Environmental Sustainability By Recycling of PET Plastic Bottles And Reusing Them In Textile Industry: A Game-Theoretic Approach

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Environmental sustainability by recycling of PET plastic bottles and reusing them in textile industry: A game-theoretic approach

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Abstract

This study considers a sustainable supply chain including the collector, cleaner, and recycler for recycling of PET plastic bottles and reusing them in textile industry. In the market, some suppliers of textile industry purchase cleaned and non-fragmented bottles and then they fragment them, whereas others prefer to buy recycled materials (i.e., cleaned and fragmented bottles). The collector collects used plastic bottles. To meet demand of the recycled materials, the collector transfers a portion of the collected bottles to the recycler and then the recycler cleans and fragments them. Furthermore, the collector cleans another portion of the collected bottles himself or via a cleaner to meet demand of the cleaned and non-fragmented bottles. In this setting, two different structures are established for transferring the cleaned bottles to suppliers. Under the first structure, the collector cleans the collected bottles through the cleaner by giving a share of the profit to him, while he is equipped with the bottles cleaning technology by paying a setup cost under the second structure. Moreover, the game-theoretic models are developed including Nash, Stackelberg, and Centralized to make decisions under two considered structures.

Keywords: Sustainability; Sustainable supply chain; Recycling; Recycling of PET plastic bottles; Green production; Game theory.

1. Introduction

In the last two decades, by increasing natural resource scarceness, the plastic waste is taken into consideration as a resource that should be globally managed (Akbar and Liew 2020). It has been reported that about 50% of the plastic waste is recyclable and can be reused in different industries (Goli et al. 2020). Recycling is an efficient approach to improve the plastic waste management (Caetano et al. 2020; Zgheib and Takache 2021). As a matter of fact, burning the plastic waste emits dangerous chemicals to the environment and this leads to increasing carbon emission (Eneh and Policy 2021). Therefore, recycling of the plastic waste avoids toxic pollution as well as saves natural resources (Menges et al. 2021). In this point of view, manufacturing using these recyclables rather than the virgin materials makes the environment friendlier (Gautam and Kumar 2005; Van Caneghem et al. 2019).

PET plastic bottles (bottles made of polyethylene terephthalate) are taken into account as a considerable portion of the plastic waste (Mohanraj et al. 2017). Reports indicate that approximately 86% of PET plastic bottles used in the United States are dumped in the landfills (Minakova et al. 2018). Moreover, up to 450 years are taken for the plastic bottles to decompose (Kreiger et al. 2012; Ros-Chumillas et al. 2007). Thus, it seems that recycling of PET plastic bottles has a significant role to make the environment friendlier.

By increasing the petroleum prices, recycling of PET plastic bottles leads to higher profits for the manufacturers compared with the situation in which they use the virgin materials (Jacobs and Subramanian 2012). In fact, due to the environmental effects, recycling of the plastic bottles for reusing them in different industries has attracted a considerable attention in recent years (Doan et al. 2020; Gopinath et al. 2020). As an example, PET plastic bottles can be collected, cleaned, and recycled to be reused in textile industry (Majumdar et al. 2020). They are considerably used to produce garments. Green clothing concept refers to fabrics made from the sustainable materials like plastic and bamboo (Leonas 2017; Shirvanimoghaddam et al. 2020). Nowadays, many people wear the green garments produced from the used plastic bottles (Casadesus-Masanell et al. 2009). In fact, buying the green garments is as a sign of the responsibility to sustain the environment. Thus, it can be stated that recycling of PET plastic bottles and reusing them in textile industry leads to a significant decrease in carbon emission and raw materials consumption (Kumar et al. 2020; Rausch and Kopplin 2020).

Game theory investigates the competitive and cooperative behaviours on different situations (Lou et al. 2004; Yu et al. 2020; Zhou et al. 2019). Many studies have discussed how to make decisions using the game-theoretic framework in various supply chain structures. Recently, applications of the game-theoretic approach have greatly increased in the sustainable supply chain management. Nevertheless, to our knowledge, few studies on the waste recycling issue have applied the game-theoretic approach to make decisions under the considered supply chain. Most of these studies are addressed as follows:

He and Yuan (2020) studied the waste recycling issue by considering the consumers' quality perceptions of the recycled materials. Krikke et al. (2003) and Chen and Sheu (2009) investigated the recyclability rate of a product applying the game theory. Lu et al. (2014) developed a cooperative game theory model for analyzing the operations efficiency in a recycling industry. Jin et al. (2020) proposed a game-theoretic model to recycle the plastic waste in industrial parks and revealed some standards for the waste recycling. Qiu and Huang (2007) studied the recycling issue on a closed-loop supply chain under the stochastic demands. Grimes-Casey et al. (2007) applied the game theory to specify the lifecycle of the bottle packaging and present a framework to select between the disposable and refillable bottles. Xu et al. (2020) explored a decision-making mechanism to determine the prices and collection rate under a closed-loop supply chain. Moreover, Kaushal and Nema (2013), Kaushal and Nema (2012), and Kaushal et al. (2015) used the game theory to make decisions related to management of the electronic waste.

