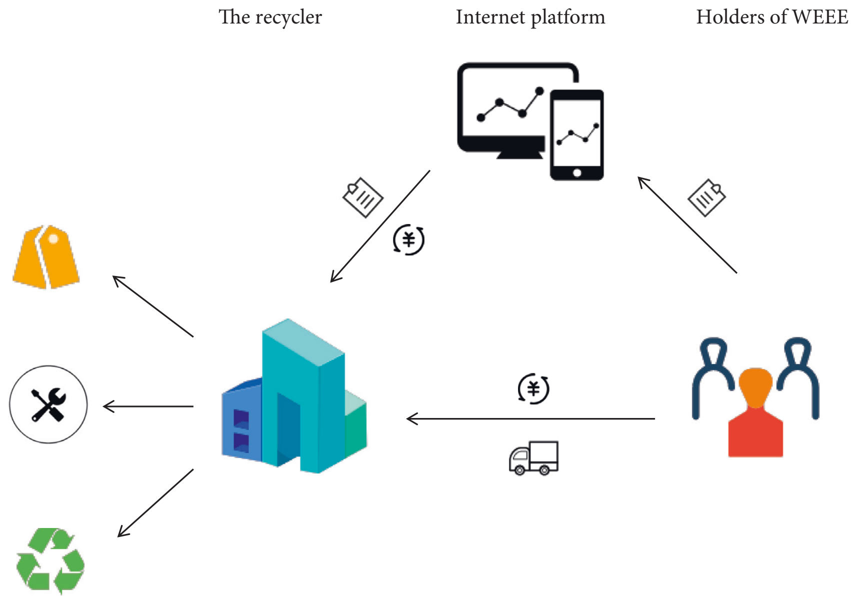

Figure 1: Reverse supply chain with E-platform channel.

channel outperforms a single-channel depends on the competitive intensity, dual-channel recycling is better than single-channel recycling only when the competition in dual channels is not very intense [19, 20]. Hong et al. [20] and Liu et al. [21] extended this and introduced hybrid dual-channel recycling modes (manufacturer and retailer dual recycling model, retailer and third-party dual recycling model, manufacturer and third-party dual recycling model, respectively) into the closed-loop supply chain. Under the same condition, the amounts that the manufacturer and retailer collected together was superior to that of the other two models and single-channel recycling model.

The studies above focus on traditional recycling modes; with the rise in "Internet + recycling," many studies have expanded from traditional recycling channels to online. Feng et al. [22] derive that the online recycling channel can serve as a lever to force the recycler to enhance the recycling price in traditional recycling channels and help the dealer and the supply chain improve profits. However, Li et al. [23] discovered that the introduction of an online channel can be beneficial or harmful and the mixed recycling channels model may be worse off than the single offline recycling channel model in terms of system profit. Chen et al. [24] developed a dual-channel reverse supply chain by introducing online recycling channels based on offline TPRs, uncovering that the benefits of recycling centers are affected by consumer sustainability awareness and the logistics costs of the online channel.

E-platform can use data collection and analysis to provide personalized and targeted promotional services through segment customers [25]; it also plays an increasingly important role in the reverse supply chain. Xiang and Xu [26] found that enterprises could obtain higher goodwill through cooperation with Internet service platforms. Ren et al. [27] explored a cooperative relationship between the manufacturer and Internet sharing platform that purchases new products from the manufacturer and leases products to customers in two structures, without and with recycling, and the results showed that the cooperative model was superior to the noncooperative model in terms of profitability and services for both parties. Wang et al. [28] developed a low-carbon e-commerce closed-loop supply chain (LCE-CLSC) consisting of the remanufacturer and the e-commerce platform and found that the altruistic preference behavior increases the revenue of the e-platform and improves the efficiency of the LCE-CLSC. Based on "Internet + recycling", Jian et al. [29] proposed collection effort cost-sharing mechanisms to optimize the collaborative recycling strategy between a third-party collector and an e-business platform, finding that it is more profitable for the collector and the e-business platform to share a portion of the other's collection investments under the cooperative mode. Zhang et al. [30] considered the technological innovation of a third-party Internet recycling platform and found that carbon reduction was better when the third party leads recycling.

2.2. Reverse Supply Chain Pricing Strategy. The price strategy of the reverse supply chain is closely related to the recycling volume, corporate profit, and consumer welfare, and many scholars have conducted in-depth studies on it. Giri et al. [31] investigated the optimal pricing strategy for the dual-channel closed-loop supply chain when a different member of the supply chain is dominant (e.g., manufacturer, retailer, and third-party) and found that higher profit can be achieved when the retailer is dominant. Ranjbar et al. [32] reached a similar conclusion. In addition, some scholars have also studied the influence of product quality and consumers' bargaining power on dual-channel reverse supply chain pricing decisions [33–35].

With the emergence of Internet platforms in the reverse supply chain, several scholars have studied the pricing decisions under this recycling model [26, 28, 36, 37]. However, related studies have mainly focused on qualitative analysis or single-channel recycling and mostly have been conducted on (re)manufacturers and retailers. In fact, third-party recycling is a more common model and competition between recycling channels is widespread. In particular, regarding the pricing strategy of the dual-channel reverse supply chain, most studies focus on the form of separate pricing for different recycling channels, while in real life, some specialized and large-scale recycling enterprises adopt a uniform pricing model, and this pricing strategy also needs our attention.

2.3. Consumer Behavior. Consumer behavior can affect the choice of reverse supply chain and enterprises' decision-making. In the multichannel reverse supply chain, recyclers in different channels will adopt some strategies to attract consumers, such as recycling price, service level, and channel convenience [38]. Wang et al. [39] built an extended theory of planned behavior (TPB) theoretical framework to find that perceived behavior control, subjective norms, attitudes, and economic motivation had a significant positive impact on residents' willingness to participate in online recycling. With the development of the Internet + recycling, online recycling with more convenience and privacy attracts increasing concern. The recycling price has no longer the only factor that affects consumers' recycling decisions; this also affects the decision-making of recyclers. He et al. [40] found that the convenience of channel has an impact on recycling efficiency. Wang et al. [11] constructed a closed-loop supply chain composed of a manufacturer, a retailer, and a third-party platform.

Preference for third-party recycling platforms will affect the price decisions of retailers and third-party recycling platforms. Kang et al. [12] studied the dual-channel recycling problems based on different regions and found the changes in consumers' preference for the online channel have an effect on optimal decisions and profits of multiregion recycling companies. Feng et al. [22] established a two-stage reverse supply chain model composed of a recycler and a dealer, which involves a traditional channel and online channel. They find that consumers' preference for online recycling channels will affect dealer's choice of coordination mechanisms. Li and Feng [41] discovered that there exists a Pareto interval with respect to consumers' preference for the online channel, which makes the profits of WEEE disposers and collectors under the dual recycling channel higher than the corresponding profits under the single recycling channel. Unlike the above studies, we study the impact of consumers' preferences not for the online channel but for the e-platform channel on firms' pricing decisions, to further balance the profitability of the dual channels.

The above literature has primarily considered the traditional, self-built online recycling model or single-channel reverse supply chain with e-platform participation; few studies have considered competition in the context of e-platform recycling and unified pricing strategy. The more relevant article to our research is the study by Wang et al. [28]; however, they do not consider reverse channel competition and the resulting consumers' preference for channels. In this article, we build the single-channel reverse supply chain model and the dual-channel reverse supply chain models consisting of the recycler and the e-platform. In the dual-channel reverse supply chain, we investigate the impact of the recycler's pricing strategy (unified and differentiated) on supply chain performance. A brief summary of the literature review is shown in Table 1 to clarify the novelty of this research.

