Research Article

Research on Investment Decision of Construction and Demolition Waste Recycling Technology from the Perspective of Government Subsidy

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To achieve more efficient recycling management of construction and demolition waste (C&D waste) and to encourage investment in recycling enterprise technology in underdeveloped areas, this study develops a dynamic Nash supply chain model, with and without government subsidy, for a C&D waste recycling treatment system comprised of two recycling enterprises and one builder. We investigate the mechanism of government subsidy regulation on recycling enterprises’ technology decisions, the optimal proportion of technology upgrades of recycling enterprises, and the effects of other exogenous factors on the decision of government and recycling enterprises in an early stage of the recycling industry. The results show that with the subsidy, the recycling enterprises’ proportion of technology upgrade and profits is always improved. And recycling enterprise will actively increase investment to increase the proportion of technology upgrades. Furthermore, the government should prioritize assisting enterprises that are among the first to invest in recycling technology. Interestingly, the proportion of subsidy and technology upgrades is also affected by the unit environmental benefit and the degree of substitution of renewable products with different technological levels. When the degree of substitution is low, not only government subsidies are required to play a role but also builders’ awareness of the benefits of using high-tech renewable products, in order to drive enterprise technology investment from the demand side. The study provides detailed information on government and recycling enterprise C&D waste recycling strategies.

1. Introduction

According to the United Nations, the expansion of global urbanization is now as high as 55% and is expected to increase to 68% by 2050. Rapid urbanization not only increases the use of nonrenewable resources but also produces a large amount of construction and demolition waste (C&D waste). It is estimated that over 10 billion tons of C&D waste are generated globally [1, 2]. The majority of C&D waste is disposed off through landfills and random discharge, which not only pollutes the environment but also leads to land and resource shortages [3]. This has become a major obstacle to the development of sustainable and ecological security.

Promoting C&D waste recycling can reduce dependence on landfills, and it is an important means to handle C&D waste, curb environmental degradation, and improve the level of ecological civilization effectively [4–7]. Developed countries have achieved remarkable results in this respect; for example, the waste recycling ratio in Japan, the Netherlands, Denmark, Germany, and the United States is 90%, 90%, 90%, 88%, and 70%, respectively [8–10]. However, the ratio of waste recycling in developing countries is much lower than in developed countries. Some developed countries or regions, in particular, have a relatively high proportion of high recycling technology, owing to the government’s strong policy and subsidy support [9]. For example, a chemical building material company in Shenzhen has made mature achievements in the technology of C&D waste recycling, preparation, and high-liquid lightweight walls, which have been applied in practical construction projects. These regions have been at the forefront of China’s and even the world’s efforts to build “waste-free cities,” and the virtuous circle between their recycling technology, economy, and environment is growing [6]. While there are a
small number of recycling enterprises in underdeveloped areas, the recycling ratio remains less than 10%, and landfill is still the most common method of waste disposal [11]. The development of waste recycling in underdeveloped areas is related to environmental goals, and it is no longer just a regional issue.

According to relevant studies, the use of advanced recycling technology is an effective measure for increasing the recycling ratio of C&D waste [12]. However, factors such as high initial investment and complex technology have deterred potential recycling technology investors in developing countries [13, 14]. The recycling rate is affected by economic feasibility, which is often reported in different regions around the world, such as Brazil [15], Chongqing [16], and Suzhou [13]. The government subsidy, as the free financial support provided by the government, has gradually attracted attention to its influence on the investment and achievements of enterprises’ technology. For example, the government has been providing subsidies for the R&D of clean technologies through the National Development and Reform Commission and the Ministry of Science and Technology. Many enterprises that have benefited from government subsidies have achieved technical and commercial success. In recent years, governments in underdeveloped regions have intended to guide local recycling enterprises’ improvement of the proportion of technology upgrade through subsidy regulation, based on the successful experience of developed cities. Recycling enterprises may have more incentives to increase technology investment at this time. Nevertheless, on the one hand, the effect of the government’s decision on the recycling enterprises’ technology level is not clear. On the other hand, after increasing technology investment, one of the most pressing concerns for recycling enterprises is whether they profit from renewable products that can cover the cost of the technology. The following are the main research issues in this paper, based on the technological status of recycling enterprises in China’s underdeveloped areas:

1. What is the mechanism of government subsidies on the decisions of recycling enterprises’ proportion of technology upgrade?
2. How do recycling enterprises decide on the proportion of technology upgrade?
3. What are the effects of other exogenous factors on the decision making of government and recycling enterprises?

Due to the rapid development of the recycling industry, it is necessary to study these issues from a long-term and dynamic perspective. Therefore, we consider a two-period dynamic Nash game model, in which two recycling enterprises enter the C&D waste recycling industry sequentially. This is a common occurrence in emerging recycling industries, attempting to solve the three problems mentioned above from a dynamic standpoint. In theory, this research contributes to the improvement of the current C&D waste recycling system. In practice, it not only assists recycling enterprises in optimizing technical decisions but it also provides valuable insights to the government. It is of great significance for promoting efficient C&D waste recycling and reducing the environmental impact in underdeveloped areas. In addition, it also has a certain reference value for decision makers and recycling enterprises in other underdeveloped countries.

The remainder of this paper is organized as follows: Section 2 summarizes the related literature. Section 3 introduces the method in the paper. Section 4 provides the analysis of the equilibrium result. Section 5 verifies the accuracy of the results by numerical simulations. Section 6 discusses the main research results, and the final section concludes the paper.

2. Literature Review

2.1. C&D Waste Recycling Management. Recycling of C&D waste is the process of converting C&D waste into new resources for use [17]. In the past few decades, to improve environmental benefits, many qualitative and quantitative research studies on C&D waste recycling have been conducted.

In qualitative research studies, some scholars have conducted empirical investigations on the recycling management of C&D waste in specific cities of China, including Shenzhen [14], Hong Kong [18], Beijing [19], Shanghai [20], Chongqing, and Chengdu [11]. There is a significant gap between the recycling process of the underdeveloped areas and that of the developed areas [9]. Other scholars have studied potential challenges of C&D waste recycling in different countries through empirical investigations, including imperfect government regulation, immature recycling technology, uncertainty in the quality of recycled aggregates, and underdeveloped market of renewable products [14, 21–24]. For example, Bao et al. [25, 26] investigated the obstacles to the implementation of C&D waste recycling by adopting a mixed-method approach combining case study, site visits, and interviews in Hong Kong and Kunshan city of China, including the lack of government policy support and off-site recycling support. In quantitative research studies, Su et al. [27] examined how to improve the renewable products’ quality and market acceptance in C&D waste recycling by establishing a tripartite evolutionary game model consisting of government, contractor, and recycling enterprise. Considering consumers’ quality perceptions toward renewable products, He and Yuan [28] investigated the optimal strategies of the traditional building material enterprises and the waste recycling enterprises through Stackelberg game theory for the first time.