Sheu (2011) and Sheu and Chen (2012) established a three-stage game-theoretic model between a supplier and a manufacturer who produces a recyclable product. Jafari et al. (2017) considered a three-echelon supply chain including a collector, a recycler, and a manufacturer to procure a new product from the recyclable materials.

Yi et al. (2014), Feng et al. (2017), and Fu et al. (2012) studied the issue of the channel selection on the closed-loop supply chain. Furthermore, Huang et al. (2013) established a closed-loop supply chain with dual recycling channels. In this structure, products are sold via a retailer in the forward supply chain, whereas the retailer and a third party collect the used products in the reverse supply chain.

Long et al. (2020), Ma et al. (2020), and Chen and Hu (2018) investigated the manufacturing and recycling processes on the green development performance using an evolutionary game model. Su (2020), Ji et al. (2015), and Soltani et al. (2016) established an evolutionary game model among three stakeholders including the government agency, waste recycler, and waste producer. Moreover, Shen et al. (2018) proposed an evolutionary game consisting of the contractors and some manufacturers of the construction materials based on the prospect concept of the behavioral economics.

The current study discusses recycling of PET plastic bottles under a sustainable supply chain including the collector, cleaner, and recycler. PET plastic bottles are collected, cleaned, and fragmented to be reused in textile industry. Some suppliers of textile industry buy the cleaned and non-fragmented bottles and then they fragment them, while others prefer to purchase the recycled materials (i.e., the cleaned and fragmented bottles). Under the considered supply chain, the used plastic bottles are collected by the collector. A portion of these collected bottles is transferred to the recycler and then he cleans and fragments them and another portion meets the suppliers' demand for the cleaned bottles through the collector or cleaner. In this point of view, two different structures can be established for transferring the cleaned bottles to suppliers. Under the first structure, the collected bottles are cleaned via the cleaner giving a share of the profit by the collector to him, whereas the collector setups the bottles cleaning technology himself by paying a fixed cost under the second structure. Moreover, the game-theoretic approach is applied to make the decisions under various behaviors established among the members.

In summary, in this study, efforts are done to answer to the following research questions:

Research Question 1. Under the various interactions established among the members, what are the value of the decisions made by them?

Research Question 2. Under the various interactions among the members, which of the following structures is more beneficial from the collector's point of view?

- Cleaning the collected bottles via a cleaner by giving a share of the profit to him.
- Establishing the bottles cleaning technology by paying a setup cost.

Research Question 3. How the decisions are affected by developing different game-theoretic models?

Research Question 4. How the decisions are changed by implementing a sensitivity analysis?

Hence, it can be stated that the major characteristics that distinguish this study from those found in the literature are:

(1) In this study, a novel sustainable supply chain structure is established to collect, clean, and fragment PET plastic bottles and reuse them in textile industry.
(2) The study is the first one that analyzes the collector's decision about whether to clean the collected bottles through a cleaner giving a share of the profit to him or to establish the bottles cleaning technology himself by paying a setup cost.

The rest of the paper is organized as follows: Section 2 provides a detailed description of the research problem. In Section 3, the game-theoretic models are developed and the equilibrium strategies are obtained under the various interactions among the members. Section 4 deals with the results and a discussion of the equilibrium decisions given by the games. Moreover, conclusions and directions for future studies are included in Section 5.

2. Problem description

In this study, recycling of PET plastic bottles and reusing them in textile industry is discussed. PET plastic bottles can be collected, cleaned, and fragmented to be reused in textile industry as appropriate substitutable for virgin materials. In the market, some suppliers of textile industry procure the cleaned and non-fragmented bottles and afterward fragment them themselves, while others prefer to buy the recycled materials (i.e., the cleaned and fragmented bottles). As a matter of fact, some suppliers able to fragment the cleaned bottles themselves and others are not equipped with this technology and have to purchase the recycled materials. Obviously, the suppliers' demands for these two materials depend on their prices. In this setting, a sustainable supply chain is established including the collector, cleaner, and recycler firms to price the collected, cleaned, and fragmented plastic bottles in the market as follows.