3. Problem Statement

3.1. Problem Statement. Three reverse supply chain models are developed in this study, as shown in Figure 2. (1) Single-channel recycling model (Model-S), the recycler only recycles WEEE through the e-platform channel. The recycler pays commissions to the e-platform for unit recycling WEEE and gains profits through further processing of WEEE. This pattern is becoming increasingly common with the development of the Internet platform. (2) For the dual-channel recycling model with unified prices (Model-DU), in this model, the recycler builds own recycling channel in addition to settling in the e-platform. The recycler sets the same recycling price for the same quality of used electronics for different channels. (3) For the dual-channel recycling model with differentiated prices (Model-DD), the only difference from Model-DU is that the recycler price of the two channels separately and the recycling prices of the self-built channel and the e-platform channel are p_r and p_p respectively. The related symbols used in this article are summarized in Table 2.

3.2. Assumptions. Assume that the recycling volume is a linear function with respect to recycling price: in Model-S, $q = S + ap_p$. When there are two recycling channels, the recycling volume of one channel is influenced not only by the recycling price of its own channel but also by the recycling price of another channel. In the Model-DD, the demand functions with respect to the recycling prices can be given by the following [42]:

$$\begin{aligned} q_p &= \theta S + a p_p - b\left(p_r - p_p\right), \\ q_r &= (1-\theta)S + a p_r - b\left(p_p - p_r\right), \end{aligned} \tag{1}$$

where θ denotes the consumers' preference for the e-platform channel and $1-\theta$ represents consumers' preference for the self-built channel, $0 < \theta < 1$. In Model-S, there is no consumer preference. b can be explained as the competition intensity between channels.

In the e-platform channel, the total expenditure of the recycler is the sum of recycling price and commission; that is $\omega = p^p + m$; the decision variable of the e-platform is commission (m). To simplify the calculation, use ω as the decision variable of the recycler. Then the demand function under the single-channel recycling model can be further expressed as follows:

$$q = S + a(\omega - m). \tag{2}$$

Table 1: Summarized literature review.

Reference	Structure of supply chain		Channel selection	Number of reverse channels		Members					Pricing strategy of two channels	
	Reverse supply chain	Closed-loop supply chain		1	2	Third-party recycler	Manufacturer	Retailer	E-platform	Recycling center	Unified	Differentiated
Savaskan et al. [13]		√	√	√		√	√	√				
Ma et al. [14]		√	√	√		√	√	√				
Huang et al. [19]		√			√	√	√	√				√
Giri et al. [31]		√			√	√	√	√				√
Liu et al. [33]	√				√	√						√
Feng et al. [22]	√		√	√	√	√						√
Li et al. [23]	√		√	√	√	√	√					√
Xiang and Xu [26]		√		√			√	√	√			
Ren et al. [27]		√		√			√		√			
Wang et al. [28]		√		√			√		√			
Jian et al. [29]	√				√	√		√	√			
Chen and Gao [36]		√	√	√		√	√		√			
Ma and Hu [37]		√		√			√	√	√			
Chen et al. [24]	√		√	√	√	√				√	√	√
This paper	√		√	√	√	√			√		√	√

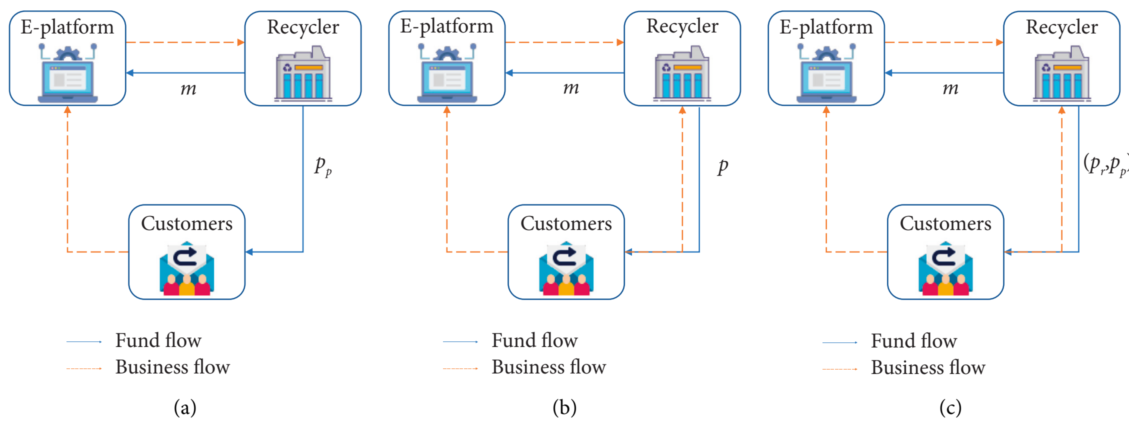

Figure 2: Schematic diagram of the reverse supply chain. (a) Single channel. (b) Dual channel with unified pricing. (c) Dual channel with differentiated pricing.

Table 2: Description of the symbols of this article.

Symbols	Description
Indices	
i	Index of recycling models, $i \in \{S, DU, DD\}$
j	Index of recycling channels, $j \in \{p, r\}$
Superscripts/subscripts	
S, DU, DD	Single-channel recycling model, dual-channel recycling model with unified pricing and dual-channel recycling model with differentiated pricing, respectively
p, r	E-platform channel and self-built channel, respectively
$i*$	Optimal values for model i
Parameters	
S	Basic recycling members when recycling price is zero
a	Elasticity coefficient of the recycling price
b	Elasticity coefficient of the cross recycling price
θ	The consumers' preference for platform channel
Δ	The recycler's unit profit by processing WEEE
Decision variables	
ω	Total payment of the recycler
m	Commission charged by the e-platform
p_r	Recycling price of the self-built channel
Derived functions	
q_j^i	Recycling volumes of channel j in model i
q^i	Total recycling volumes in model i
π_r^i	Profit of the recycler in model i
π_p^i	Profit of the e-platform in model i
π^i	The profit of the reverse supply chain in model i

The demand functions under the dual-channel recycling models can be expressed as follows:

$$\begin{aligned} q_p &= \theta S + a(\omega - m) - b(p_r - \omega + m), \\ q_r &= (1-\theta)S + a p_r - b(\omega - m - p_r). \end{aligned} \tag{3}$$

Assumption 1. The recycler and the e-platform play a Stackelberg game, and the recycler serves as the game leader. Both parties are rational completely; they make decisions to maximize their own profits.

Assumption 2. E-platform merchant entry fees usually include an annual fee, deposit, and commission, since the annual fee and deposit are one-time and have no effect on the results; therefore, they are set to 0e

Assumption 3. Assume that the basic recycling volume under the single-channel and dual-channel recycling models are equal, and the recycled wasted electronic products have homogeneity.

Table 3: The optimal decisions in Model-S, Model-DU, and Model-DD.