Based on the preceding discussions, it has been determined that the problem of unbalanced development of C&D waste recycling has yet to be resolved. Furthermore, previous quantitative studies on potential challenges such as the uncertainty in the quality of recycled aggregates and the underdeveloped market of renewable products have been involved, while the immature recycling technology remains
to be broken [29]. There has been little research into how to overcome the technology obstacle in order to improve the efficiency of C&D waste recycling management. Therefore, this research intends to focus on the development of recycling technology and government regulation in underdeveloped areas.

2.2. Recycling Technology Investment. Up to now, many scholars have carried out research studies from the recycling technology. For example, the recycled aggregate obtained by crushing and separating C&D waste with appropriate technology has been reported to display comparable compressive strength with that of natural aggregates; in some cases, even better performance was reported [29], which lays a solid foundation for the technical field. By comparing the recycling performance of two recycling enterprises with different technological levels, Galán et al. [30] found that the enterprises with advanced technology have a higher recycling ratio. The above finding is similar to the following studies. That is, advanced recycling technology will help the C&D waste shift from degraded recycling to higher-value utilization, and increasing investment in technology research and development (R&D) may promote the development of waste recycling industry [31, 32]. However, due to the high investment cost of technology R&D, many recycling enterprises tend to use low technology to produce low-quality renewable products, which hinders the development of recycling industry [33]. None of these studies has conducted systematic research on the influencing factors of recycling technology investment. In fact, government regulation will encourage recycling enterprises to invest in technology, especially in China [9, 34]. Therefore, we introduce government regulation into our Nash game model to explore its mechanism and try to find out the impact of other factors on technology investment.

2.3. Government Regulation. As we all know, government pressure and incentives are the primary driving forces behind the global promotion of C&D waste recycling [16, 24, 35–38]. Previous research has found that imposing waste disposal fees can encourage builders to recycle, classify, and reduce waste to the greatest extent possible, thereby promoting C&D waste recycling [39]. Nevertheless, most of the C&D waste disposal fees used in many areas of the country were determined based on empirical rules, resulting in very limited effectiveness. Yuan and Wang [40] used the system dynamics method to model the C&D waste disposal fee, filling this research gap, and found that the C&D waste disposal fee of 80 Yuan per ton is the best choice to achieve a reduction of C&D waste in Shenzhen. Chen et al. [41] used the evolutionary game to theoretically identify the decision-making behaviors of builders and government departments, and assigned a penalty value based on a simple model of both parties’ decision-making behavior. When the government determines that the likelihood of illegal dumping is 60%, a government-specified fine of 66.67 Yuan per ton, and the supervision probability at 22.5%, the illegal dumping of builders can be controlled effectively.

The above studies focused on the government’s waste disposal fees to promote enterprises’ eco-friendly decision making. However, without subsidies, the enterprises lack funds for technology investment [42]. As a result, our research includes government subsidies as a tool. Some researchers have studied the impact of various types of government subsidies in the manufacturing industry. Wang et al [43] compared and explained the characteristics of four subsidy policies, including initial subsidies, R&D subsidies, production subsidies, and recycling subsidies. Other researchers have studied different objects of government subsidies. Safarzadeh and Rasti-Barzoki [44] proved that subsidized manufacturers can achieve better management effects compared with subsidizing consumers. In the construction field, Jia et al. [45] introduced a subsidy mechanism and developed a system dynamics model to calculate reasonable values for the subsidies. They calculated that by providing recycling enterprises with a renewable product subsidy of 40 Yuan/ton, the recycling rate could significantly increased. Using qualitative research methods, such as case studies, field investigations, and semistructured interviews in Shenzhen, China, Bao and Lu [46] discovered that government subsidy is one of the factors influencing the feasibility of recycling technology and the selection of recycling strategy.

There have been investigations and discussions about the types and targets of government subsidy in the manufacturing industry. However, these are not entirely consistent with the situation in the construction field. C&D waste recycling is an emerging industry. In the construction field, although there are qualitative studies on the effect of government subsidy on investment in recycling technology in previous literature, the evolution of the recycling industry and competition among recycling enterprises are ignored. Unlike these studies, our paper is unique. Based on the current state of the construction industry, we conduct a quantitative study from a dynamic standpoint on the technology investment decisions of two competitive recycling enterprises receiving government subsidies, which can provide more realistic and targeted guidance to the government and recycling enterprises.

Based on the above analysis, this study makes the following contributions: (1) Previously, most studies focused on the interactions between the government and a single recycling enterprise. On the one hand, despite the fact that recycling is a new industry, with the industry’s continued growth, more and more recycling enterprises will enter the market. Recycling technology advancement, on the other hand, adheres to the law of dynamic change: the generation of new technology and the elimination of old technology, or the reduction of technical efficiency. Therefore, we introduce two competitive recycling enterprises into the Nash game model to discuss recycling technology investment and upgrade decisions under government regulation from the dynamic perspective, which makes our research closer to reality. (2) In the past, there has been no quantitative study on the investment decision of recycling technology in the construction field. In view of the current situation of low recycling rate and immature recycling technology in
underdeveloped areas, we quantify the mechanism of government subsidy, unit environmental benefit, and other factors on C&D waste recycling technology investment so as to improve the technology investment and government subsidy regulation system of recycling enterprises in recycling industry and provide more targeted decision-making reference for government and recycling enterprises in underdeveloped regions around the world.

3. Method

With the continuous development of recycling industry, the competition between enterprises related to recycling is becoming more and more fierce. In recycling industry, there is competition among contractor, recycling enterprise, and landfill site, as well as competition between recycling enterprise and recycling enterprise. At present, the game research of stakeholders mostly focuses on the former in recycling industry. Our paper focuses on the competition between two recycling enterprises based on the reality of recycling development in underdeveloped areas. The Stackelberg game model is typically developed to examine the pricing strategies of stakeholders in an imbalanced market power structure (i.e., a market with a leader and a follower); by contrast, the Nash game model is applied to a balanced power scenario among stakeholders. To meet the research objectives, considering a two-period dynamic problem, this study firstly build a Nash supply chain model consisting of the government, two recycling enterprises, and one builder.