The collector collects the used plastic bottles and then transfers them to suppliers. In fact, to meet the suppliers' demand for the recycled materials, he sells the collected bottles to the recycler and then the recycler cleans and fragments them. Finally, the recycled materials are transferred by the recycler to suppliers. Moreover, to meet the demand of the cleaned bottles, the collector cleans the collected bottles himself or through a cleaner. Note that the collector is not equipped with bottles cleaning technology, but he can buy the required equipment and establish this technology paying a setup cost or clean the collected bottles via the cleaner. In this point of view, two different structures are considered for transferring the cleaned bottles to suppliers. In the first structure (hereafter referred to as "structure S1"), the collector cleans the collected bottles through the cleaner by giving a share of the profit obtained from selling in this channel to him. Furthermore, in the second structure (hereafter referred to as "structure S2"), the collector establishes the bottles cleaning technology paying a setup cost.

Notations used in this study are defined as follows:

Parameters:

c_t	Collecting cost per ton
c_c	Cleaning cost per ton
c_f	Fragmenting cost per ton
K	Setup cost paid by the collector to establish bottle cleaning equipment
γ	Share of the profit obtained from selling the cleaned bottles given by the collector to the cleaner ($0 < \gamma < 1$)
a_c	Market scale (maximum possible demand) of the cleaned bottles
a_r	Market scale of the recycled materials
φ	Self-price sensitivity of demands
τ	Cross-price sensitivity of demands

Prices (Independent variables):

P_t	Price per ton charged by the collector to the recycler for the collected bottles
P_c	Price per ton charged by the collector or cleaner to suppliers for the cleaned bottles
P_r	Price per ton charged by the recycler to suppliers for the recycled materials

Demands (Dependent variables):

D_c	Suppliers' demand for the cleaned bottles
D_r	Suppliers' demand for the recycled bottles

Profits (Dependent variables):

π_t	Collector's profit
π_c	Cleaner's profit
π_r	Recycler's profit
π_s	Profit of the whole system

The suppliers' demands of the cleaned and recycled materials are assumed to be a linear function of the prices set for them. These demands are as follows:

$$D_c = a_c - \varphi P_c + \tau P_r \quad (1)$$

$$D_r = a_r - \varphi P_r + \tau P_c \quad (2)$$

Moreover, the profit functions of the collector, cleaner, recycler, and whole system are formulated as follows:

$$\pi_t = \begin{cases} \pi_t{}^{S1} = (1-\gamma)(P_c - c_t - c_c)D_c + (P_t - c_t)D_r & \text{under S1} \\ \pi_t{}^{S2} = (P_c - c_t - c_c)D_c + (P_t - c_t)D_r - K & \text{under S2} \end{cases} \tag{3}$$

$$\pi_c = \gamma(P_c - c_t - c_c)D_c \tag{4}$$

$$\pi_r = \left(P_r - P_t - c_c - c_f\right)D_r \tag{5}$$

$$\pi_s = \begin{cases} \pi_s{}^{S1} = \pi_t{}^{S1} + \pi_c + \pi_r = (P_c - c_t - c_c)D_c + \left(P_r - c_t - c_c - c_f\right)D_r & \text{under S1} \\ \pi_s{}^{S2} = \pi_t{}^{S2} + \pi_r = (P_c - c_t - c_c)D_c + \left(P_r - c_t - c_c - c_f\right)D_r - K & \text{under S2} \end{cases} \tag{6}$$

Below, some assumptions are considered in the problem:

(1) The collector has enough capacity to meet the suppliers' demands for the cleaned and recycled materials.
(2) The considered costs (i.e., the collecting, cleaning, and fragmenting costs) are the same for the members.
(3) $\varphi > \tau$: The self-price sensitivity is higher than the cross-price sensitivity of the demands.
(4) $a_c \leq a_r$: More suppliers prefer to buy the recycled materials rather than to purchase the cleaned bottles and then fragment them themselves.
(5) $a_c - \varphi(c_t + c_c) + \tau\left(c_t + c_c + c_f\right) \geq 0, a_r - \varphi\left(c_t + c_c + c_f\right) + \tau(c_t + c_c) \geq 0$: The suppliers' demands are nonnegative when the profit margins of the members are equal to zero (i.e., $P_c = c_t + c_c, P_t = c_t, P_r = c_t + c_c + c_f$).