	Model-S	Model-DU	Model-DD
Recycling price of e-platform channel	$(a\Delta - 3S)/4a$	$(2a\Delta - (1+2\theta)S)/6a$	$((-a(3a+4b)\theta - 2(a+b)b)S + a(a+2b)^2\Delta)/4a(a+b)(a+2b)$
Recycling price of self-built channel	n/a	$(2a\Delta - (1+2\theta)S)/6a$	$((a\theta - a - b)S + a(a+2b)\Delta/2a(a+2b)$
E-platform's commission	$(S+a\Delta)/4a$	$(2a\Delta + (4\theta - 1)S)/6a$	$(\theta S + a\Delta)/4(a+b)$
Recycling quantity of WEEE	$(S+a\Delta)/4$	$(2a\Delta + 2(1-\theta)S)/3$	$(-a\theta + 2(a+b)]S + a(3a+4b)\Delta)/4(a+b)$
E-platform's profit	$(S+a\Delta)^2/16a$	$(2a\Delta + (4\theta - 1)S)]^2)/36a$	$(\theta S + a\Delta)^2/16(a+b)$
Recycler's profit	$(S+a\Delta)^2/8a$	$(4a^2\Delta^2 - 8a(\theta - 1)S\Delta - (8\theta^2 - 4\theta - 1)S^2/12a$	$(a(a+2b)(a(3a+4b)\Delta^2 + (4(a+b) - 2a\theta]\Delta S)$ $+(a((3a+2b)\theta^2 - 4(a+b)\theta) + 2(a+b)^2)S^2)/8a(a+b)(a+2b)$
Profit of the reverse supply chain	$3(S+a\Delta)^2/16a$	$[a\Delta + (1-\theta)S][4a\Delta + (1+2\theta)S]/9a$	$(a(a+2b)(a(7a+8b)\Delta^2 + (8(a+b) - 2a\theta]\Delta S)$ $+(a((7a+6b)\theta^2 - 8(a+b)\theta) + 4(a+b)^2)S^2/16a(a+b)(a+2b)$

Assumption 4. In addition to the recycling price and platform commission, other recycling costs (such as logistics cost and testing cost) are not considered.

3.3. Models and Solution. In this section, three reverse supply chain models are constructed and solved; optimal recycling prices, optimal recycling volumes, and optimal profits are calculated.

3.3.1. Model-S. In the Model-S, customers can participate in recycling only through the e-platform. The profit functions of the recycler and the e-platform are formulated as follows:

$$\begin{aligned}\pi_r^S(\omega) &= (\Delta - \omega)[S + a(\omega - m)],\\ \pi_p^S(m) &= m[S + a(\omega - m)].\end{aligned} \tag{4}$$

The recycler, as the leader, decides ω first; the e-platform then decides the commission m. Note that $d^2\pi_p^S(m)/dm^2 = -2a < 0$, $\pi_p^S(m)$ is a concave function of m. Therefore, we can derive the e-platform's best response is as follows:

$$m = \frac{S + a\omega}{2a}. \tag{5}$$

By substituting equations (5) into (6), it is easy to find that $\pi_r^S(\omega)$ is a concave function of ω. According to the first-order condition of $\pi_r^S(\omega)$ with respect to ω, we derive that

$$\omega^{S*} = \frac{a\Delta - S}{2a}. \tag{6}$$

After substituting equations (6) into (5), the e-platform's optimal decision and optimal recycling price can be calculated as follows:

$$\begin{aligned}m^{S*} &= \frac{S + a\Delta}{4a},\\ p_p^{S*} &= \omega^{S*} - m^{S*} = \frac{a\Delta - 3S}{4a}.\end{aligned} \tag{7}$$

3.3.2. Model-DU. In the Model-DU, the e-platform channel and self-built channel exist simultaneously; the recycling prices of the two channels are equal and expressed as follows: $p = p_r = p_p = \omega - m$. Profit functions of the recycler and the e-platform are as follows:

$$\begin{aligned}\pi_r(\omega) &= (\Delta - \omega)[\theta S + a(\omega - m)]\\ &\quad + [\Delta - (\omega - m)][(1-\theta)S + a(\omega - m)],\\ \pi_p(m) &= m[\theta S + a(\omega - m)].\end{aligned} \tag{8}$$

The optimal decisions of the recycler and the e-platform can be obtained in Table 3 by backward induction.

3.3.3. Model-DD. In the Model-DD, consumers can also participate in recycling through the e-platform channel or self-built channel. Different from Model-DU, the recycler can develop different recycling prices for different channels. The profit functions of the recycler and the e-platform are given by

$$\begin{aligned}\pi_r(\omega, p_r) &= (\Delta - \omega)[\theta S + a(\omega - m) - b(p_r - \omega + m)]\\ &\quad + (\Delta - p_r)[(1-\theta)S + ap_r - b(\omega - m - p_r)],\\ \pi_p(m) &= m[\theta S + a(\omega - m) - b(p_r - \omega + m)].\end{aligned} \tag{9}$$

At first, the recycler determines ω and the recycling price of the self-built channel p_r. Then, the e-platform determines commission m based on the decisions of the recycler.

Note that $d^2\pi_p/dm^2 = -2(a+b) < 0$, where $\pi_p(m)$ is a concave function of m. Therefore, we can derive the e-platform's best response is

$$m = \frac{\theta S + (a+b)\omega - bp_r}{2(a+b)}. \tag{10}$$

By substituting the equations (10) into (14), we get the Hessian matrix of $\pi_r(\omega, p_r)$ as

$$H(\omega, p_r) = \begin{bmatrix} \dfrac{\partial^2\pi_r}{\partial\omega^2} & \dfrac{\partial^2\pi_r}{\partial\omega\,\partial p_r}\\[2ex] \dfrac{\partial^2\pi_r}{\partial p_r\partial\omega} & \dfrac{\partial^2\pi_r}{\partial p_r^2}\end{bmatrix} = \begin{bmatrix} -(a+b) & b\\[2ex] b & \dfrac{-\left(2a^2 + 4ab + b^2\right)}{a+b}\end{bmatrix}. \tag{11}$$

Since $\partial^2\pi_r/\partial\omega^2 < 0, \partial^2\pi_r/\partial p_r^2 < 0, |H(\omega, p_r)| = 2a(a+2b) > 0$, $\pi_r(\omega, p_r)$ is a joint concave function of ω and p_r. The optimal decisions of the recycler can be obtained from the first-order condition as

$$\omega^{DD*} = \frac{-(a\theta + b)S + a(a+2b)\Delta}{2a(a+2b)}, \tag{12}$$

$$p_r^{DD*} = \frac{(a\theta - a - b)S + a(a+2b)\Delta}{2a(a+2b)}. \tag{13}$$

The optimal commission can be obtained by substituting the equations (12) and (13) into (10):

$$\begin{aligned}m^{DD*} &= \frac{\theta S + a\Delta}{4(a+b)},\\ p_p^{DD*} &= \omega^{D*} - m^{D*}\\ &= \frac{[-a(3a+4b)\theta - 2(a+b)b]S + a(a+2b)^2\Delta}{4a(a+b)(a+2b)}.\end{aligned} \tag{14}$$

Substituting the optimal decisions under the three models into the demand functions and profit functions, the optimal recycling quantities and profits of the supply chain can be further obtained; all optimal solutions are shown in Table 3.

