OPTIMAL STRATEGIES OF A DUAL-CHANNEL GREEN SUPPLY CHAIN WITH RECYCLING UNDER RETAILER PROMOTIONAL EFFORT

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Abstract. Due to the hugely populated world, recycling of the used products has become the most significant perspective in e-commerce. The scientists have been exploring how increases the degree of recyclability and the green innovation level. This paper considers a supply chain with a manufacturer, a retailer, a supplier, and a collector. The manufacturer can increase or decrease the level of green innovation by changing the quality of raw materials. He sells them through his direct channel as well as the retailer's traditional channel. The retailer enforces the strategy promotional effort for enlarging his market demand. After formulating the problem, the strategies in collector-led, supplier-led, collector–supplier Nash, and collector–supplier–retailer Nash game are studied under manufacturer Stackelberg games along with the centralized policy. The parameters' sensitivity has been analyzed to the profits and decision variables and then draw significant managerial insights. The model declares the optimal strategies for each player as well as the chain. It is achieved that the higher level of green innovation and promotional effort always increases all the profit. The optimal pricing decisions be lowest under the Collector–Supplier Nash game.

1. Introduction

1.1. Motivation

Green innovation (GI) is a notion of managing the environment to reduce environmental pollution such as urban sprawl, non-sustainable resource consumption, industrial and household waste, etc. European Union sets a target to recycle at least 70% of all packaged goods by 2030 and for household recycling rates to be 65% by 2035 (https://www.nspackaging.com/analysis/best-recycling-countries/). To increase the recycling rate, one can take small steps like using biodegradable plastics while packaging and using more eco-friendly materials to produce household products. In the recycling process, used products are pulled together from the customers in several ways, and the manufacturer receives the recyclable wastes. This type of supply chain (SCN) is called a closed-loop (CLP) SCN. In this article, the collector collects the used products which are recyclable and then deliver to the manufacturer. To avoid the shortfall of raw material, the manufacturer may have brought fresh raw materials from the supplier [29].

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Again, it may be profitable to make some agreement among the members. For instance, many reputed companies, like Dell, Adidas, etc., cooperate with their respective raw material suppliers, and also soft drinks companies deal with some third party suppliers [10]. In this study, two types of strategies have been considered, such as Centralized policy (CP) and Manufacturer Stackelberg (MS) game. All the possible subcases have been studied under the MS game. In the commercial world, promotional effort (PE) is an essential useful tool for the retailer's standpoint. The effort is given to the customers by advertising, free sample show, free installation, sponsoring, and explanation of using methods [3]. For instance, if a retailer explains the basic features, offers installation free services, shows a free practical demonstration, customers automatically become biased to buy it from that retailer.

1.2. Novelties

The recent articles with CL SCN have been listed in Table 1. In the present article, we consider strategies: CP, three different strategies under MS, NG. Some of the strategies have been considered for the first time under this model formulation. In recent trends, recycling of the used products becomes an important aspect for the environment and, consequently, for the customers. So it is very exigent to include the collector of the waste as a member of the SCN and recycle the used products. Our present study focuses on optimizing the players' profits and the total profit (TPT) by using some specific game-theoretic approaches under the DC CLP green SCN. The parameters' sensitivity against the profit functions and the decision variables are analyzed, and then managerial insights are obtained.

The remaining paper is oriented as follows:

some related literature has been reviewed in Section 2. Then the notations are listed, and the assumptions of the model are defined in Section 3. Section 4 framed the model, and the profit functions are obtained under different strategies. In Section 5, a numerical example is constructed and analyzed the outcomes. Then the sensitivity of some of the parameters is analyzed in Section 6. After that, managerial insights have been discussed in the Section 7. Then the overall conclusion of the study is drawn in Section 8.

2. LITERATURE REVIEW

In this section, the literature related to our research directions are discussed such as: Dual channel (DC) supply chain (SCN) with recycling, GI and PE.

2.1. Dual channel supply chain with recycling

Due to the rapid increment of population and short life-cycled products, the wastes have increased dramatically in recent times. Many first economic countries like Germany, has implemented various strategies to increase the rate of recycling. The useful waste materials of the households and industries have recycled and then used to produce new materials [2, 28]. Then, Giovanni [9] have characterized a two-echelon (2En) CLP SCN in the battery industry and formulated a model with considering a manufacturer–retailer duality under MS game with recycling, where they have found that a maximum joint incentive always increases the GI level and profit of the manufacturer. After that, Shi *et al.* [25] has constructed a stylized DC CLP SCN with one manufacturer, one retailer, and one recycler. They have considered the manufacturer as a leader and then optimize the effectiveness and competitiveness by incorporating one of the remaining entities. The main findings of the study are that it has connected the business practices and theoretical explorations. Yuan *et al.* [34] has adopted useful method of optimization analysis and game theory to analyze for the players to achieve interest coordination under equilibrium states. They have also demonstrated the strength of their obtained results by numerical analysis.

2.2. Green innovation

In the study [33], a 2En SCN has been considered where a supplier sells through a retailer. The supplier is liable to impose GI in the materials that reduce the unit production cost and the harmfulness on the environment.

TABLE 1. Comparison between existing literatures and current article.

Representing paper (s)	Structure of the model	Attributes				Considering strategies	Members of the model
		Production size	Pricing	GI	PE		
Shi *et al.* [25]	DC CL SCN	×	✓	×	×	CP, four strategies under MS	a manufacturer, a retailer, a recycler
Cao *et al.* [2]	DC SCN	✓	✓	✓	×	remanufacturing subsidy, carbon tax	Government, a manufacturer, a retailer
Yuan *et al.* [34]	DC CL SCN	×	✓	×	×	CP, decentralized, Nash game (NG)	a manufacturer, a retailer, a recycler
Giovanni [9]	CL SCN	×	✓	✓	×	Benchmark game with and without incentive, NG	a manufacturer, two retailer
Yenipazarli [33]	2En sustainable SCN	×	✓	✓	×	NG, decentralized, collaboration with with sharing contract	a recycler, a collector
Jafari *et al.* [14]	3En Sustainable SCN	×	✓	✓	×	CP, collector stackelberg, recycler stackelberg, NG	a manufacturer, a retailer, a recycler
Mondal *et al.* [18]	DC CL green SCN	×	✓	✓	×	CP, decentralized, Stackelberg	a manufacturer, a retailer
Gao *et al.* [7]	Single channel green SCN	×	✓	✓	×	Government stackelberg, marginal- cost and development intensive GnP	a manufacturer, Government
Giri and Dey [10]	DC CL SCN	×	✓	✓	×	MS, CP, NG	a manufacturer, a collector, a recycler, a supplier
Roy *et al.* [21]	2En single channel SCN	×	✓	×	✓	CP, Stackelberg	a retailer, a supplier
Ranjan and Jha [20]	DC SCN	×	✓	✓	✓	CP, decentralized, collaboration	a manufacturer, a retailer
This article	DC CL SCN	×	✓	✓	✓	CP, three strategies under MS, NG	a manufacturer, a retailer, a supplier, a collector