3.1. Model Description. In the first period (Period 1), when the recycling industry is just established, a single enterprise enters the industry. We call this enterprise a "pioneer" (denoted by $I$). The government determines the proportion of subsidy for the pioneer’s R&D investment with the goal of improving recycling technology and encouraging enterprises to increase technology investment. The pioneer then decides whether or not to invest in recycling technology in order to maximize profits. The investment of recycling technology reflects the proportion of recycling technology upgrade. The more investment, the higher the proportion of technology upgrades ($0 \leq t_i < 1$), and the higher the recycling technology level of the enterprise. It is noted that the technology investment of enterprises is usually not accomplished overnight but a phased process. When the enterprise is short on funds, it will prioritize the upgrade of some recycling technologies (such as the investment and upgrading of sand stirring machine, dehydration screen, and other major production equipment). When the enterprise has a large amount of capital, it will consider the overall upgrading of technology investment. As a result, the model’s settings are accurate. A part of the technology upgrade will be transformed into recycling technology with a high utilization rate and environmental performance (denoted by $H$). The part that has not been upgraded is still the recycling technology whose utilization rate and environmental performance are lower than that of high technology (denoted by $L$). After the achievement of technological investment, the pioneer decides the quantity of renewable products to be produced and sells them all to the builder. The builder uses the purchased renewable products to build construction products and sells them.

In the second period (Period 2), the pioneer who upgraded recycling technology in Period 1 makes a second investment and upgrades all technologies to high technology. This assumption is made because enterprises grow in size, and there will be more money available to upgrade technology across the board in Period 2 than in Period 1. Simultaneously, the other enterprise enters the industry. This enterprise is known as a follower (denoted by $f$). With the goal of maximizing social welfare, the government announces the proportion of subsidy for the follower’ investment ($s_f$). Similarly, the part of technology upgrading will be transformed into high technology. The part that has not been upgraded is still the low technology. To simplify the model, we no longer consider the technical decisions of the follower after two periods. Finally, the two enterprises decide on the quantity of renewable products to be produced and sell them all to the builders at the same time. The builder constructs and sells the construction products made from the purchased renewable products. Both enterprises’ renewable products are interchangeable and sold in the same market. As a result, there is competition among enterprises in the second period. The flowchart of the events is illustrated in Figure 1. The timeline of the events is illustrated in Figure 2.

3.2. Assumptions. The definitions of symbols used in this article are shown in Appendix A. In order to facilitate interpretation and analysis, we make the following key assumptions:

1. Recycling enterprises have enough sources of C&D waste, and the reverse recycling of construction waste is not taken into account.

2. Unit fixed product cost of the recycling enterprises is $c > 0$; we assume the unit variable cost of the recycling enterprises as 0, which is commonly used in the literature [47].

3. The cost of R&D investment is $F = -\alpha \ln (1 - t)$ and $\alpha$ is the difficulty coefficient of R&D technology. $F'(t) > 0$, it shows that the R&D investment cost increases in recycling technology level; $F''(t) > 0$, it shows that the R&D investment cost accelerates in the technology level. In addition, the function satisfies $F(0) = 0$, $F(1) = +\infty$.

4. The R&D investment cost of the follower is $b$ times that of the pioneer, where $b$ is the technical barrier of recycling industry established by the pioneer, and $b > 0$. A larger $b$ implies a higher technical barrier.

5. Recycling enterprises can observe each other’s technology implementation which is consistent with reality.
(6) Both recycling enterprises remain risk neutral and make decisions with the goal of maximizing their own profits. The government makes decisions with the goal of maximizing social welfare.

(7) The market potential is 1 in Period 1. With the development of the recycling industry, the market potential continues to rise. The market potential is $m$ in Period 2, with $m \geq 1$.

(8) In Period 1, the pioneer acts as a monopolist in the market. The inverse demand function is given by $p_{(HH)} = 1 - \beta q_f(q_{HH}) + \mu(1 - \beta q_{HL});$ in Period 2, when both the pioneer and the follower have high technology, the inverse demand function is given by $p_{(HH)} = p_{f(HH)} = 1 - \beta q_f(q_{HH})/m - \beta q_f(q_{HH})/m$, and when the pioneer has high technology and the follower has low technology, the inverse demand function is given by $p_{(HL)} = 1 - \beta q_f(q_{HL})/m - \mu \beta q_f(q_{HL})/m$. Detailed derivation is in appendix B. It is noted that the market price of high-tech renewable products is higher than the low-tech renewable products. Among them, $\mu$ is the degree of substitution of low-tech renewable products for high-tech renewable products. A lagger $\mu$ implies a less sensitive the market is to the technical level of renewable products.

(9) Inverse demand function of the builder is given by $p' = 1 - \beta q', q' = \rho q$. $\rho$ is the conversion coefficient between renewable products and construction products which is related to the type of building, and $0 < \rho < 1$.

(10) The environmental benefit of low-tech renewable products is 0, and the environment benefit of high-tech renewable products is $E = eq_H$, where $q_H$ is the output of high-tech renewable products.

(11) In order to encourage recycling enterprises to research and develop recycling technology, the government subsidizes them based on the $s_r$ ratio of the sum of R&D and additional costs. The total government subsidy is $\eta$. We note that the government only provides subsidy to the pioneer in Period 1.

(12) The social welfare is linearly addable. That is, social welfare ($SW$) = government welfare ($\pi_g$) + surplus of the recycling enterprises ($\pi_c$) + surplus of the builder ($\pi_b$). Among them, government welfare ($\pi_g$) = environmental benefit ($E$) + profit contribution of the builder ($G_B$) + profit contribution of recycling enterprises ($G_C$) - total government

\[\text{Figure 1: Recycling system of C&D waste.}\]

\[\text{Figure 2: Sequence of the events.}\]
subsidy (η); surplus of the recycling enterprises (π_C) = profit of the enterprise (I) + total government subsidy (η) - cost of R&D investment (F) - fixed product cost (C) - profit contribution of recycling enterprises (G_C); surplus of the builder (π_B) = profit of the builder (p'q') - fixed product cost of the builder (C_B) - profit contribution of the builder (G_B).

4. Results

In this section, we present the model equilibrium analysis of the recycling enterprises’ and government’s decisions. This is a three-stage problem: in the first stage, the government decides the subsidy proportion; in the second stage, the recycling enterprises make their investment decision, and finally the recycling enterprises make their product quantity decision. We use backward induction to solve this problem.