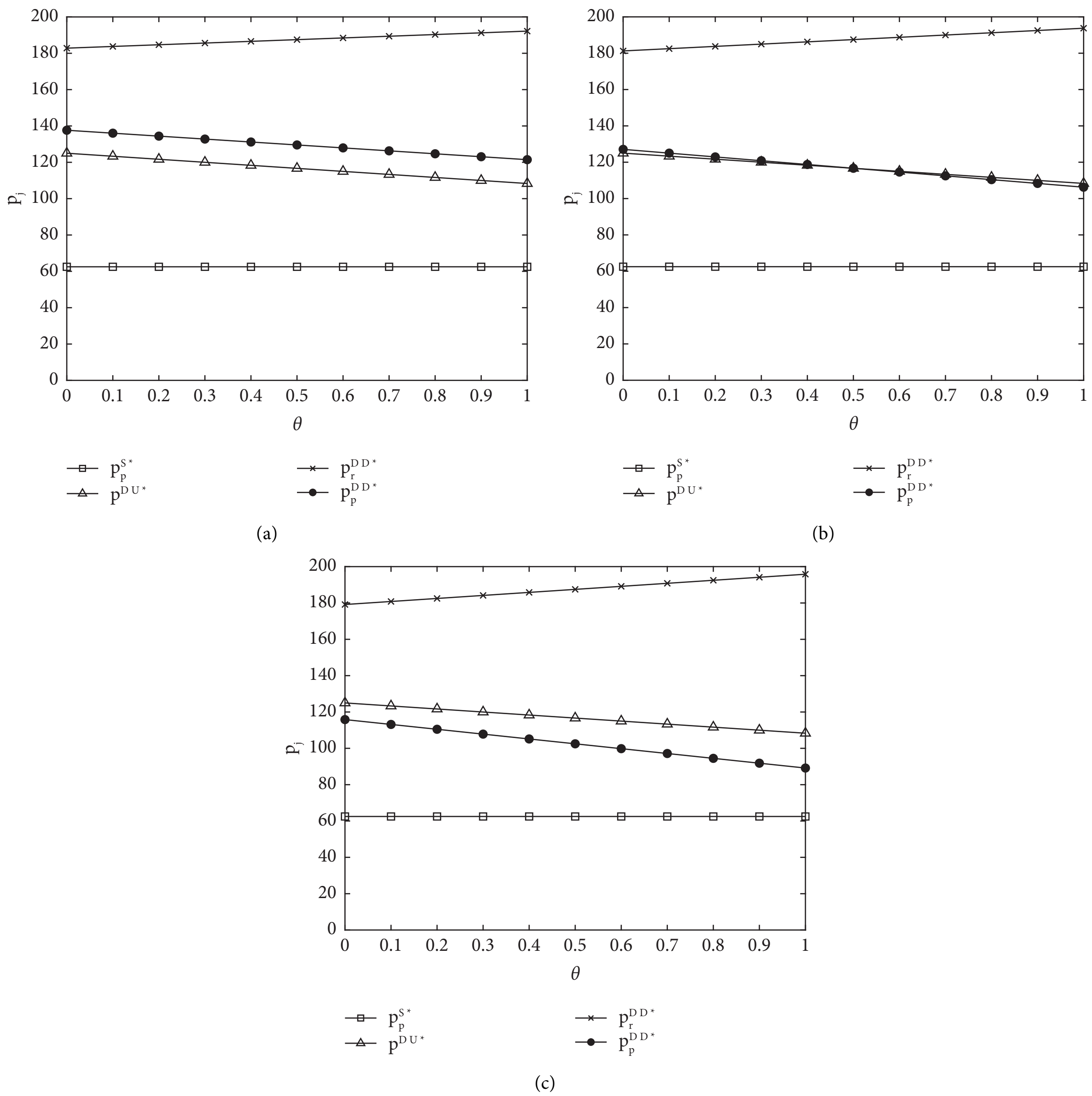

Figure 3: Comparison of optimal recycling prices among three models: (a) $b = 0.5$; (b) $b = 0.3$; (c) $b = 0.15$.

4. Results

4.1. Sensitivity Analysis

Proposition 1. *In the Model-S, Model-DU, and Model-DD, $m^{i*}, p_j^{i*}, q^{i*}, \pi_j^{i*}, \pi^{i*}$ are increasing and convex functions with respect to Δ.*

Proposition 1 can be obtained by the first and second derivatives of the equilibrium solutions under three models with respect to Δ. Proposition 1 shows that the high disposal revenue of WEEE makes the recycler increase the recycling price to attract consumers to participate in recycling. With the same minimum price accepted by consumers, consumer surplus increases and more WEEE can be recycled, resulting in higher profits for the recycler and the e-platform. In other words, high processing revenue is beneficial to the enterprises, consumers, and environment, and this positive effect is marginally increasing. Therefore, recyclers should make efforts in promoting recycling technologies, optimizing recycling process for a higher benefit.

Proposition 2. *In the Model-DU and Model-DD, m^{i*}, p_r^{DD*} are increasing functions with respect to θ and $p_r^{DU*}, p_p^{i*}, q^{i*}$ are decreasing functions with respect to θ.*

Proposition 2 can be obtained by the first derivative of the optimal results with respect to θ in the Model-DU and Model-DD. It is obvious that when consumers show a higher preference for e-platform recycling channels, the e-platform will charge higher commission. In order to reduce the recycling cost, the recycler will uniformly reduce the recycling price of both channels in the Model-DU. And in the Model-DD, the recycler will increase the recycling price of the self-built channel while reducing the recycling price of the platform channel. In short, as consumers' preference for e-platform channels increases, the recycler will face higher recycling costs. This leads to a reduction in recycling volume and poses a threat to recycling efficiency and environmental sustainability.

Proposition 3

(1) *In the Model-DU and Model-DD, π_p^{i*} is an increasing and convex function with respect to θ, π_r^{DU*}, π^{DU*} are decreasing and concave functions with respect to θ, and π_r^{DD*} is a decreasing and convex function with respect to θ.*

(2) *If $\Delta < (3a+2b)S/a(a+2b)$ and $\theta > \theta^*$ are satisfied, π^{DD*} is an increasing function with respect to θ; otherwise, π^{DD*} is a decreasing function with respect to θ. $\theta^* = (a(a+2b)\Delta + 4(a+b)S)/(7a+6b)S$.*

Proof of Proposition 3. See Appendix

Proposition 3 shows that consumers' preference for the e-platform channel is beneficial to the e-platform but harmful to the recycler because the recycler needs to pay higher commissions. With the increase in consumers' preference for e-platform, this positive effect is more pronounced for the e-platform. But for the recycler, there are different scenarios: in the Model-DU, the recycler's profit decreases faster as θ increases; on the other hand, in the Model-DD, the recycler can use a differentiated pricing strategy to reduce losses. This also reflects the flexibility and environmental adaptability of Model-DD.

In addition, the supply chain profit in the Model-DU is negatively correlated with θ. While in the Model-DD, when the disposal revenue of WEEE is low and consumers' preference for e-platform channel is beyond the threshold θ^*, the supply chain profit is positively related to θ, vice versa. In short, in the dual-channel reverse supply chain, recyclers should build an effective self-built channel to attract consumers by improving service quality and optimizing recycling process instead of relying solely on e-platforms.

Proposition 4. *(1) m^{DD*} is a decreasing function with respect to b.*

(2) *If $\theta < 1/2$, p_r^{DD*} is an increasing function with respect to b; otherwise, p_r^{DD*} is a decreasing function with respect to b. If $\{\Delta < 2(a+b)^2S/a(a+2b)^2\} \cap \{\theta < \overline{\theta}\}$ are satisfied, p_p^{DD*} is a decreasing function with respect to b; otherwise, p_p^{DD*} is an increasing function with respect to b. $\overline{\theta} = (2(a+b)^2S - a(a+2b)^2\Delta)/(5a^2+12ab+8b^2)S < 1/2$.*

(3) *q_p^{DD*} is independent of b, and q_r^{DD*}, q^{DD*} are increasing functions with respect to b.*

Proof of Proposition 4. See Appendix .

Proposition 4 demonstrates how the recycler and the e-platform respond to changes in competition intensity between channels. Firstly, as the competitive intensity between channels increases, the commission charged by the e-platform always decreases. Secondly, recycling prices in different channels are related to consumers' preference for channels and the disposal revenue of WEEE. When consumers prefer the self-built channel, as competition intensity between channels increases, the recycler will increase the recycling price of a self-built channel to attract consumers and will also increase the recycling price of the e-platform channel when the recycler is profitable. On the contrary, when consumers prefer the e-platform channel, the recycler will reduce the recycling price of their own channel and increase the recycling price of the e-platform channel, relying on the platform's customer resources to recycle more WEEE. In addition, $\overline{\theta}$ is negatively correlated with b; in other words, when the channel competition is fierce, the recycler is more likely to increase recycling prices of both channels even if consumers' preference for the e-platform channel is low because this can diminish the price difference and weaken channel conflict.