Then they have studied the profit for upstream eco-efficient innovation under CP. Jafari *et al.* [14] has studied the economic and environmental perspectives under a 3En DC SCN with one collector, one manufacturer, and one recycler. They have found that the manufacturer opted for the collector when some thresholds are met. They have also determined the optimal strategy for the manufacturer under various games. A SCN has been considered by Gao *et al.* [7] in which a manufacturer can produce a green product (GnP), and the GI level has been determined by the manufacturer only if the GI level does not violate the green standard of government rule. They have also analyzed the sensitivity between GnP and non-GnP. The article Mondal *et al.* [18] have considered a green SCN where the manufacturer can produce and sell GnP through the online and traditional retail channel. The manufacturer collects the used products from the customers to recycle them. Then the susceptibility of the assumed parameters on the optimal decisions has been analyzed. Also, they have obtained important results with the assistance of a numerical example. Xie *et al.* [30] has studied the effect of green subsidies on the relationship between GI and financial performance. They have also drawn some useful managerial insights with the support of observations. Wang and Song [27] has investigated the pricing policies for the DC SCN within the presence of GI and PE. They have also considered that the manufacturer can produce two kinds of products: GnP, and non-GnP. The optimal decisions have been compared under three models and implemented the sensitivity analysis of the parameters. After that, the article Karim and Nakade [16] has considered a SCN model with a retailer and a manufacturer under demand disruption. This paper aims to optimize the production, green investment, and the resourcing decisions of the product so that the players can grab the maximum profit. They have concluded that the rate of disruption of the products affects all the decision variables.

2.3. Promotional effort

The retailer gives this effort to the customers to prompt his/her products. Advertising, public relations, free sample show, direct response marketing, sponsoring, social media, explanation of the guidelines of uses are examples of the PE [4, 6]. Roy *et al.* [21] has considered a 2En SCN with one supplier and one retailer where the demand rate is uncertain and depending on PE. All the profit functions of the proposed model have been analyzed and also compared them under different strategies. The pricing and coordination strategies have been studied by Ranjan and Jha [20] for a DC SCN. Here, the manufacturer can produce GnP and non-GnP and sell them to the retailer who provides the sales effort of the non-green-products. They have also developed a Stackelberg game-theoretic approach and then obtained the equilibrium results. After that, a 2En SCN has been considered by Yang *et al.* [32] consisting of a supplier and a retailer. They have identified the effects of the advertising elasticity and the interest rate on the pricing decisions. Also, numerical examples have been studied and analyzed the sensitivity of the parameters of the model. He and Zhou [12] has proposed a DC green SCN consisting of a manufacturer and a retailer. To prompt himself, the retailer gives more effort to sell products, which are called PE. They have examined the performance of the SCN under PE and analyzed the sensitivity of the PE parameters.

Besides these, many of the researchers have worked in these directions in recent trends [8, 23, 31]. From the Table 1, it can be concluded that this study is partially similar to Ranjan and Jha [20] and Mondal *et al.* [18]. But in this study, DC CLP green SCN has been considered with promotional effort. In the previous study, no researchers have considered such type of model.

3. Problem description

In this section, the problem is described at first and secondly listed down the assumptions and defines the used notation. Due to the enormous population and using eco-harmful products, recycling the used products has become crucial. On behalf of this, the present study aims to collect the recyclable used products and refurbish them accordingly. A 2En DC CLP SCN is formulated with a manufacturer, a collector, a supplier, and a retailer. Now, the question is, how be the raw materials collected? The collector gathers the waste (*i.e.*, used products) from the customers and sells them to the manufacturer. Then, the manufacturer converts this waste into fresh

raw materials. The rest of the raw materials are brought from the suppliers to make sure that they can produce enough finished GnP to soothe the customers' demand. The manufacturer produces the items for customers and sells them through the retailer or his online channel. Then the optimal pricing decisions and the Level of GI and PE are computed under different strategies like CP, NG and three types of decision making under MS.

3.1. Notation

The following notations have been used throughout the paper:

	Parameters
c_c	Unit collection cost of recyclable wastes to the collector (\$).
ϕ	Recyclability degree of waste denoting the portion of waste $(0 < \phi < 1)$ that can be recovered and turned into new product.
γ	Number of finished product by one unit of raw material $(0 < \gamma < 1)$.
β	Fractional part of recyclable product of one unit used product $(0 < \beta < 1)$.
$a_1, b_1 (> 0)$	Maximum possible demand faced by the manufacturer for the finished product in online channel and traditional channel.
$a_2, a_3, b_2 (> 0)$	Price sensitivity of the customers demand.
$a_4 (> 0)$	Sensitivity of the PE on the customers demand.
$a_5, b_5 (> 0)$	Positive and negative effects of the GIs on the customers' demand respectively.
p_{so}	Cost of the new raw material of the supplier (\$).
p_{rc}	Cost to recycle the waste collected from the collector.
	Decision variables
p_d	Price charged by the collector for one unit of recyclable waste (\$).
p_2	Price charged by the manufacturer to the customers for one unit of finished product in online channel (\$).
p_m	Price charged by the manufacturer to the retailer for one unit of finished product in indirect channel (\$).
p_1	Price charged by the retailer to the customers for one unit of finished product in indirect channel (\$).
p_s	Price charged by the supplier for one unit of fresh raw material (\$).
s	Level of promotional effort.
θ	GI level $(0 < \theta < \theta_{\max})$.
	Dependent variables
D_1	Customer demand of the manufacturer in online channel.
D_2	Customer demand of the manufacturer in traditional channel.
D_{rc}	Manufacturers demand of recyclable wastes meet up by the collector.
D_s	Manufacturers demand of fresh raw materials meet up by the supplier.

3.2. Assumptions

The assumptions which are made in this article, are listed below:

– The collector collects the used recyclable waste from the customers at a price c_c and sells it to the manufacturer at p_d.
– The manufacturer has the ability to enlarge or reduce the GI level of produced products accordingly. Here, we use a scale 0 to 100 to measure the level of GI, where 100 means the product is 100% green innovative, and it can be recycled completely, and 0 means these kinds of products has 0% recyclable parts.
– The retailer buys products from the manufacturer and sells it to the customers through the traditional channel. The retailer does not allow shortage and as well as does not stock. To exist in the comparative markets, the retailer gives some effort to promote the products.
– When the decision power of a member is greater than the other members, he expects his profit value would be greater than others' profit values. In this case, when a member acts as the leader, he admits to contributing

to the supply chain if the proportion of his profit and his followers' profits is more than a constant value. For example, when the retailer has more decision powers than the collector, then the retailer contributes to the supply chain if, $\frac{\Pi_r}{\Pi_c} > \tau_r$ where $\tau_r > 1$. For similar reason, we take τ_s and so for τ_c.