4.1. Optimization of Recycling Enterprises

4.1.1. Quantity Decision of Recycling Enterprises. In Period 1, if the pioneer’s technology is entirely high tech, and its profit is given by

\[ I_{(H)} = p_I(1)q_I(H). \]  

When the pioneer’s technology is entirely low tech, and its profit is given by

\[ I_{(L)} = p_I(L)q_I(L). \]  

In Period 2, when both enterprises’ technology is entirely high tech, the enterprises’ profits are given based on

\[ I_{(HH)} = p_{(HH)}q_{(HH)}r, \]

\[ I_{(HL)} = p_{(HL)}q_{(HL)}r. \]

When the pioneer’s recycling technology is entirely high tech, while the follower’s technology is entirely low tech, the enterprises’ profits are given based on

\[ I_{(HL)} = p_{(HL)}q_{(HL)}r. \]

\[ I_{(LH)} = p_{(LH)}q_{(LH)}r. \]

The equilibrium decisions and profits are obtained by the backward induction, as shown in Table 1.

<table>
<thead>
<tr>
<th>Equilibrium decisions</th>
<th>Profits</th>
</tr>
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<tbody>
<tr>
<td>( q_{(H)} = 1/2\beta )</td>
<td>( I_{(H)} = 1/4\beta )</td>
</tr>
<tr>
<td>( q_{(L)} = 1/2\beta )</td>
<td>( I_{(L)} = 1/4\beta )</td>
</tr>
<tr>
<td>( q_{(HH)} = m/3\beta )</td>
<td>( I_{(HH)} = m/9\beta )</td>
</tr>
<tr>
<td>( q_{(HL)} = m/3\beta )</td>
<td>( I_{(HL)} = m\beta(4-\mu) )</td>
</tr>
<tr>
<td>( q_{(LH)} = m/3\beta )</td>
<td>( I_{(LH)} = m\beta(4-\mu) )</td>
</tr>
<tr>
<td>( q_{(LL)} = m/3\beta )</td>
<td>( I_{(LL)} = m\beta(4-\mu) )</td>
</tr>
</tbody>
</table>

The equilibrium decisions and profits of the pioneer and follower are, respectively, given by

\[ 1/2 \beta, 1/4 \beta \]

\[ 1/2 \beta, 1/4 \beta \]

4.1.2. Technology Decision of Recycling Enterprises without Government Subsidy. To investigate the mechanism of the government subsidy, we analyze the situation where there is no subsidy firstly. In Period 2, the pioneer takes the expected profit maximization within two periods as the goal to make the decision of proportion of technology upgrade. Knowing the pioneer’s proportion of technology upgrade, the follower takes the expected profit maximization as the goal to make the decision of proportion of technology upgrade. The expected profits of the pioneer and follower are, respectively, given by

\[ \Pi_C = t_f[I_{(HH)} + (1-t_f)I_{(HL)}] + (1-t_f)[I_{(LH)} + t_fI_{(HH)} + (1-t_f)I_{(HL)}] \]

\[ \Pi_F = t_f[I_{(HH)} + (1-t_f)I_{(HL)}] - \{ -a(1-t_f) + \} \]

The pioneer only makes the decision on the product quantity of renewable products in Period 2, which is irrelevant to the decision on the proportion of technology upgrade in Period 1. Based on the above expected profits, the recycling enterprises’ optimal proportion of technology upgrade is found in Proposition 2.
Proposition 2

(1) In period 1, the equilibrium outcome of the pioneer’s proportion of technology upgrade is
\[ t_1^l = 1 - 4\alpha\beta/4\beta r + 1 - \mu \]
(2) In period 2, the equilibrium outcome of the follower’s proportion of technology upgrade is
\[ t_2^f = 1 - 9\alpha\beta b(4 - \mu)^2/m(16 - 17\mu + \mu^2) \]

Corollary 2. \( t_1^l > t_2^f \)

In the case of no subsidy, the follower’s optimal proportion of technology upgrade is lower than that of the pioneer. With recycling industry development, the C&D waste recycling technology barriers established by the pioneer and the existence of competition hinder the follower’s driving for recycling technology investment.

It is not clear how the government subsidies play a role in the technology decision making of recycling enterprises. We will study this in the next section.

4.1.3. Technology Decision of Recycling Enterprises with Government Subsidy. Under the government subsidy regulation, the expected profit function of enterprises is as follows:

\[ \Pi_{CI}^1 = t_1[I_{II(I)}^1 + t_f I_{II(H)}^1 + (1-t_f)I_{II(L)}^1] + (1-t_i)[I_{II(I)}^1 + t_f I_{II(H)}^1 + (1-t_f)I_{II(L)}^1] \]
\[ -\{r(1-t_i)[-\alpha Ln(1-t_i)] + c_i\} + s_f[r(1-t_i) + [-\alpha Ln(1-t_i)]], \]

\[ \Pi_{CF}^1 = t_f I_{II(H)}^1 + (1-t_f)I_{II(L)}^1 - \{[-ba Ln(1-t_f)] + c_f\} + s_f[-ba Ln(1-t_f)]. \]

Based on the above expected profits, the recycling enterprises’ optimal proportion of technology upgrade under the government subsidy is shown in Proposition 3.

Proposition 3.

(1) In Period 1, the equilibrium outcome of the pioneer’s proportion of technology upgrade is
\[ t_1^l = 1 - 4\beta a(1 - s_l)/4\beta r (1 - s_l) + 1 - \mu \]
(2) In Period 2, the equilibrium outcome of the follower’s proportion of technology upgrade is
\[ t_2^f = 1 - 9\alpha\beta b(4 - \mu)^2(1 - s_f)/m(16 - 17\mu + \mu^2) \]

The enterprises’ proportion of technology upgrade \( t_i \) increases in the government subsidy \( s_i \). The government subsidy promotes the development of recycling technology and has a positive impact on the enterprises’ increasing investment in recycling technology.

Corollary 3. \( t_1^l > t_2^f \).

In the case of no government subsidy, the recycling enterprises are obviously lacking motivation for recycling technology investment. The importance of government subsidy regulation to improve the enthusiasm of technology investment in recycling enterprises is verified again.