Therefore, in the dual-channel reverse supply chain, the recycler needs to comprehensively consider the consumers' preferences and profit of the recycling industry to formulate the optimal pricing strategy in a different competitive environment. In addition, channel competition also positively impacts the recycling quantities of the reverse supply chain. To realize a circular economy, the government should encourage recyclers to build their own recycling channels and guide orderly competition in the recycling market.

Proposition 5. *When $\{\sqrt{10}/10a < b < \sqrt{3}/3a\} \cap \{\theta < \theta_0\}$ or $b > \sqrt{3}/3a$ is satisfied, $p_p^{S*} < p^{DU*} < p_p^{DD*} < p_r^{DD*}$; otherwise, $p_p^{S*} < p_p^{DD*} < p^{DU*} < p_r^{DD*}$. $\theta_0 = (2(a^2-b^2)S + a(4b^2-a^2)\Delta/(5a^2-8b^2)S$.*

Proof of Proposition 5. See Appendix .

Proposition 5 indicates that the recycling price of the dual-channel recycling model are higher than that of the single-channel recycling model. Thus, the competition between channels is conducive to improving consumer surplus. In the Model-DD, the recycler will provide the highest recycling price among the three models. When the competition intensity between channels is relatively low ($b < \sqrt{10}/10a$), p^{DU} is higher than p_p^{DD*}, because when the channel competition is not too fierce, the recycler has no greater willingness to raise prices, and a unified pricing strategy forms certain constraints and avoids negative pricing by the recycler. When the competition intensity between channels is relatively high ($b > \sqrt{3}/3a$), p_p^{DD*} is higher than p^{DU}, because a differentiated pricing strategy can flexibly adapt to changes in the competitive environment. When the competition intensity between channels is moderate ($\sqrt{10}/10a < b < \sqrt{3}/3a$), if consumers have a low preference for the e-platform channel, p_p^{DD*} is higher than p^{DU}; otherwise, p^{DU} is higher.

It can be seen from $\partial\theta_0/\partial b = 12a^2b(2a\Delta + S)/(5a^2 - 8b^2)^2 S > 0$ that the threshold, θ_0, increases as b increases, showing that the price advantage in the Model-DU continues to weaken as the competition intensity between channels increases. As shown in Figure 3 ($S = 30$, $a = 0.6$, $\Delta = 400$), $p_p^{DD\,*}$ decreases faster than $p^{DU\,*}$. When competition intensity between channels is moderate, there exists a point of intersection with respect to the consumers' preference for channels, which means the price advantage of $p_p^{DD\,*}$ gradually decreases with θ increases.

Proposition 6

(1) $\pi_r^{S\,*} < \pi_r^{DU\,*} < \pi_r^{DD\,*}$

(2) If $\{\Delta < 5S/a\} \cap \{\theta < \theta_1\}$ *is satisfied,* $\pi_p^{DD\,*} < \pi_p^{DU\,*} < \pi_p^{S\,*}$*; otherwise,* $\pi_p^{DD\,*} < \pi_p^{S\,*} < \pi_p^{DU\,*}$. $\theta_1 = (5S - a\Delta)/8S$.

(3) $\pi^{S*} < \pi^{DU\,*}$, $\pi^{S*} < \pi^{DD\,*}$.

Proof of Proposition 6. See Appendix .

Proposition 6 (1) shows that the recycler's profit in the Model-DD is the highest among three model, in other words, it is beneficial for the recycler to build its own channel. At the same time, a differentiated pricing strategy can provide the recycler with a larger pricing space, to obtain higher profit, as shown in Figure 4 (the parameter values are $S = 30, a = 0.6,\ b = 0.3, \Delta = 400$). Moreover, the recycler's optimal profit under Model-DU is more susceptible to changes in consumers' preferences than Model-DD. This illustrates that Model-DD enables the recycler to adjust its own decisions in accordance with external changes to avoid greater profit losses.

For the e-platform, the Model-DD is always unfavorable because the e-platform is at a disadvantage in channel competition. When the disposal revenue of WEEE and consumers' preference for e-platform is low, Model-S is better for the e-platform; otherwise, Model-DU is preferable, as shown in Figure 5 ($S = 30, a = 0.6, b = 0.3$). That is because high consumers' preference for e-platform channels or high profitability of the recycler helps the e-platform to obtain higher commission and profit, even if there exists another recycling channel. Therefore, the e-platform should strive to improve its reputation and cultivate more platform users.

Regarding Proposition 6 (3), compared to Model-S, the dual-channel recycling model can bring more profit to the supply chain. Figure 6 ($S = 30, a = 0.6, \Delta = 400$) shows the comprehensive impact of consumers' preferences and competitive intensity on the supply chain's profit. The profit of the reverse supply chain in the Model-S is independent of b, θ. It can be seen that π^{DU*} is higher than π^{DD*} only when competition intensity between channels is low and consumers' preference for the e-platform is not too high. Although the recycler building its own recycling channel will cause losses of the e-platform, under certain conditions, both parties can achieve a win-win situation through profit sharing in the Model-DD.

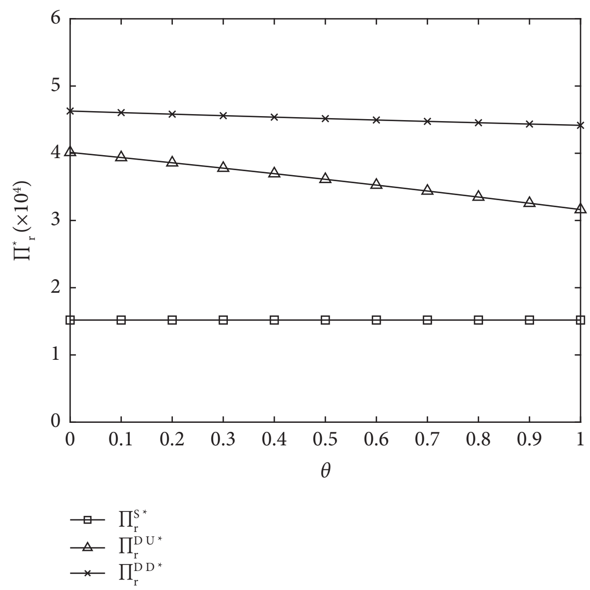

Figure 4: Comparison of optimal recycler's profits among three models.

Proposition 7. $q^{S*} < q^{DU*} < q^{DD*}$.

Proof of Proposition 7. See Appendix.

Proposition 7 indicates that the recycling quantities in the Model-DD are the highest among the three models, while in the Model-S, they are the lowest. Compared to Model-DU, Model-DD takes advantage of pricing flexibility to improve the recycling efficiency of the reverse supply chain and is superior in terms of resource reuse. Therefore, to promote the circular economy and environmental sustainability, the government should encourage recyclers to establish their own recycling channels and further improve the recycling efficiency of WEEE through competition between channels.

Setting $S = 30, a = 0.6, \Delta = 400$, the effect of consumers' preference for channels on recycling quantities in the three models is shown in Figure 7(a). It is consistent with Proposition 2 that the recycling quantities in the Model-DU and Model-DD decrease with θ; it also can be seen that recycling quantities in the Model-DU are more sensitive to θ than in Model-DD. Therefore, Model-DD is more stable in terms of recycling volume.