– In the model, we consider that the customers' demand depends linearly on the pricing of the products, the service, and the GI level of the products [5, 13]. It is the most simple form of demand, and most of the researchers like to choose such types. Next, the demand is monotonically decreasing with its own channel pricing and monotonically increasing with cross-channel pricing. It is also assumed that GI and PE positively affect the customers' purchasing rate and so on the demand. Therefore, the demand rates of the channels are as follows:

$$\text{Retail channel: } D_1 = a_1 - a_2 p_1 + a_3 p_2 + a_4 \theta + a_5 s, \tag{3.1}$$

$$\text{Direct channel: } D_2 = b_1 - b_2 p_2 + a_3 p_1 + a_4 \theta - b_5 s. \tag{3.2}$$

Therefore the total demand by the customer is $D_1 + D_2 = D$ (say) (D_1 and D_2 are taken from (3.1) and (3.2)). All the associated parameters of the demand rates are described in the Notation Section 3.1.

– Next, a discount policy is considered to improve the relationship between the manufacturer and the retailer. We assume that the manufacturer will provide a discount (k_1) on the online price to the retailer as the retailer brought a large quantity of the products at a time, i.e., $p_m = k_1 p_2$ and the production cost of the manufacturer is assumed negligible.

– In recent trends, due to the accessibility of online channels is greater than the retail channel from the customers' point of view. Therefore, The market potential of direct channel is assumed to be greater than the traditional channel (i.e., $b_1 > a_1$). Also, the own-channel pricing sensitivity is higher than the cross-channel pricing sensitivity on the demand rates (i.e., $a_2 > a_3$ and $b_2 > b_3$) [17].

– The total possible collected recyclable products are β times of total used product D. Therefore, the demand of the collector is $D_{rc} = \beta D$. Here, D is the number of finished products is produced from γD raw materials.

– From the collected recyclable products, the manufacturer recycles $\phi \beta D$ number of raw materials, and the supplier deals rest of the raw materials. Therefore the demand of the supplier is $D_s = (\gamma D - \beta \phi D)$, where $\beta = \rho_1 \frac{\theta}{\theta_{\max}} < 1$ and $\rho_1 > 0$ is constant. The value of the "fractional part of the recyclable product of one unit used product" directly depends on the GI level of the respective product.

– GI does not hamper the marginal cost of the manufacturer [1, 26] but, to produce GnP, the manufacturer should spend some extra to achieve the GI level. Here the cost function of GI level is considered as $\frac{1}{2}\xi\theta^2$ [17]. Also, the cost of offering PE is $\frac{1}{2}\eta s^2$ [3]. In general, the marketing executive (ME) measures the volume of the PE by observing PE's effectiveness on the customers' minds. As a result, the ME and the selling strategies' efficacy are the main goals for scaling PE. So that PE has no specific unit.

4. MODEL FORMULATION

In this section, the profit functions of the members of the proposed model are derived. Then three types of strategies are considered, such as CP, MS, and NG. Then the solutions for decision variables are derived for each strategy. The diagram of the proposed model can be understood in Figure 1.

To calculate the profit functions of the members, first, calculate the revenue and then the cost functions for each individual. Then, the revenue of the manufacturer is = total demand in the retail channel × wholesale price + total demand in online channel × direct channel price = $p_1 D_1 + p_2 D_2$, and the manufacturer's total cost is = cost of purchasing recyclable waste from collector + cost of purchasing row materials from supplier + cost of imposing GI + cost of recycle the waste = $D_{rc} \times p_d + D_s \times p_s + \frac{1}{2}\xi\theta^2 - p_{rc}D_{rc}$. Therefore, the profit of the manufacturer is = the revenue of the manufacturer – the manufacturer's total cost = $p_2 D_2 + D_1 p_m - (D_{rc}p_d + D_s p_s + \frac{1}{2}\xi\theta^2 + p_{rc}D_{rc})$. Next, the revenue of the retailer is = the total demand in the retail channel × retail price = $p_1 \times D_1$, and the retailer's cost is = products brought from the manufacturer × wholesale price + cost of giving promotional effort = $p_m \times D_1 + \frac{1}{2}\eta s^2$. Hence, the TPT of the retailer is = total revenue – total cost = $p_1 D_1 - p_m D_1 - \frac{1}{2}\eta s^2$. Consequently, the TPT of the collector is = total revenue – total cost = $p_d D_{rc} - c_c D_{rc}$,
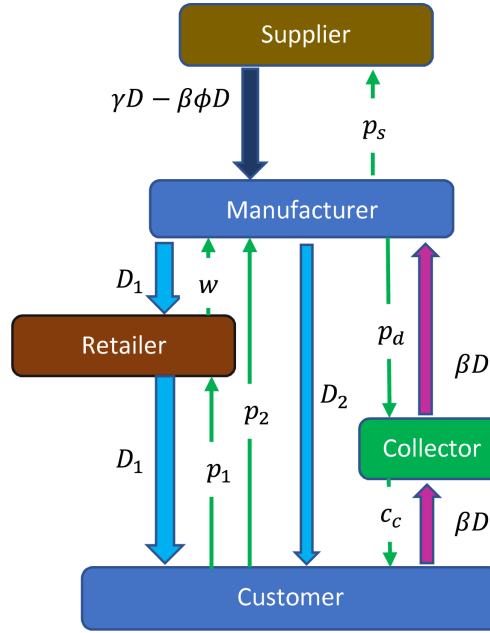
FIGURE 1. Graphical representation of the model. Descriptions of the symbol are given in Section 3.1.

and the profit of the supplier is $= p_s D_s - p_{so} D_s$. Therefore, the profit functions of the manufacturer, retailer, collector and the supplier are given by

$$\Pi_m = p_2 D_2 + D_1 p_m - \left(D_{rc} p_d + D_s p_s + \frac{1}{2} \xi \theta^2 \right) - p_{rc} D_{rc} \tag{4.1}$$

$$\Pi_r = (p_1 - p_m) D_1 - \frac{1}{2} \eta s^2 \tag{4.2}$$

$$\Pi_c = (p_d - c_c) D_{rc} \tag{4.3}$$

$$\Pi_s = (p_s - p_{so}) D_s \tag{4.4}$$

respectively, where the profits of manufacturer, retailer, collector and supplier are donated by subscripting m, r, c and s.

4.1. Centralized policy

The CP is a scheme where all the players act collectively, *i.e.*, there does no exist neither follower nor leader. Therefore, the total channel profit (Π_T) is given by

$$\Pi_T = \Pi_m + \Pi_r + \Pi_c + \Pi_s$$

$$= p_1 D_1 + p_2 D_2 - c_c D_{rc} - p_{s0} D_s - \frac{1}{2} \xi \theta^2 - \frac{1}{2} \eta s^2 - p_{rc} D_{rc}. \tag{4.5}$$

Now the optimal level of pricing, green level, and PEs are discussed of the proposed model under the CP.