4.2. Optimization of the Government. Firstly, we give the social welfare function for each period.

The social welfare in Period 1 is given by

\[ SW_1^1 = \text{et}[q_{II(I)} + t_i I_{II(I)}] + (1-t_i)I_{II(L)} - \{r(1-t_i) - \alpha Ln(1-t_i) + c_i\} \]
\[ + \rho(q_{II(H)} + q_{II(L)})[1 - \beta p(q_{II(H)} + q_{II(L)})] - c_B. \]

Among them, \( SW_1^1 = \pi_{G,I} (s_i) + \pi_{G,II} (s_i) + \pi_{G,L} (s_i) \); \( \pi_{G,I} (s_i) = E_{1}(s_i) + G_{C,I} (s_i) + G_{R,I} (s_i) - \eta_{1}(s_i) \), \( E_{1}(s_i) = et[q_{II(I)}] \) is the environmental benefit brought by the pioneer’s high-tech renewable products in Period 1; \( G_{C,I} (s_i), G_{R,I} (s_i) \) are the profit contributions of the pioneer and the builder to the government in Period 1; \( \eta_{1}(s_i) \) is the government subsidy to the pioneer in Period 1;
\[ \pi_{C1,i}(s_i) = t_iI_{i(H)} + \left(1 - t_i\right)I_{i(L)} - \left[r(1 - t_i) + \left\lceil -\alpha L_n(1 - t_i) \right\rceil + c_i\right] + s_i\left[r(1 - t_i) + \left\lceil -\alpha L_n(1 - t_i) \right\rceil\right] - G_{C1,i}(s_i), \]

\[ \pi_{B,i}(s_i) = \rho\left(q_i(H) + q_i(I)\right)\left(1 - \beta p\left(q_i(H) + q_i(I)\right)\right) - c_B - G_{B,i}(s_i), \]

The social welfare in Period 2 is given by

\[ SW^1_2 = e(t_f q_i(H) + q_i(H)) + \left(1 - t_f\right)q_i(I) + t_f I_{i(H)} + \left(1 - t_f\right)I_{i(L)} \]

\[ + T_f I_{f(H)} + \left(1 - T_f\right)I_{f(L)} - \left(-\beta a L_n\left[1 - T_f\right]\right) + C_f \]

\[ + p\left(q_i(H) + q_i(I) + q_f(H) + q_f(I)\right)\left(1 - \beta p\left(q_i(H) + q_i(I) + q_f(H) + q_f(I)\right)\right) - c_B. \]

Among them,

\[ SW^2_2 = \pi_{g,i}(s_f) + \pi_{C,i}(s_f) + \pi_{C,f,i}(s_f) + \pi_{B,i}(s_f). \]

\[ \pi_{g,i}(s_f) = E_2(s_f) + G_{C,i}(s_f) + G_{C,f,i}(s_f) + G_{B,i}(s_f) - \eta_i(s_f). \]

We obtain the equilibrium outcome of the government subsidy proportion and analyze its properties through the following propositions and corollaries.

**Proposition 4**

1. In Period 1, the equilibrium outcome of the government subsidy proportional to the pioneer is

\[ s_i = 2e/1 + 2e - \mu. \]
(2) In Period 2, the equilibrium outcome of the government subsidy proportion to the follower is

\[
s_f = \begin{cases} 
3e\left(-8 - 2\mu + \mu^2\right) + 4\left(5 - 7\mu + 2\mu^2\right) & \text{if } e > 4\left(5 - 7\mu + 2\mu^2\right) \\
4 - 11\mu + 7\mu^2 + 3e\left(-8 - 2\mu + \mu^2\right) & \text{if } e > 4\left(5 - 7\mu + 2\mu^2\right) \\
0, & \text{otherwise}
\end{cases}
\]

In Period 1, the government’s subsidies to the pioneer can always achieve the social optimum. In Period 2, the government’s subsidies to the follower depend on the environmental benefits brought by recycling. Only when the unit environmental benefit \( e > 4\left(5 - 7\mu + 2\mu^2\right)/3(8 + 2\mu - \mu^2) \), the government can provide subsidies to the follower to achieve social optimum. Blindly increasing subsidy will instead cause the involution of technology investment.

**Corollary 4.** \( s_f > s_j \).

The government’s subsidies to the pioneer are higher than those to the follower. Some people may think that the government should provide more subsidies for the follower, because competition and barriers of the C&D waste recycling industry established by the pioneer will hinder the follower’s investment of recycling technology. Instead, the government offers a higher subsidy level to the pioneer. On the one hand, there is a complementary relationship between subsidy and competition. The emergence of competition reduces the government’s incentive to subsidize the follower. On the other hand, the existence of the pioneer who has the high technology in period 2 increases the consumption of the high-tech renewable products in addition to the follower, which weakens the need of the subsidies for the follower to develop the high technology.

This is a certain inspiration for the government’s subsidy policy. In the early stage of the C&D waste recycling industry, the government should actively provide subsidy to the pioneer.

**Corollary 5.** \( \partial s_f/\partial \mu > 0 \)

The government’s subsidy proportion increases in the degree of substitution \( \mu \). The greater the degree of substitution \( \mu \), the less sensitive the market is to the level of renewable products, and the weaker the technology investment motivation of recycling enterprises. At this point, it is necessary for the government to increase subsidies to stimulate enterprises to improve their proportion of technology upgrade or guide the builder in the market to increase their sensitivity to the level of renewable products.

**Corollary 6.** \( \partial s_f/\partial e > 0 \)

The government’s subsidy proportion increases in the unit environmental benefit \( e \). The increase of unit environmental benefit prompts the government to provide more subsidies. So, the external environmental benefits generated by C&D waste recycling are also factors that the government should pay attention to when providing subsidies.

**Proposition 5.** In Period 2, the equilibrium outcome of the pioneer’s and the follower’s proportion of technology upgrade is

\[
t^1_f = \frac{1 - 4\alpha \beta + 4\beta r + 2e - \mu}{1 + 4\beta r + 2e - \mu},
\]

\[
t^1_p = \begin{cases} 
\frac{9\alpha \beta \left(4 - \mu\right)^2}{m\left(4 - 11\mu + 7\mu^2 + 3e\left(8 + 2\mu - \mu^2\right)\right)} & \text{if } e > 4\left(5 - 7\mu + 2\mu^2\right)/3(8 + 2\mu - \mu^2), \\
1 - \frac{9\alpha \beta \left(4 - \mu\right)^2}{m\left(16 - 17\mu + \mu^2\right)} & \text{otherwise}
\end{cases}
\]

**Corollary 7.** \( t_f^1 > t_p^1 \).

Under the government subsidy regulation, the follower chooses a lower proportion of technology upgrade than the pioneer. In the early stage of recycling industry in underdeveloped regions, competition is weak, and the government subsidized the pioneer at a relatively high level, which weakened the investment motivation of the follower. Therefore, it is
necessary for the government to guide more followers to join the recycling industry and stimulate continuous technological upgrading of followers through strong competition among enterprises.