As shown in Figure 7(b), the recycling quantities in the Model-S and Model-DU are not affected by b. It is noted that the curve of q^{DD*} with respect to b is concave and increasing, which indicates that more e-wastes can be recycled with competition intensity increases, and the marginal increase is diminishing.

4.2. Discussion. In this section, we discuss the corporate profits, consumer surplus, and environmental benefits of different models based on a comparison of optimal results. Due to channel competition, the recycling price in the dual-channel reverse supply chain is always higher than that in the

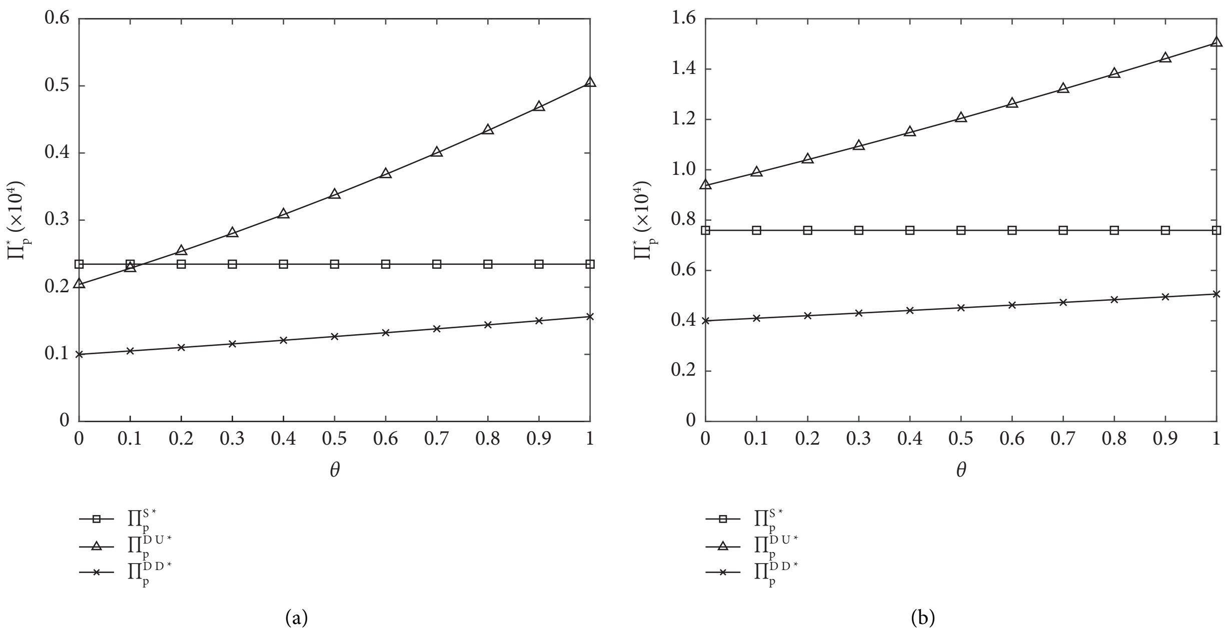

FIGURE 5: Comparison of optimal e-platform's profits among three models: (a) $\Delta = 200$; (b) $\Delta = 400$.

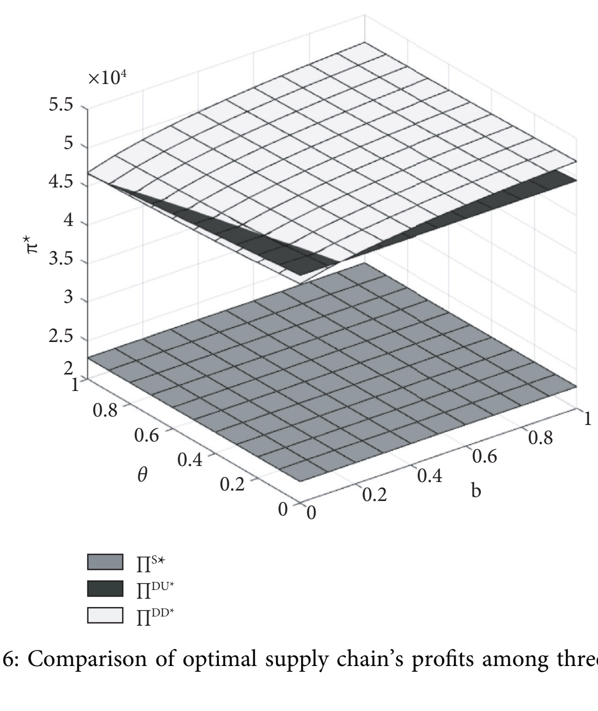

FIGURE 6: Comparison of optimal supply chain's profits among three models.

single-channel reverse supply chain, and the recycling price of the recycler's own channel in Model-DD is the highest among the three models. That is, competition between channels can increase consumer surplus. In addition, the recycling price of the e-platform channel with a differentiated pricing strategy is more sensitive to the consumers' preference, while the unified pricing strategy creates a certain constraint. In addition, the amount of WEEE recycling in Model-DD is higher than that in the other two models, achieving higher environmental benefits. As the intensity of channel competition increases, the system recycling volume increases. In terms of corporate profits, we find that the recycler has the highest profits in Model-DD while the e-platform prefers Model-DU or Model-S, which also reflects the positional advantage of the recycler in the game. By comparing supply chain profits under different models, we find that dual-channel reverse supply chains have higher total profits, and in some cases, the recycler and the e-platform may achieve a win-win situation by cooperation.

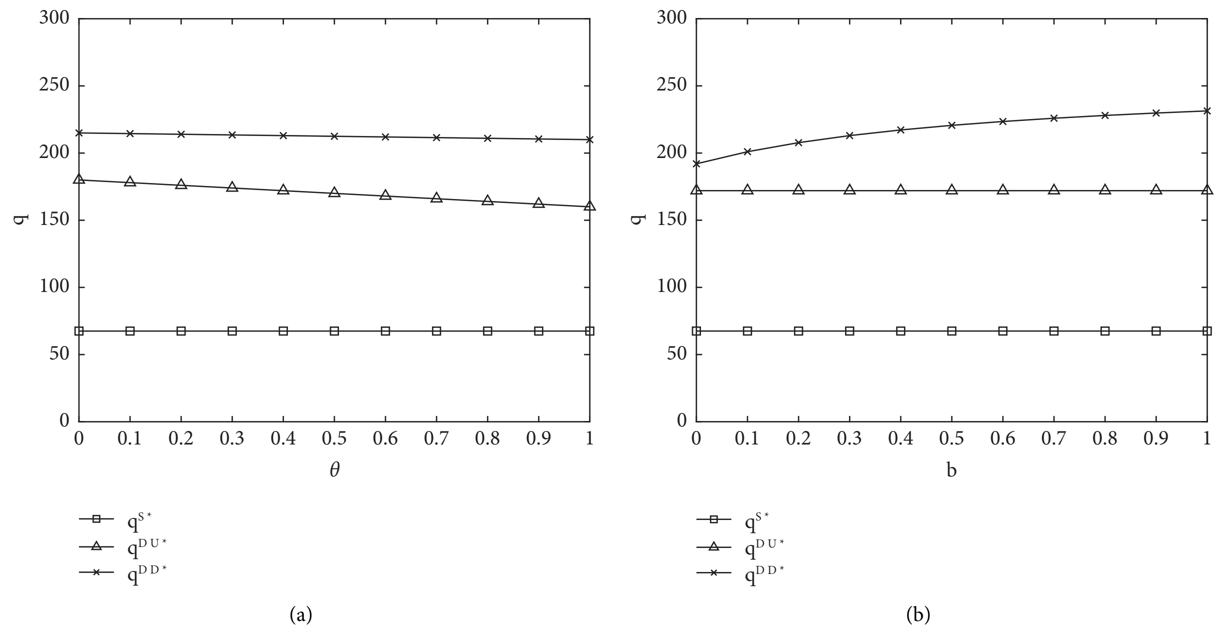

FIGURE 7: Comparison of optimal recycling volumes among three models: (a) $b = 0.3$; (b) $\theta = 0.4$.