4.1.1. Solution procedure

To obtain the maximum profit for the CP, at first the first order conditions of (4.5) is solved, i.e., we have to solve the following system of equations:

$$\begin{cases} \frac{\partial \Pi_T}{\partial p_1} = 0 \\ \frac{\partial \Pi_T}{\partial p_2} = 0 \\ \frac{\partial \Pi_T}{\partial \theta} = 0 \\ \frac{\partial \Pi_T}{\partial s} = 0 \end{cases} \Rightarrow$$

$$\begin{cases} a_1 - 2a_2 p_1 + 2a_3 p_2 + a_5 s + a_4 \theta + a_2 p_{s0}\gamma - a_3 p_{s0}\gamma + (a_2 - a_3)\theta (c_c + p_{rc} - p_{s0}\phi) \rho_1' = 0 \\ b_1 + 2a_3 p_1 - 2b_2 p_2 - b_5 s + a_4 \theta - a3 p_{s0}\gamma + b_2 p_{s0}\gamma - (a_3 - b_2)\theta (c_c + p_{rc} - p_{s0}\phi) \rho_1' = 0 \\ a_4 p_1 + a_4 p_2 - \theta\xi - 2a_4 p_{s0}\gamma - 2a_4\theta (c_c + p_{rc} - p_{s0}\phi) \rho_1' \\ \quad - (a_1 + b_1 - a_2 p_1 + a_3 p_1 + a_3 p_2 - b_2 p_2 + a_5 s - b_5 s + 2a_4\theta) (c_c + p_{rc} - p_{s0}\phi) \rho_1' = 0 \\ - b_5 p_2 - s\eta + b_5 p_{s0}\gamma + a_5 (p_1 - p_{s0}\gamma) - (a_5 - b_5)\theta (c_c + p_{rc} - p_{s0}\phi) \rho_1' = 0, \text{ where } \rho_1' = \frac{\rho_1}{\theta_{\max}}. \end{cases}$$

Solving the above equations, we get p_1^*, p_2^*, θ^*, and s^*. If the Hessian matrix (HM) of the profit function (4.5) is negative definite, then p_1^*, p_2^*, θ^*, and s^* will be the optimal value of the decision parameters p_1, p_2, θ and s respectively.

4.2. Manufacturer Stackelberg game

In this section, the manufacturer acts as a leader, and the other players (retailer, collector, and the supplier) follow the leader. Therefore, the manufacturer sets all the pricing decisions first, and the followers also decide their pricing decisions according to their decision power. Also, it is considered that the retailer has the next most power to decision making after the manufacturer. Based on the ability of decision making of the collector and supplier, three gaming plans are considered such as collector-led game (CL game), supplier-led game (SL game), and collector–supplier Nash (CS Nash). We also analyze the NG model among the retailer, supplier, and collector under MS game.

4.2.1. Collector-led game

In this model, the collector has more decision power than the supplier. So, the collector fixes his price, and then the supplier sets his own accordingly. Then the formulation of the model is as follows:

$$\begin{cases} L_1 : \max \ \Pi_m = p_2 D_2 + D_1 pm - \left(D_{rc} p_d + D_s p_s + \frac{1}{2}\xi\theta^2\right) - p_{rc} D_{rc} \\ L_2 : \max \ \Pi_r = (p_1 - p_m)D_1 - \frac{1}{2}\eta s^2 \\ L_3 : \max \ \Pi_c = (p_d - c_c)D_{rc} \\ L_4 : \max \ \Pi_s = (p_s - p_{so})D_s. \end{cases} \tag{4.6}$$

Now, using the equation (4.6) and setting $\frac{\Pi_r}{\Pi_c} \geq \tau_r$, we get $p_d \leq \mathfrak{F}_1(p_1, p_2, s, \theta, p_s; \tau_r)$. Since Π_c is linearly increasing on p_d, the optimal value of p_d is the upper bound of p_d. Therefore we set

$$p_d = \mathfrak{F}_1(p_1, p_2, s, \theta, p_s; \tau_r). \tag{4.7}$$

By similar procedure, setting $\frac{\Pi_c}{\Pi_s} \geq \tau_c$, the optimal value of p_s can be decided by supplier as

$$p_s = \mathfrak{F}_2(p_1, p_2, s, \theta; \tau_c). \tag{4.8}$$

Now, substituting (4.8) in (4.7), we get

$$p_d = \mathfrak{F}_1'(p_1, p_2, s, \theta; \tau_c, \tau_r). \tag{4.9}$$

Then, We partially differentiate the profit function of the retailer Π_r with respect to p_1 and s. Then, by equating the first order derivative to zero and by solving, we get

$$\begin{cases} p_1 = \mathfrak{F}_3 \left(p_2, \theta; \tau_c, \tau_r\right) \\ s = \mathfrak{F}_4 \left(p_2, \theta; \tau_c, \tau_r\right). \end{cases} \tag{4.10}$$

These values are optimal if the HM of the profit function is negative definite. In this case, for the complexity, The negative definiteness of the HM of the profit function can be checked numerically as expressions. Using (4.8)–(4.10), we transfer the profit function of manufacturer Π_m to a function of p_2 and θ. Then the function is optimized with respect to p_2 and θ and get constant values p_2^* and θ^* respectively. Similarly, Using these values, we obtain the optimal values of p_r, p_d and p_s as p_r^*, p_d^* and p_s^* respectively from (4.8) to (4.10).

4.2.2. Supplier-led game

In this model, the supplier has more decision power than the collector. So, the supplier determines his price, and then the collector adjusts his own accordingly. The model is formulated as follows:

$$\begin{cases} L_1 : \max \ \Pi_m = p_2 D_2 + D_1 pm - \left(D_{rc} p_d + D_s p_s + \frac{1}{2}\xi\theta^2 + p_{rc} D_{rc}\right) \\ L_2 : \max \ \Pi_r = (p_1 - p_m)D_1 - \frac{1}{2}\eta s^2 \\ L_3 : \max \ \Pi_s = (p_s - p_{so})D_s \\ L_4 : \max \ \Pi_c = (p_d - c_c)D_{rc}. \end{cases} \tag{4.11}$$

Using $\frac{\Pi_r}{\Pi_s} \geq \tau_r$, and then making some calculation, we obtain $p_s \leq \mathfrak{G}_1(p_1, p_2, s, \theta, p_d; \tau_r)$. Since the profit of the supplier Π_s linearly increasing in p_s, the upper bound is the optimal value of p_s. Therefore,

$$p_s = \mathfrak{G}_1 \left(p_1, p_2, s, \theta, p_d; \tau_r\right). \tag{4.12}$$

Similarly, using $\frac{\Pi_s}{\Pi_c} \geq \tau_s$ and (4.12), we have $p_d \leq \mathfrak{G}_2(p_1, p_2, s, \theta; \tau_r, \tau_s)$. As Π_c is linearly increasing in p_d, the optimal value of p_d is given by

$$p_d = \mathfrak{G}_1 \left(p_1, p_2, s, \theta; \tau_r, \tau_s\right). \tag{4.13}$$

Substituting (4.13) on (4.12), we get

$$p_s = \mathfrak{G}_1' \left(p_1, p_2, s, \theta; \tau_r, \tau_s\right). \tag{4.14}$$

After that, the profit of the retailer Π_r is optimized with respect to p_1 and s, the optimal values can be obtained as follows:

$$\begin{cases} p_1^* = \mathfrak{G}_3 \left(p_2, \theta; \tau_r, \tau_s\right) \\ s^* = \mathfrak{G}_4 \left(p_2, \theta; \tau_r, \tau_s\right) \end{cases} \tag{4.15}$$

respectively. Using (4.13)–(4.15), we also optimize the profit of the manufacturer Π_m with respect to p_2 and θ and get the optimal values of them as p_2^* and θ^* respectively. Using the values of p_2^* and θ^*, the optimal values p_1^*, s^*, p_d^* and p_s^* can be obtained.