**Corollary 8.** \( \partial t^1 / \partial \mu < 0, \{ \partial t^1 / \partial \mu > 0, \ e > \max \{ 4(5 - 7\mu + 2\mu^2) / 3(8 + 2\mu - \mu^2) \}, s^2 / \partial \mu < 0, \text{otherwise.} \)

It shows that \( t^1 \) is decreasing in \( \mu \), and when the unit environmental benefit is greater than the critical value, \( t^1 \) is increasing in \( \mu \). With a lower degree of substitution \( \mu \), the market is more sensitive to the level of renewable product technology, and thus market differentiation is more obvious. The pioneer occupies the market for producing high-tech renewable products and increases the enthusiasm for investment in recycling technology under the government’s incentives. On the contrary, to avoid the high investment and fierce competition with the pioneer, the follower abandons technology investment directly and tries to obtain sufficient profits by producing and selling low-tech products.

It can be seen that, influenced by the degree of substitution, government subsidies do not achieve expected effect. The government must raise the awareness of the builder in the market to use the high-tech renewable products so as to drive the follower’s technology investment from the demand side.

**Corollary 9**. \( \partial t^1 / \partial \epsilon > 0, \{ \partial t^1 / \partial \epsilon > 0, \ e > 4(5 - 7\epsilon + 2\epsilon^2) / 3(8 + 2\epsilon - \epsilon^2), \partial t^1 / \partial \epsilon = 0, \text{otherwise}. \)

Under the government subsidy regulation, \( t^1 \) is decreasing in \( \epsilon \). If there is no subsidy, the enterprises’ technology investment will not be affected by the unit environmental benefit (see Proposition 2). Thus, it is not the environmental benefits brought about by improving the proportion of technology upgrade that plays the role, but the government subsidies stimulate the development of recycling enterprises’ technology.

### 5. Numerical Analysis

In order to verify the correctness of our model and gain more management insights, we describe numerical analysis in this section. The parameter setting is based on the field investigation of two typical recycling enterprises in Chongqing and the analysis of relevant literature. We select two typical recycling enterprises in Chongqing: Guangyang C&D waste recycling enterprise and Heishi C&D waste recycling enterprise, analyze their recycling activities, and determine the reasonable values of model parameters. Finally, we assign values to some parameters with \( b = 0.95, m = 1.05, \mu = 0.5, r = 0.005, \alpha = 5, \beta = 0.01, \rho = 0.001, \epsilon = 0.5, \zeta_1 = 10, \zeta_2 = 5 \), and \( e_B = 5 \), which makes the model not only have practical significance but also can get simple numerical analysis results.

We take the case with subsidy as an example, where the benefit of the government is \( p_g(s_f) = E_1(s_f) + E_2(s_f) + G_{CL1}(s_f) + G_{CL2}(s_f) + G_{CF1}(s_f) + G_{FB1}(s_f) + G_{FB2}(s_f) \), \( E_1(s_f) = \epsilon t f q_f(s_f) \), \( E_2(s_f) = e t f q_f(s_f) + q_f(s_f) + (1 - t_f) q_f(s_f) \) are the environmental benefits brought by the high-tech renewable products by pioneers in the first and second periods, respectively; \( G_{CL1}(s_f) \), \( G_{FB1}(s_f) \) are the profit contributions of the pioneer and the builder to the government in Period 1; \( G_{CL2}(s_f) \), \( G_{CF1}(s_f) \), and \( G_{FB2}(s_f) \) are the profit contributions of the pioneer, the follower, and the builder to the government in Period 2; government cost is the total subsidy expenditure: \( \eta_t(s_t) + \eta_f(s_f) \). Benefit of the pioneer is \( \pi_{CL1}(s_f) + \pi_{CL2}(s_f) = t_f I_f(s_f) + \left( 1 - t_f \right) I_f(s_f) - \left[ -a t f L n \left( 1 - t_f \right) + c_f \right] \) total profit of the pioneer in Period 1 + \( s_f \left[ r \left( 1 - t_f \right) + -a t f L n \left( 1 - t_f \right) \right] + t_f I_f(s_f) + \left( 1 - t_f \right) I_f(s_f) \) government subsidy to the pioneer total profit of the pioneer in Period 2 + government subsidy to the follower, the cost of pioneer is \( G_{CL1}(s_f) + G_{CL2}(s_f) \). Benefit of the follower is \( \pi_{CF2}(s_f) = t_f I_f(s_f) + \left( 1 - t_f \right) I_f(s_f) - \left[ -a t f L n \left( 1 - t_f \right) \right] + c_f \) total profit of the follower in Period 2 government subsidy to the follower, government subsidy to the follower, the cost of follower is \( G_{CF2}(s_f) \). Sensitivity analysis is made to study the impact of the unit environmental benefit \( \epsilon \), the degree of substitution of renewable products \( \mu \) on government, and recycling enterprises’ profits and costs (see Tables 2 and 3).

The results are shown as follows:

1. Generally speaking, the government and the recycling enterprises’ profits and social total welfare in the situation with government subsidy are higher than those without government subsidy, which once again highlights the importance of government subsidy.

2. In the situation with subsidy, when \( \epsilon = 0.1 \), the government’s marginal cost is the highest. For one thing, lower environmental benefits bring lower profits to the government. For without subsidy, the government needs to provide an amount of subsidy costs to incentivize the recycling enterprises’ technology investment. That is, the costs required for unit profit is the largest. With increasing in unit environmental benefit, the government profits gradually compensate for the initial subsidy costs, and the marginal cost has a certain downward trend; when \( \epsilon \in (0.3, 0.5) \), the government should increase subsidies to help recycling enterprises break through the recycling technological bottleneck. Then, the government can obtain higher profits with lower costs, so the marginal cost decreases.

Moreover, the marginal cost of the government increases in the degree of substitution \( \mu \). The smaller \( \mu \) is, the more sensitive the market is to the technology level of renewable products, and the lower costs that the government can invest in stimulating recycling enterprises’ technological investment. It can be seen that increasing the market’s sensitivity to the technological level can reduce government subsidies for promoting the development of recycling technology.