5. Managerial Insights and Practical Implications

We construct three reverse supply chain models considering consumers' preference for channels, analyze and compare supply chain members' optimal decisions and profits, and further illustrate results using numerical examples. Some managerial insights are obtained as follows.

First, in terms of channel management, recyclers build their own recycling channels to facilitate the recovery of more e-wastes, and the competition between channels brings higher consumer surplus. Therefore, recycling enterprises should be encouraged to open direct recycling channels and explore diversified recycling systems to promote sustainable economic and environmental development. Second, e-platforms with high consumer preference will set higher commissions, and this will undoubtedly affect the interests of other stakeholders. Therefore, for some third-party network platforms in the reverse supply chain, it is necessary to restrict and guide the platform operators to set reasonable payment and settlement, platform commission, and other service fees to reduce the transaction fees of recyclers, promoting the efficient operation of the reverse supply chain. Finally, in the dual-channel reverse supply chains, the pricing strategy of recyclers should be formulated with careful consideration of the competitive environment and their own profitability. It is worth noting that the differentiated pricing strategy can be more flexible to adapt to changes in the external environment and reduce the profit loss of recyclers. However, when the competition intensity between channels is low, the unified pricing strategy can achieve higher supply chain profit.

6. Conclusions and Outlook

Based on the "Internet + recycling", we construct three reverse supply chain models consisting of the recycler and the e-platform and analyze the influence of consumers' preference for channels and channel competition on the supply chain equilibrium solution. We also compared optimal recycling prices, optimal profits, and optimal recycling quantities in the three models to explore the optimal recycling model from different angles. The main findings are listed as follows:

(i) It is proved that the high disposal revenue of WEEE is always beneficial to enterprises, consumers, and the environment. Therefore, the government should encourage enterprises to innovate processing technologies and improve resource utilization to build an efficient recycling system. It is also necessary to consider compatibility and cascade utilization in the product design stage, achieving higher reusable value.

(ii) Competition between channels can encourage enterprises to increase recycling prices and improve the recycling rate of WEEE. At the same time, a differentiated pricing strategy allows the recycler to flexibly adjust decisions to maximize own profits and environmental benefit. The government should promote the construction of a diversified recycling system and guide recycling enterprises to compete in an orderly manner.

(iii) In Model-DU and Model-DD, the high consumers' preference for e-platform channels is beneficial to the platform but harmful to the recycler. In Model-

DU, the consumers' preference for e-platform has a negative effect on the supply chain's profit. However, in Model-DD, if the disposal revenue of WEEE is low and consumers' preference for e-platform is beyond the certain threshold, the consumers' preference for e-platform has a positive effect on the supply chain's profit.

(iv) The recycler prefers Model-DD, while the e-platform prefers Model-S or Model-DU. When consumers' preference for channels and channel competition meet certain conditions, Model-DD has a higher total benefit than Model-DU, and a win-win situation may be achieved via in-depth cooperation, such as profit segmentation.

This study focuses on three recycling models based on e-platform considering consumers' preferences and provides some suggestions on pricing strategy and channel management for the recycler. In the future, the research can be expanded to multiple recyclers, the privacy protection during recycling can also be considered.

Appendix

Proof of Proposition 3. In the Model-DU, from the first and second derivative of the optimal profits with respect to θ, based on the nonnegative condition of optimal recycling price, $2a\Delta > (1+2\theta)S$, the authors can obtain

$$\frac{\partial \pi_p^{DU\ *}}{\partial \theta} = \frac{(8\theta-2)S^2 + 4a\Delta S}{9a} > \frac{4\theta S^2}{3a} > 0, \frac{\partial^2 \pi_p^{DU\ *}}{\partial \theta^2} = \frac{4S^2}{3a} > 0, \tag{A.1}$$

$$\frac{\partial \pi_r^{DU\ *}}{\partial \theta} = \frac{(4-16\theta)S^2 - 8a\Delta S}{12a} < -\frac{2\theta S^2}{a} < 0, \frac{\partial^2 \pi_r^{DU\ *}}{\partial \theta^2} = -\frac{2S^2}{a} < 0, \tag{A.2}$$

$$\frac{\partial \pi^{DU\ *}}{\partial \theta} = \frac{(1-4\theta)S^2 - 2a\Delta S}{9a} < -\frac{2\theta S^2}{3a} < 0, \frac{\partial \pi^{2DU\ *}}{\partial \theta^2} = -\frac{2S^2}{3a} < 0. \tag{A.3}$$

In the Model-DD, from the first and second derivative of the optimal profits with respect to θ, based on the nonnegative condition of $\omega^{DD\ *}$, $a(a+2b)\Delta > (a\theta + b)S$, the authors can obtain

$$\frac{\partial \pi_p^{DD\ *}}{\partial \theta} \tag{A.4}$$

$$\frac{\partial \pi_r^{DD\ *}}{\partial \theta} = \frac{-aS[(2a+2b-3a\theta-2b\theta)S + a(a+2b)\Delta]}{8a(a+b)(a+2b)} < 0$$
$$\frac{\partial^2 \pi_r^{DD\ *}}{\partial \theta^2} = \frac{aS^2(3a+2b)}{8a(a+b)(a+2b)} > 0, \tag{A.5}$$

$$\frac{\partial \pi^{DD\ *}}{\partial \theta} = \frac{-aS[(4a+4b-7a\theta-6b\theta)S + a(a+2b)\Delta]}{16a(a+b)(a+2b)}. \tag{A.6}$$

Set $\theta^* = a(a+2b)\Delta + 4(a+b)S/(7a+6b)S$, when $\theta < \theta^*, \partial \pi^{DD\ *}/\partial \theta < 0$; otherwise, $\partial \pi^{DD\ *}/\partial \theta > 0$.

To ensure the existence of θ^* in the interval range of (0,1), $\Delta < 3a + 2b/a(a+2b)S$ should be satisfied. If $\Delta > 3a + 2b/a(a+2b)S$, $\theta^* > 1$ holds constantly, at this time $\partial \pi^{DD\ *}/\partial \theta < 0$.

In summary, Proposition 3 can be proved. ☐

Proof of Proposition 4. In the Model-DD, after taking first-order derivatives of the recycler and the e-platform's optimal decisions with respect to b, the authors have

$$\frac{\partial m^{DD\ *}}{\partial b} = \frac{-a\Delta - \theta S}{4(a+b)^2} < 0, \tag{A.7}$$

$$\frac{\partial p_r^{DD\ *}}{\partial b} = \frac{(1-2\theta)S}{2(a+2b)^2}. \tag{A.8}$$

If $\theta > 1/2$, $\partial p_r^{DD\ *}/\partial b < 0$; otherwise, $\partial p_r^{DD\ *}/\partial b > 0$.

$$\frac{\partial p_p^{DD\ *}}{\partial b} = \frac{\left[\left(5a^2 + 12ab + 8b^2\right)\theta - 2(a+b)^2\right]S + a(a+2b)^2\Delta}{4(a+b)^2(a+2b)^2}. \tag{A.9}$$

Set $\overline{\theta} = 2(a+b)^2 S - a(a+2b)^2\Delta/(5a^2+12ab+8b^2)S$, based on the nonnegative condition of $p_p^{DD\ *}$: $a(a+2b)^2\Delta \geq [a(3a+4b)\theta + 2(a+b)b]S$, the authors have $\overline{\theta} < 1/2$.