4.2.3. Collector–Supplier Nash

Here, let us consider that the collector and supplier have equal decision power. Therefore, both of them fix their prices independently and simultaneously only after the manufacturer and the retailer. The model is formulated as follows:

$$\begin{cases} L_1 : \max \ \Pi_m = p_2 D_2 + D_1 pm - \left(D_{rc} p_d + D_s p_s + \frac{1}{2}\xi\theta^2\right) - p_{rc} D_{rc} \\ L_2 : \max \ \Pi_r = (p_1 - p_m)D_1 - \frac{1}{2}\eta s^2 \\ L_3 : \max \ \Pi_s = (p_s - p_{so})D_s \\ L_3 : \max \ \Pi_c = (p_d - c_c)D_{rc}. \end{cases} \tag{4.16}$$

Since Π_c is linearly increasing in p_d, it can be argued similarly to the previous game models to get the optimal price of the collector. The optimal price of p_d is given by

$$p_d = \mathfrak{H}_1'\left(p_1, p_2, s, \theta, p_s; \tau_r\right). \tag{4.17}$$

Similarly, the optimal price of the supplier can be obtained as

$$p_s = \mathfrak{H}_2'(p_1, p_2, s, \theta, p_d; \tau_r). \tag{4.18}$$

From (4.17), the value value of p_s can be obtained. Let

$$p_s = \mathfrak{H}_2''(p_1, p_2, s, \theta, p_d; \tau_r). \tag{4.19}$$

Equating the right hand side of (4.18) and (4.19), we have

$$p_d = \mathfrak{H}_1''(p_1, p_2, s, \theta; \tau_r). \tag{4.20}$$

Now from (4.18) and (4.20), we have

$$p_s = \mathfrak{H}_2\left(p_1, p_2, s, \theta; \tau_r\right). \tag{4.21}$$

Then using this value of p_s, we can obtain

$$p_d = \mathfrak{H}_1\left(p_1, p_2, s, \theta; \tau_r\right). \tag{4.22}$$

Then using the values of p_d and p_s from (4.21) and (4.22), the optimal values of p_1, p_2, s and θ can be obtained in similar method as previous models.

4.2.4. Nash game

In this model, all the players except the manufacturer have the same decision power and decide independently and simultaneously. The proposed model is formulated below:

$$\begin{cases} L_1 : \max \ \Pi_m = p_2 D_2 + D_1 p_m - \left(D_{rc}p_d + D_s p_s + \frac{1}{2}\xi\theta^2 + p_{rc}D_{rc}\right) \\ L_2 : \max \ \Pi_r = \ (p_1 - p_m)D_1 - \frac{1}{2}\eta s^2 \\ L_2 : \max \ \Pi_s = \ (p_s - p_{so})D_s \\ L_2 : \max \ \Pi_c = \ (p_d - c_c)D_{rc}. \end{cases} \tag{4.23}$$

As the previous model, using $\frac{\Pi_m}{\Pi_s} \geq \tau_m$ and $\frac{\Pi_m}{\Pi_c} \geq \tau_m$ and with some calculation, the following inequalities can be obtained as $p_s \leq \mathfrak{K}_1(p_1, p_2, s, \theta, p_d; \tau_m)$ and $p_d \leq \mathfrak{K}_2(p_1, p_2, s, \theta, p_s; \tau_m)$ respectively. Since Π_s and Π_c are linearly increasing with p_s and p_d respectively, so the optimal values of p_s and p_d exist at the upper bounds. Therefore, the optimal values are as follows:

$$p_s = \mathfrak{K}_1\left(p_1, p_2, s, \theta, p_d; \tau_m\right) \tag{4.24}$$
$$p_d = \mathfrak{K}_2'\left(p_1, p_2, s, \theta, p_s; \tau_m\right). \tag{4.25}$$

Now, we solve the first order condition of the profit function Π_r with respect to p_1 and s. Let the solutions are $p_1 = p_1^*$ and $s = s^*$. If the HM of the profit function Π_r is negative definite at p_1^*, s^* then the function is maximum at that point and the values, p_1^* and s^* are optimal. Then putting all the optimal values of the decision variables p_1, s, p_d and p_s on the profit function Π_m, we get Π_m^*. Then the first-order conditions of Π_m^* for p_2 and θ is solved and getting their values as p_2^* and θ^* respectively. If the HM of the profit function Π_m^* is negative definite, then p_2^* and s^* are the optimal values of p_2 and s respectively. Then the optimal profits of the collector, the retailer, and the manufacturer can be obtained from equation (4.23).

TABLE 2. Optimal values of decision variables under different game models.

Optimal results	CP ($)	CL game ($)	SL game ($)	CS Nash ($)	NG ($)
p_1^*	136.18	124.408	104.40	103.18	112.01
p_2^*	132.54	113.24	99.38	98.89	102.44
θ^*	95.87	56.2634	28.63	26.42	42.45
s^*	9.76193	5.63591	4.15	4.01	5.01
p_d	–	14.0468	29.30	40.7599	32.39
p_s	–	26.1083	32.84	32.5578	35.12
Π_m^*	–	14050.9	8173.24	7430.86	5977.45
Π_r^*	–	5526.85	2994.77	2799.17	4365.51
Π_c^*	–	921.14	1535.78	2153.21	3415.69
Π_s^*	–	368.46	2303.67	2153.21	3415.69
Π_T^*	24539.8	20867.35	15007.46	14536.45	17174.3

5. NUMERICAL EXAMPLE

To illustrate our formulated model, we consider the values of the parameters as follows: $c_c = \$10$; $p_{rc} = \$1$; $\rho_1 = 1$; $\theta_{\max} = 100$; $\gamma = 1.3$; $p_{s0} = \$25$; $a_1 = 300$; $a_2 = 5$; $a_3 = 2.25$; $a_4 = 4$; $a_5 = 2$; $b_1 = 325$; $b_2 = 5.2$; $b_5 = 1$; $\xi = \$12$; $\eta = \$12$; $k_1 = 0.8$; $\phi = 0.85$; $\tau_m = 1.75$; $\tau_r = 6$; $\tau_c = 2.5$; $\tau_s = 1.5$. For this hypothetical data set, the eigenvalues of the HM of the profit function Π_T be -15.868, -13.799, -10.8526, -2.24039 under CP at the values of the decision variables listed in the following Table 2. Hence the profit Π_T is maximum, and the optimal values of the decision variables are stored, and each players' profits are calculated as in Table 2. Under the strategy-CL, the eigenvalues of the HMs corresponding to the profit functions Π_m and Π_r are -16.2986, -3.74321, and -13.2361, -8.76393, respectively. Hence, the optimality condition holds, and the functions Π_m and Π_r are maximum at the respective values of decision variables. Again for the strategy SL, the HMs corresponding to the profit functions Π_m and Π_r are negative definite as the eigenvalues of the Matrices are -16.3788, -3.75069, and -13.2361, -8.76393 respectively. Hence the profit functions are maximum. Similarly, under the strategies CS and NS, the HMs of the profit functions are negative definite. Hence, the functions are maximum at the optimal values of the decision variables.