### 6. Discussion

In this study, we look into the mechanism of government subsidies on the decision of recycling enterprises’ proportion of technology upgrade, as well as the effects of other exogenous factors on the decision of government and recycling enterprises, such as the unit environmental benefit and the...
degree of substitution of low-tech renewable products for high-tech renewable products. We obtained several new findings with management significance.

In underdeveloped areas, C&D waste recycling is an emerging and developing industry now. The advancement of recycling technology and industry is inextricably linked to government subsidies. The government’s main focus is to encourage recycling enterprises’ investment and technological upgrading through subsidy regulation, with a particular emphasis on subsidizing the pioneer. When there is a high degree of substitution, the market is not sensitive to the technological level of renewable products. At this time, it is necessary for government to increase the subsidy to stimulate the motivation of technological upgrading of enterprises or to guide the builders in the market to improve their sensitivity to product technological differences. When the unit environment benefit is large, the enterprises’ recycling behavior has a greater positive impact on the environment. At this time, the government should increase subsidies to assist recycling enterprises in breaking through technological bottlenecks.

When the government provides a subsidy to promote the development of recycling technology, we believe that recycling enterprises should actively increase technology investment rather than maintaining the current technology level. In addition, affected by factors, such as technical barriers and government subsidy, the proportion of technology upgrades chosen by the follower is always lower than that of the pioneer. Interestingly, recycling enterprises’ decision on technology upgrade proportion is also affected by two parameters: unit environmental benefit and degree of substitution. Under the government subsidy, the greater the unit environmental benefit, the greater the proportion of

<table>
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<th>Table 2: With subsidy.</th>
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<tr>
<td><strong>Government</strong></td>
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<td><strong>profit cost</strong></td>
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<th>Table 3: Without subsidy.</th>
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<td><strong>Government</strong></td>
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<td><strong>profit cost</strong></td>
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0.7 | 60.44 | 0 | 36.57 | 14.59 | 0.399 | 6.92 | 7.09 | 1.025 |
| 0.8 | 68.83 | - | - | - | - |
| 0.9 | 77.22 | - | - | - | - |
| 1 | 85.61 | - | - | - | - |

0 | 51.96 | 4.78 | 0.092 | 51.80 | 26.09 | 0.501 | - | - | - |
| 0.1 | 52.55 | 4.89 | 0.093 | 49.04 | 25.51 | 0.520 | - | - | - |
| 0.2 | 52.88 | 5.53 | 0.105 | 47.23 | 25.10 | 0.531 | 5.36 | 7.56 | 1.410 |
| 0.3 | 53.04 | 6.43 | 0.121 | 46.02 | 24.81 | 0.539 | 7.23 | 8.28 | 1.145 |
| 0.4 | 53.09 | 7.44 | 0.140 | 45.20 | 24.60 | 0.544 | 8.97 | 8.90 | 0.992 |
| 0.5 | 53.06 | 8.51 | 0.160 | 44.67 | 24.45 | 0.547 | 10.60 | 9.43 | 0.890 |
| 0.6 | 52.94 | 9.61 | 0.182 | 44.35 | 24.36 | 0.549 | 12.14 | 9.90 | 0.815 |
| 0.7 | 52.75 | 10.74 | 0.204 | 44.22 | 24.33 | 0.550 | 13.61 | 10.31 | 0.758 |
| 0.8 | 52.48 | 11.89 | 0.227 | 44.24 | 24.37 | 0.551 | 15.04 | 10.67 | 0.709 |
| 0.9 | 51.13 | 13.05 | 0.255 | 44.41 | 24.49 | 0.552 | 16.45 | 10.98 | 0.667 |
| μ | 0.5 | 43.66 | 0 | 36.57 | 14.59 | 0.399 | 6.92 | 7.09 | 1.025 |
| 0.6 | 39.15 | 36.35 | 13.47 | 0.371 | 6.28 | 0.908 |
| 0.7 | 31.61 | 36.14 | 12.03 | 0.333 | 5.16 | 0.746 |
| 0.8 | 16.47 | 35.92 | 10.01 | 0.279 | 3.50 | 0.506 |
| 0.9 | - | 35.70 | 6.554 | 0.184 | 0.48 | 0.069 |
technology upgrade. When the degree of substitution is low, the market is sensitive to the technological level of renewable products. At this time, the pioneer increases the proportion of technology upgrade and chooses to occupy the high-tech renewable product market. To avoid competition with the pioneer and higher investment in recycling technology, the follower foregoes technology investment upgrading and opts to occupy the low-tech renewable product market to generate sufficient income.

Differing from previous studies, we investigate the game between several recycling enterprises and government in the C&D waste recycling system. In addition, we carry out research from dynamic and quantitative perspectives to supplement the previous research gaps. The research findings provide detailed theoretical guidance for the government and recycling enterprises to collaborate on C&D waste recycling, as well as insights for improving recycling efficiency in underdeveloped areas.

7. Conclusions

Given the current state of the recycling industry, it is possible to reduce the environmental pollution caused by C&D waste by upgrading recycling technology; however, a large amount of capital is required, and a single recycling enterprise may not be able to bear it entirely. In order to improve the current situation of a low recycling rate and immature recycling technology in underdeveloped areas, this research explores recycling enterprises’ technology decisions under the government subsidy regulation from a quantitative perspective based on a dynamic Nash game model of two recycling enterprises. We consider the evolution of the recycling industry and competition among recycling enterprises which makes up the gap of the previous research studies on the interaction between the government and several recycling enterprises. We characterize the equilibrium outcome for the government and recycling enterprises in each period, describe the mechanism of government subsidy and the recycling enterprises’ technology decisions in detail, and analyze the effects of the unit environmental benefit and the degree of substitution on the decision of government and recycling enterprises. We offer references for effectively promoting recycling technological development in underdeveloped areas, as well as promoting C&D waste recycling and mitigating environmental degradation. The following are the main findings.

The government is the main promoter of the development of recycling technology in the early stage of the C&D waste recycling industry. First of all, the government can promote recycling enterprises’ investment and upgrading of technology through subsidy regulation, especially focusing on subsidizing the pioneer. Second, the government can actively publicize the benefits of using high-tech renewable products, as well as increase builders’ sensitivity to high-tech recycled products, to drive follower investment in recycling technology from the demand side. Finally, the government can direct more enterprises to join the recycling industry through a variety of policies such as incentives, and use the fierce competition among multiple enterprises to stimulate enterprises’ continuous motivation for technological upgrading.