Then if $\left\{\Delta < 2(a+b)^2/a(a+2b)^2 S\right\} \cap \left\{\theta < \overline{\theta}\right\}$ are satisfied, $\partial p_p^{DD\ *}/\partial b < 0$; otherwise, $\partial p_p^{DD\ *}/\partial b > 0$.

If $\Delta > 2(a+b)^2/a(a+2b)^2 S$, $\overline{\theta} < 0$ holds constantly; therefore, $\partial p_p^{DD\ *}/\partial b > 0$.

After taking first-order derivative of $q_r^{DD\ *}$ with respect to b, the authors have

$$\frac{\partial q_r^{DD\ *}}{\partial b} = \frac{a(a\Delta + \theta S)}{4(a+b)^2} > 0. \tag{A.10}$$

In summary, Proposition 4 can be proved. □

Proof of Proposition 5. To compare the optimal recycling prices in the three models, the authors compute the difference between recycling prices as follows:

$$p_p^{S*} - p_j^{DU*} = \frac{-a\Delta + (4\theta - 7)S}{12a} < 0, p_p^{S*} < p_j^{DU*}. \quad (A.11)$$

Based on the nonnegative condition of p_p^{S*}, $a\Delta \geq 3S$, the authors derive the following:

$$p_j^{DU\ *} - p_r^{DD\ *} = \frac{-a(a+2b)\Delta + [(-4b-5a)\theta + 2a + b]S}{6a(a+2b)} < 0, p_j^{DU\ *} < p_r^{DD\ *}, \quad (A.12)$$

$$p_p^{S*} - p_p^{DD\ *} = \frac{[a(3a+4b)\theta - (a+b)(3a+4b)]S - ba(a+2b)\Delta}{4a(a+b)(a+2b)} < 0, p_p^{S*} < p_p^{DD\ *}, \quad (A.13)$$

$$p_p^{DD\ *} - p_r^{DD\ *} = \frac{[-(5a+6b)\theta + 2(a+b)]S - a(a+2b)\Delta}{4(a+b)(a+2b)} < 0, p_p^{DD\ *} < p_r^{DD\ *}, \quad (A.14)$$

$$p_p^{DD\ *} - p^{DU\ *} = \frac{\left[\left(-5a^2 + 8b^2\right)\theta + 2\left(a^2 - b^2\right)\right]S + a\left(4b^2 - a^2\right)\Delta}{12a(a+b)(a+2b)}. \quad (A.15)$$

If $\{b > \sqrt{3}/3a\}$ or $\{\sqrt{10}/10a < b < \sqrt{3}/3\} \cap \{0 < \theta < \theta_0\}$ is satisfied, $p_p^{DD\ *} - p_j^{DU\ *} > 0$; if $\{b < \sqrt{10}/10a\}$ or $\{\sqrt{10}/10a < b < \sqrt{3}/3a\} \cap \{\theta_0 < \theta < 1\}$ is satisfied, $p_p^{DD\ *} - p^{DU\ *} < 0$.

In summary, Proposition 5 can be proved. □

Proof of Proposition 6. To compare the optimal profits in the three models, the authors compute the difference between the optimal recycler's profits as follows:

$$\pi_r^{DU\ *} - \pi_r^{S*} = \frac{-(4\theta-1)^2S^2 + 2(5-8\theta)a\Delta S + 5a^2\Delta^2}{24a} > 0, \pi_r^{DU\ *} > \pi_r^{S*}, \quad (A.16)$$

$$\pi_r^{DD\ *} - \pi_r^{DU\ *} = \frac{\begin{array}{c}\left[\left(25a^2 + 54ab + 32b^2\right)\theta^2 - 4\left(5a^2 + 9ab + 4b^2\right)\theta + 2(2a+b)(a+b)\right]S^2 \\ +2(a+2b)[(5a+8b)\theta - 2(a+b)]a\Delta S + (a+2b)(a+4b)a^2\Delta^2\end{array}}{24a(a+b)(a+2b)} > 0, \pi_r^{DD\ *} > \pi_r^{DU\ *}. \quad (A.17)$$

Then, the authors compute the difference between the optimal e-platform's profits as follows:

$$\pi_p^{DU\ *} - \pi_p^{S*} = \frac{[a\Delta + (8\theta-5)S][7a\Delta + (8\theta+1)S]}{144a}. \quad (A.18)$$

Setting $\theta_1 = 5S - a\Delta/8S$, based on the nonnegative condition of p_p^{S*}, $a\Delta \geq 3S$, the authors know $\theta_1 < 1/4$. When $\{\Delta < 5S/a\} \cap \{\theta < \theta_1\}$ is satisfied, $\pi_p^{DU\ *} < \pi_p^S$; otherwise, $\pi_p^{DU\ *} > \pi_p^S$.

$$\pi_p^{DD\ *} - \pi_p^{DU\ *} = \frac{\begin{array}{c}\left[(32\theta-4)(a+b) - (55a+64b)\theta^2\right]S^2 - \\ 2[(23a+32b)\theta - 8(a+b)]a\Delta S - (7a+16b)a^2\Delta^2\end{array}}{144a(a+b)} < 0, \pi_p^{DD\ *} < \pi_p^{DU\ *}, \quad (A.19)$$

$$\pi_p^{DD\ *} - \pi_p^{S*} = \frac{\left(a\theta^2 - a - b\right)S^2 + 2(a\theta - a - b)a\Delta S - ba^2\Delta^2}{16a(a+b)} < 0, \pi_p^{DD\ *} < \pi_p^{S*}. \quad (A.20)$$

Computing the difference between the optimal supply chain's profits as follows:

$$\pi^{DU*} - \pi^{S*} = \frac{\left(-32\theta^2 + 16\theta - 11\right)S^2 + 2(-16\theta + 13)a\Delta S + 37a^2\Delta^2}{144a} > 0, \pi^{DU*} > \pi^{S*}, \tag{A.21}$$

$$\pi^{DD*} - \pi^{S*} = \frac{\left[\left(7a^2 + 6ab\right)\theta^2 - 8a(a+b)\theta + (a+b)(a-2b)\right]S^2 + 2(a+2b)[(1-\theta)a+b]a\Delta S + (a+2b)(4a+5b)a^2\Delta^2}{16a(a+b)(a+2b)} > 0, \pi^{DD*} > \pi^{S*}. \tag{A.22}$$

In summary, Proposition 6 can be proved. □

Proof of Proposition 7. To compare the optimal recycling volumes in the three models, the authors compute the difference between recycling volumes as follows:

$$q^{S*} - q^{DD*} = \frac{[a\theta - a - b]S - a(2a+3b)\Delta}{4(a+b)} < 0. \tag{A.23}$$

Based on the nonnegative condition of p_p^{S*}, $a\Delta \geq 3S$, the authors derive the following:

$$q^{DU*} - q^{DD*} = \frac{[2(a+b) - (5a+8b)\theta]S - a(a+4b)\Delta}{12(a+b)} < 0, \tag{A.24}$$

$$q^{S*} - q^{DU*} = \frac{-5a\Delta + (8\theta - 5)S}{12} < 0. \tag{A.25}$$

Then, the authors have $q^{S*} < q^{DU*} < q^{DD*}$; Proposition 7 can be proved. □

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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