From Table 2, some results can be concluded as follows:

(1) The leader manufacturer holds a higher profit for all the studied cases.
(2) The best fit game, according to the profits for the players, is listed in the following:
 (a) The manufacturer and the retailer gain most under CP.
 (b) The Collector and the supplier make their maximum profit under the NG.
(3) The PE is maximum in CP. Therefore the customers will get the best effort from the retailer if the players participate centrally.
(4) The customers have to pay the lowest under the case: CS Nash. Although, in this game, the level of PE is also the smallest respect for the other games.
(5) Under the CP, the manufacturer can produce most eco-friendly products (*i.e.*, the level of GI is maximum under this game). As a result, the environment-conscious players will be keener to join in the CP.

6. SENSITIVITY ANALYSIS

Now, the sensitivity of the parameters ρ_1, ξ, η, a_2 and b_2 are analyzed on the players' profits, TPTs, and the decision variables. Initially, the values of the parameters are set as below: $c_c = 10$; $\phi = 0.85$; $p_{rc} = 1$; $\theta_{\max} = 100$; $\gamma = 1.3$; $k_1 = 0.8$; $p_{s0} = 25$; $\tau_m = 1.75$; $\tau_c = 2.5$; $\tau_s = 1.5$; $\tau_r = 6$; $a_1 = 300$; $a_3 = 2.25$; $a_4 = 4$; $b_1 = 325$; $a_5 = 2$; $b_5 = 1$; $\rho_1 = 1$. In the figure 2, it can be observed that the curve representing the TPT under CP is placed

topmost and then the TPTs under NG, SL game, CL game one by one and lastly, the curve representing the TPT of CS nash placed at the bottom. Therefore the sequence of the TPTs under each parameters' effect is as $\Pi_c \geq \Pi_T^n \geq \Pi_T^{sl} \geq \Pi_T^{cl} \geq \Pi_T^{csn}$, where n, sl, cl, csn stands for NG, SL game, CL game, and CS Nash respectively.

Whenever ρ_1 increases, the rate of recyclable waste materials increases, and the number of fresh materials decreases with an increment of ρ_1. Consequently, all the decision variables increase with the increment of ρ_1 except p_d (see Tab. 3). As a result, the demand rates and the profit margins of the chain increase. Also, the profits of the manufacturer and the retailer increase with the increment of ρ_1 (see Figs. 2a, 3a, and 4a).

In the Figures 2b, 3b and 4b, the horizontal axis represents the values of ξ and the vertical axis represents the profits. It can observed that, the curves are in downward direction with the increment of the value of horizontal axis. Hence the cost parameter of the GI level (ξ) is inversely proportional to the profits of the manufacturer, retailer, and SCN since all the decision variables except p_d, and the demand rates decrease with the increment of this parameter.

In Figure 3c, the curve representing the profits of the manufacturer remains fixed with the change of η. Because, it is considered in the numerical example that the impact of PE is not as much as of GI on the customer's mind. Furthermore, the retailer provides PE. Therefore, the decision variables of the manufacturer (see Tab. 3) change a niggling and also is the same for his profit (see Fig. 3c). Again, in Figures 2c and 4c, the curves represent the retailer's and total chain profit respectively and it can be observed that they go gradually in the downward direction with the increment of the cost parameter of the PE (η). Hence, if η increases then all the profits decreases. Again, in Figure 2d and 2e, the curves are downward direction with the increment of the values of horizontal axis. Hence, the TPT of the SCN decreases for higher values of the own channel price sensitivity parameters (a_2 and b_2), because all the decision variables and the demand rates diminish with the increments of those parameters (see Tab. 3). It can be concluded similarly for the sensitivity of these two parameters on the manufacturer's and the retailer's profit (see Figs. 3d, 4d, 3e and 4e).
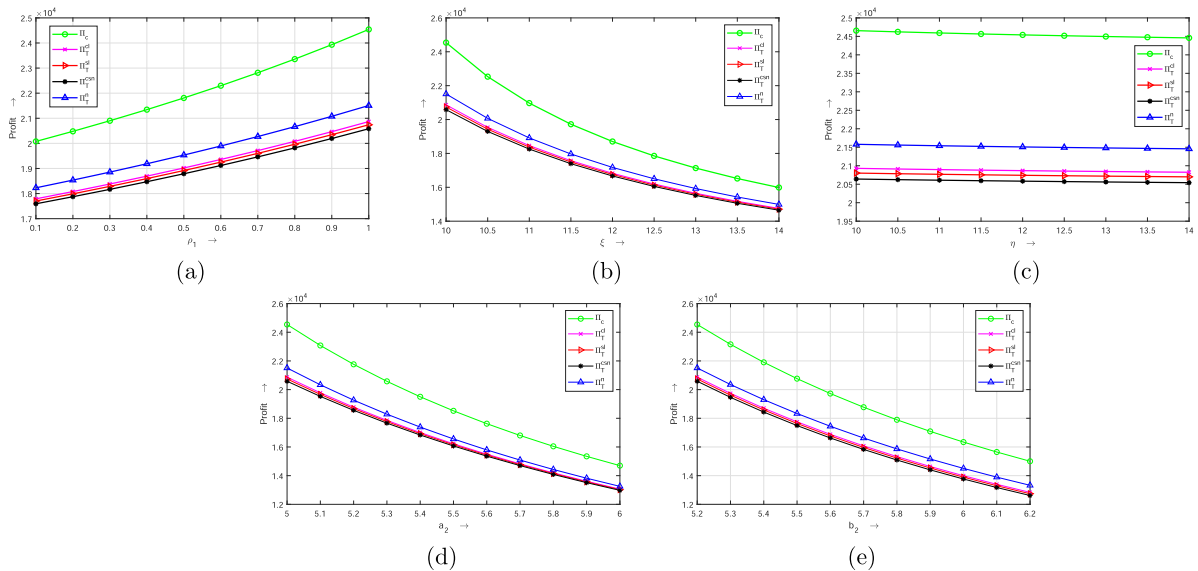
6.1. Total profit