Recycling enterprises are the main body of recycling technology development. On the one hand, with subsidies, recycling enterprises should have a long-term vision and choose to upgrade technology to obtain more profits in the future rather than focusing on current investment expenditures. On the other hand, they also should pay attention to the government’s policy trends and respond positively, improve their environmental awareness, establish the concept of high-quality development, and make contributions to the realization of recycling development in underdeveloped areas.

The results also show that the degree of substitution of renewable products and unit environmental benefit affects the government’s and recycling enterprises’ decisions. This cautions that stakeholders need to take into account these two variables before decision making. This paper provides insights for improving the recycling efficiency and C&D waste treatment efficiency in underdeveloped areas, which is expected to improve environmental benefits and narrow the recycling gap with coastal developed areas. In addition, the research methods and conclusions are universal and can be applied to other emerging industries, providing theoretical ideas for the development of other emerging industries, such as green industries and renewable energy industries.

Certain restrictions apply as well. To begin with, our model only considers two recycling enterprises and one builder, but there are many stakeholders in reality, so a key research direction is to consider the recycling system composed of multiple recycling enterprises and builders. Secondly, the research and development of complex C&D waste recycling technology usually require a large amount of capital investment, so further research should consider cooperation. Thirdly, in many cases, the R&D costs of recycling enterprises may be private information, and considering practical factors such as information asymmetry in a similar context may yield more valuable insights.

Appendix

A. Notation and definitions

Notation definition.

Decision Variables.

\[ s: \text{Proportion of the government subsidy, with } 0 \leq s < 1, \]
\[ i \in \{L, F\}: \text{Proportion of technology upgrade of recycling enterprises, with } 0 \leq t_i < 1, i \in \{L, F\}, \]
\[ q \in \{j, k\}: \text{Renewable product quantities of the pioneer enterprise with technical level } j \text{ in Period 1, with } q_{(j)} > 0, j \in \{H, L\}, \]
\[ q_{(jk)}: \text{Renewable product quantities of the enterprise when the technology level of the pioneer is } j \text{ and the technology level of the follower is } k, \]
\[ a_0: \text{Difficulty coefficient of R&D recycling technology, with } a > r \beta: \text{The sensitivity coefficient of the selling price to the selling quantity, with } \beta > 0.\]
\[ F: \text{Investment cost of the enterprises’ R&D, with } F > 0; \]
\[ c: \text{Unit fixed product cost of the recycling enterprises, with } c \in \{L, F\}, c_i > 0; \]
\[ m: \text{Unit fixed product cost of the builder, with } c_B > 0; \]
\[ c: \text{Market potential in Period 2, with } \]
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B. The Proof of the Inverse Demand Functions

The proof of the inverse demand functions in period 1.

In Period 1, the pioneer acts as a monopolist in the market. When the pioneer sells the high-tech renewable product, the inverse demand function is given by

\[ P_{f(I)} = 1 - \beta q_{f(I)} \]

When the pioneer sells the low-tech renewable product, the boundary builder buying the renewable product is located at \( m - \beta q_{f(I)} \) on the \([0,1]\) line. We notice that the market (builder) is sensitive or not sensitive between high-tech renewable product and low-tech renewable product, and the market price of high-tech renewable products is higher than the low-tech renewable products. Then, the builder’s net utility is given by \( \mu (1 - \beta q_{f(I)}) - P_{f(I)} \). Hence, equating \( \mu (1 - \beta q_{f(I)}) - P_{f(I)} \) to 0 gives the inverse demand function

\[ P_{f(I)} = \mu (1 - \beta q_{f(I)}) \]

The proof of the inverse demand functions in period 2.

When both enterprises’ renewable products are entirely of high tech, the boundary builder buying the product is located at \( m - \beta q_{f(I)} / m - \beta q_{f(I)} / m - P_{f(I)} \). Since the builder’s net utility is equivalent to 0, equating it to 0 gives the inverse demand function

\[ P_{f(I)} = P_{f(I)} = P_{f(I)} = 1 - \beta q_{f(I)} / m - \beta q_{f(I)} / m - P_{f(I)} \]

Next, the boundary builder who buys the high-tech renewable product is located at \( m - \beta q_{f(I)} / m - \beta q_{f(I)} / m, \) when the pioneer is entirely high tech and the follower is entirely low tech. In this case, the boundary builder who buys the low-tech renewable product is located at \( m - \beta q_{f(I)} / m - \beta q_{f(I)} / m, \) in \([0, m]\). Then, the net utility of the builder is given by

\[ \mu (1 - \beta q_{f(I)} / m - \beta q_{f(I)} / m - P_{f(I)} \]

Similarly, the net utility of the builder from buying the high-tech renewable product is given by \( 1 - \beta q_{f(I)} / m - P_{f(I)} \).

C. The Proof of the Propositions and Corollaries

The proof of Corollary 2.

\[ t_1 - t_0^0 = \alpha \beta \left( -\frac{4}{1 + 4 \beta r - \mu} + \frac{9 b (4 - \mu)^2}{m (16 - 17 \mu + \mu^2)} \right) > 0. \]  \hspace{1cm} (15)

The proof of Corollary 3.

\[ t_1 - t_0^0 = \frac{8 \alpha \beta e}{(1 + 4 \beta r - \mu) (1 + 4 \beta r + 2 e - \mu)} > 0, \]

\[ t_1 - t_0^0 = \frac{9 \alpha \beta b (4 - \mu)^2}{m} \left( \frac{1}{16 - 17 \mu + \mu^2} + \frac{1}{4 - 11 \mu + 7 \mu^2 + 3 e (-8 - 2 \mu + \mu^2)} \right) > 0. \]  \hspace{1cm} (16)

The proof of Proposition 4.
The authors declare that they have no conflicts of interest.

Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

Acknowledgments
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References

\[
\begin{align*}
\frac{\partial s_j}{\partial \mu} & = \frac{2e}{(1+2e-\mu^2)} > 0, \\
\frac{\partial s_f}{\partial \mu} & = 9\left(1 - \mu^2 + e(56 - 16\mu + 5\mu^2)\right) \frac{(4 - 11\mu + 7\mu^2 + 3e(-8 - 2\mu + \mu^2))^2}{(4 - 11\mu + 7\mu^2 + 3e(-8 - 2\mu + \mu^2))^2} > 0.
\end{align*}
\]