FIGURE 2. Effect of the parameters on the TPT of the SCN. (a) TPT *versus* ρ_1. (b) TPT *versus* ξ. (c) TPT *versus* η. (d) TPT *versus* a_2. (e) TPT *versus* b_2.
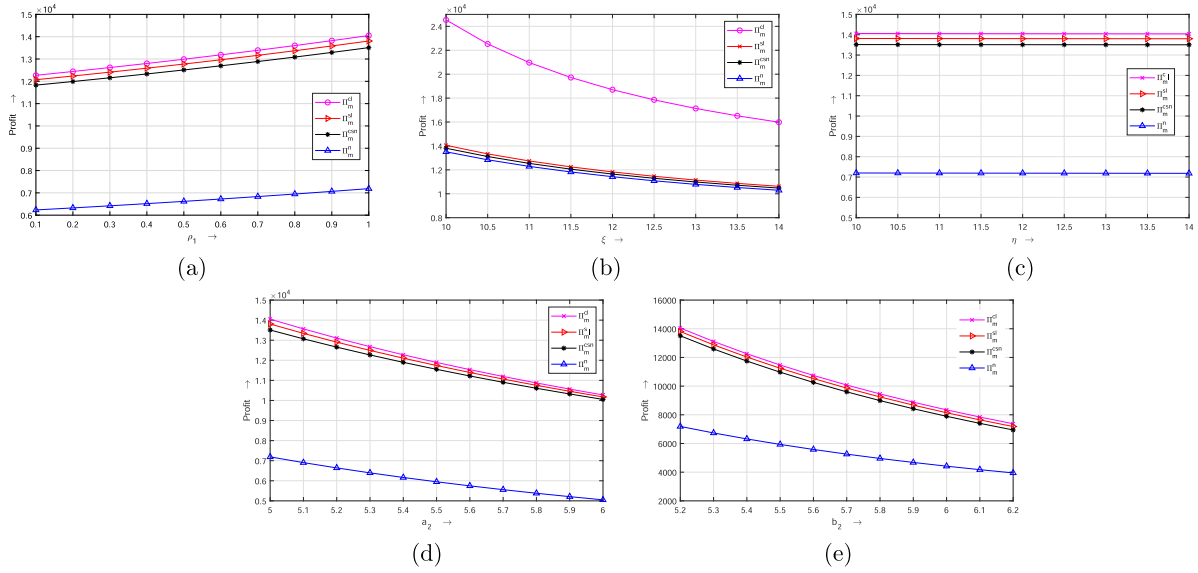
6.2. Manufacturer's profit

FIGURE 3. Effect of the parameters on the Manufacturer's profit. (a) Manufacturer profit *versus* ρ_1. (b) Manufacturer's profit *versus* ξ. (c) Manufacturer's profit *versus* η. (d) Manufacturer's profit *versus* a_2. (e) Manufacturer's profit *versus* b_2.
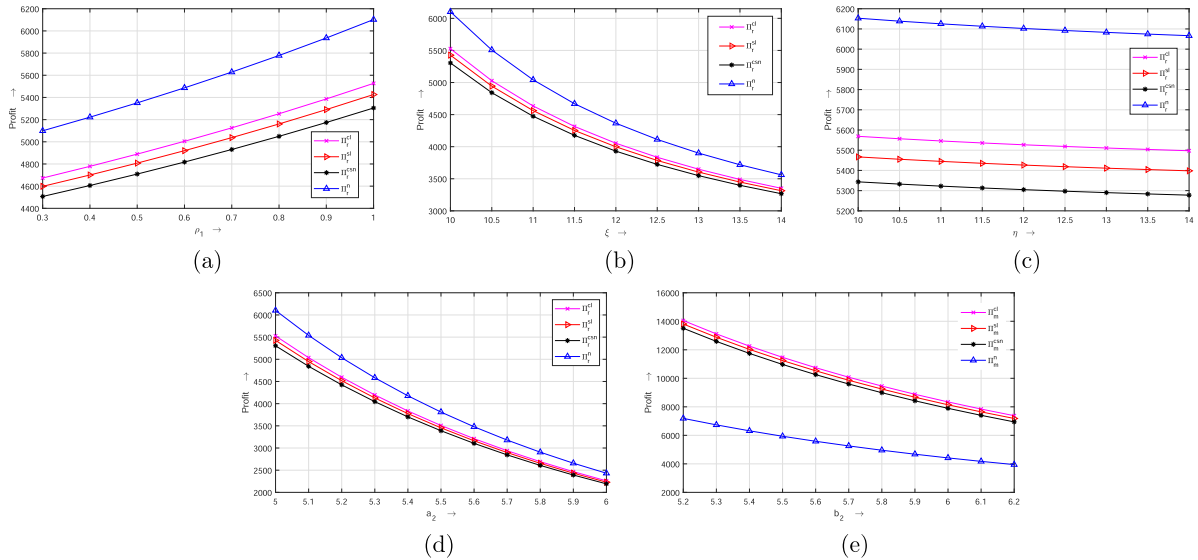
6.3. Retailer's profit

FIGURE 4. Effect of the parameters on the Retailer's profit. (a) Retailer profit *versus* ρ_1. (b) Retailer's profit *versus* ξ. (c) Retailer's profit *versus* η. (d) Retailer's profit *versus* a_2. (e) Retailer's profit *versus* b_2.

TABLE 3. Effect of the parameters on the decision variables.

			CL game						SL game						CS Nash						NG			
ρ_1	p_1^*	p_2^*	s^*	θ^*	p_s^*	p_d^*	p_1^*	p_2^*	s^*	θ^*	p_s^*	p_d^*	p_1^*	p_2^*	s^*	θ^*	p_s^*	p_d^*	p_1^*	p_2^*	s^*	θ^*	p_s^*	p_d^*
0.6	120.92	110.93	5.36	51.29	25.84	17.11	120.43	110.65	5.32	50.51	27.09	14.79	119.82	110.31	5.26	49.56	27.06	17.26	123.66	112.46	5.62	55.62	34.36	38.51
0.7	121.75	111.48	5.43	52.47	25.9	16.02	121.24	111.19	5.38	51.67	27.21	14.05	120.61	110.84	5.32	50.68	27.18	16.14	124.58	113.07	5.69	56.94	34.91	33.89
0.8	122.61	112.05	5.49	53.69	25.96	15.2	122.08	111.75	5.45	52.86	27.36	13.49	121.43	111.39	5.39	51.84	27.32	15.3	125.53	113.69	5.76	58.3	35.55	30.43
0.9	123.49	112.64	5.56	54.95	26.03	14.56	122.95	112.33	5.51	54.1	27.53	13.07	122.28	111.95	5.45	53.05	27.48	14.65	126.42	114.36	5.82	59.6	35.95	26.87
1.0	124.41	113.24	5.64	56.26	26.11	14.05	123.85	112.92	5.59	55.38	27.73	12.72	123.16	112.53	5.52	54.3	27.67	14.13	127.68	114.97	5.91	61.05	36.45	23.49
ξ			CL game						SL game						CS Nash						NG			
10	124.41	113.24	5.64	56.26	26.11	14.05	123.85	112.92	5.58	55.38	27.73	12.72	123.16	112.53	5.52	54.3	27.67	14.13	127.54	115.01	5.92	61.19	37.24	25.6
10.5	119.9	109.56	5.38	50.88	26.01	14.28	119.43	109.31	5.33	50.11	27.48	12.88	118.85	109.01	5.27	49.18	27.44	14.37	122.5	110.93	5.63	55.1	36.46	27.3
11	116.18	106.52	5.16	46.43	25.93	14.52	115.78	106.32	5.12	45.76	27.29	13.04	115.29	106.08	5.07	44.94	27.26	14.61	118.37	107.59	5.38	50.12	35.9	29
11.5	113.05	103.96	4.98	42.7	25.87	14.76	112.71	103.81	4.94	42.11	27.15	13.2	112.3	103.63	4.9	41.37	27.12	14.86	114.92	104.8	5.18	45.97	35.46	30.7
12	110.39	101.79	4.83	39.52	25.82	15	110.1	101.67	4.79	38.99	27.03	13.36	109.74	101.53	4.75	38.33	27.01	15.1	112.1	102.44	5.01	42.45	35.12	32.39
η			CL game						SL game						CS Nash						NG			
11	124.54	113.27	6.17	56.29	26.11	14.06	123.9	112.95	6.11	55.4	27.73	12.73	123.29	112.56	6.04	54.31	27.68	14.14	127.69	115.05	6.48	61.23	37.24	25.59
11.5	124.47	113.26	5.89	56.28	26.11	14.05	123.91	112.94	5.84	55.39	27.73	12.73	123.22	112.55	5.77	54.31	27.68	14.14	127.61	115.03	6.19	61.21	37.24	25.59
12	124.41	113.24	5.64	56.26	26.11	14.05	123.85	112.92	5.58	55.38	27.73	12.72	123.16	112.53	5.52	54.3	27.67	14.13	127.54	115.01	5.92	61.19	37.24	25.6
12.5	124.3	113.23	5.4	56.25	26.10	14.04	123.79	112.91	5.35	55.37	27.72	12.72	123.1	112.52	5.29	54.29	27.67	14.13	127.47	114.99	5.68	61.17	37.24	25.61
13	124.29	113.21	5.19	56.24	26.10	14.04	123.73	112.9	5.14	55.36	27.72	12.72	123.05	112.51	5.08	54.28	27.67	14.12	127.41	114.97	5.45	61.15	37.24	25.61
α_2			CL game						SL game						CS Nash						NG			
5	124.41	113.24	5.64	56.26	26.11	14.05	123.85	112.92	5.58	55.38	27.73	12.72	123.16	112.53	5.52	54.3	27.67	14.13	127.54	115.01	5.92	61.19	37.24	25.6
5.2	117.23	108.77	5.04	52.98	25.93	13.73	116.79	108.54	4.99	52.23	27.3	12.51	116.2	108.27	4.94	51.31	27.26	13.8	119.64	110.01	5.27	57.13	36.37	26.21
5.4	110.9	104.79	4.51	50.06	25.72	13.29	110.56	104.63	4.48	49.43	26.94	12.31	110.15	104.44	4.43	48.64	26.91	13.49	112.76	105.63	4.71	53.59	35.65	26.78
5.6	105.28	101.21	4.05	47.46	25.67	13.15	105.02	101.12	4.02	46.92	26.65	12.11	104.7	100.99	3.98	46.25	26.63	13.19	106.71	101.75	4.22	50.47	35.04	27.33
5.8	100.25	97.99	3.64	45.13	25.57	12.88	100.05	97.93	3.62	44.66	26.41	11.93	99.81	97.86	3.59	44.08	26.39	12.92	101.35	98.29	3.79	47.7	34.53	27.86
α_2			CL game						SL game						CS Nash						NG			
5.2	124.41	113.24	5.64	56.26	26.11	14.05	123.85	112.92	5.58	55.38	27.73	12.72	123.16	112.53	5.52	54.3	27.67	14.13	127.54	115.01	5.92	61.19	37.24	25.6
5.4	117.08	105.26	5.48	50.5	26.05	14.53	116.56	104.98	5.43	49.66	27.59	13.05	115.93	104.64	5.37	48.63	27.54	14.63	119.99	106.82	5.75	55.17	35.71	26.13
5.6	110.87	98.5	5.35	45.61	26.01	15.04	110.39	98.25	5.3	44.81	27.4	13.4	109.79	97.94	5.24	43.82	27.45	15.18	113.59	99.89	5.61	50.07	34.5	26.58
5.8	105.54	92.69	5.23	41.4	25.98	15.6	105.08	92.47	5.18	40.63	27.42	13.78	104.52	92.19	5.13	39.69	27.38	15.77	108.09	93.95	5.49	45.69	33.51	26.97
6	100.91	87.65	5.13	37.75	25.96	16.21	100.47	87.45	5.09	37	27.36	14.2	99.94	87.2	5.03	36.09	27.33	16.42	103.33	88.79	5.38	41.89	32.68	27.3

7. Managerial insights

In this section, we draw some important insights that will be more profitable for a supply chain similar to our proposed model with sensitivity analysis. The manufacturer should improve products with their GI so that the rate of recyclability of the product increases and the profits of the channel. But the cost coefficient of the GI (ξ) may affect the profits if the manufacturer does not decide to decrease GI to a certain value. The retailer's PE has a positive effect on the demand rate to help the retailer gain more. But if the cost coefficient of PE (η) decreases, the retailer should decide to increase the PE so that the demand rate of his channel increases. Besides, if the pricing sensitivity of the demand rates (a_1 and b_1) increases, then each players' profit decrease. Therefore they should decrease the values of a_1 and b_1 so that they make more profits. Under CP, the manufacturer can impose higher GI on the product, and the retailer can provide greater PE to the customers than the other strategies. From the SCN's point of view, CP is the best policy to make the most profit than any other strategy. Therefore, if the members work collaboratively, then they can make the highest profit. But the collector and the supplier make their maximum profit under NG comparing to other strategies.

8. Conclusion

In this paper, environmental sustainability has been studied by collecting waste from the end customers and recycling them. In the shortage of recyclable waste material, the manufacturer buys the extra fresh raw materials from the supplier to meet the demands. A dual-channel CLP SCN has been considered, where the collector sells the collected recyclable wastes to the manufacturer, and the manufacturer sells his finished products through retail channels as well as direct channels. The retailer provides PE to the customers, and the manufacturer imposes the greenness on the products while manufacturing. This model has described the CP and MS games, where the Stackelberg game separates the study in the four directions, such as CL game, SL game, CS Nash, and NG structures. The significant outcomes of the study are as follows:

(1) The rate of recyclable waste materials (β) is directly proportional to the GI level (θ). Whenever the rate of recyclable waste increases, then the demand of the corresponding materials increases. Consequently, it increases the profits for each player.
(2) If the cost coefficient of GI (ξ) decreases, then the manufacturer become keener to increase the level of GI. Consequently, the demand rates will increase and the profits of the members will increase with the increment of the level of GI.
(3) If the cost coefficient of PE (η) decreases, then the retailer will try to increase the level of PE so that he can attract more customers to be a part of the retail channel. Consequently, the demands of the retail channel increase with the decrement of η. As a result, a higher PE level always gives more profit to the retailer in all cases.
(4) If the pricing sensitivity of demand rate increases, then it decreases the demand of the corresponding channel as well as the profits of the members. Therefore, it can be concluded that pricing sensitivity is inversely proportional to the profit of each player.
(5) Under MS settings, the manufacturer's and the retailer's profit is utmost under the CL game, whereas the collector and the supplier are more benefitted in the NG.
(6) The TPT of the SCN under CP is higher than all other game strategies.

Several research works can be done related to this direction. In this paper, the demand function is a deterministic type, but it can be straightaway modified by considering stochastic demand. This study considers a SCN with a single manufacturer and single retailer, but investigating a DC SCN with multiple-manufacturer or multiple-retailer might make the collaboration problem more difficult. Also, one can consider different types of coordination between the players to obtain higher profit.

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