To set the considered prices rationally, the following constraints are also incorporated into the problem:

(2) $P_c \geq c_t + c_c$, $P_t \geq c_t$, and $P_r \geq P_t + c_c + c_f$: The unit profit margins are nonnegative.

(3) $P_c \geq P_t + c_c$: The price of the cleaned bottles is greater than the sum of the price set for the collected bottles and the cleaning cost. Otherwise, it is beneficial for the recycler to buy the cleaned bottles and then fragment them.

(4) $P_r \geq P_c + c_f$: The price of the recycled materials is higher than the sum of the price set for the cleaned bottles and the fragmenting cost. Otherwise, all suppliers meet their required materials via the recycler.

(5) $D_c, D_r \geq 0$: The suppliers' demands are nonnegative.

These constraints are summarized as follows:

$$P_c \geq c_t + c_c,\;\; P_t \geq c_t,\;\; P_r \geq P_t + c_c + c_f,\;\; P_c \geq P_t + c_c,\;\; P_r \geq P_c + c_f,\;\; D_c, D_r \geq 0 \tag{7}$$

Now, decisions are determined applying the game-theoretic approach under different interactions among the members.

3. Game-theoretic approach

In this section, the game theory is used to set decisions under the structures S1 and S2. Considering the competitive and cooperative interactions among the members, it is investigated which of the following structures is more beneficial from the collector's point of view?

- Structure S1: Cleaning the collected bottles through the cleaner by giving a share of the profit obtained from selling in this channel to him.
- Structure S2: Establishing the bottles cleaning technology by paying a setup cost.

In what follows, attempts are made to answer to Research Question 1 presented in Section 1. Note that all theorems appearing in this section are proved in Appendix A (*in electronic companion*).

3.1. Nash game

Under Nash game, the players make their decisions independently and simultaneously.

3.1.1. Nash game under structure S1 (Nash I game)

In Nash I game developed under the structure S1, the collector, cleaner, and recycler respectively set the price of the collected bottles to the recycler, the price of the cleaned bottles to suppliers, and the price of the recycled materials to suppliers. The decisions are made independently and simultaneously by maximizing the players' profits. Nash I game is formulated as follows:

$$\begin{cases} \max\limits_{P_t} \ \pi_t{}^{S1} = (1-\gamma)(P_c - c_t - c_c)D_c + (P_t - c_t)D_r \\ \max\limits_{P_c} \ \pi_c = \gamma(P_c - c_t - c_c)D_c \\ \max\limits_{P_r} \ \pi_r = \left(P_r - P_t - c_c - c_f\right)D_r \\ \text{s.t.} \ \ P_c \geq c_t + c_c, \ \ P_t \geq c_t, \ \ P_r \geq P_t + c_c + c_f, \ \ P_c \geq P_t + c_c, \ \ P_r \geq P_c + c_f, \ \ D_c, D_r \geq 0 \end{cases} \tag{Problem A}$$

Theorem 1. *Under Nash I game, the equilibrium prices are as follows:*

$$\begin{cases} P_t{}^{NI} = \dfrac{\tau(a_r + \tau c_c) + \varphi(2a_c + (\tau - 2\varphi)c_c + \tau c_f + 2\varphi c_t)}{4\varphi^2 - \tau^2 - \tau\varphi} \\ P_c{}^{NI} = \dfrac{\tau a_r + \varphi(2a_c + \tau c_f + 2\varphi(c_t + c_c))}{4\varphi^2 - \tau^2 - \tau\varphi} \\ P_r{}^{NI} = \dfrac{(\tau + \varphi)a_c + \varphi(2a_r + (\tau + \varphi)(c_t + c_c) + 2\varphi c_f)}{4\varphi^2 - \tau^2 - \tau\varphi} \end{cases} \tag{8}$$

Note that the concavity of the profit functions and the feasibility of the equilibrium prices in all developed games are investigated in Appendix A (*in electronic companion*).

3.1.2. Nash game under structure S2 (Nash II game)

Under Nash II game concerning the structure S2, the collector and recycler specify the prices independently and simultaneously by maximizing their own profit functions. In this situation, the collector sets the price of the collected bottles to the recycler as well as the price of the cleaned bottles to suppliers. Furthermore, the recycler gives the price of the recycled materials to suppliers. Nash II game is modelled as follows:

$$\begin{cases} \max\limits_{P_t, P_c} \ \pi_t{}^{S2} = (P_c - c_t - c_c)D_c + (P_t - c_t)D_r - K \\ \max\limits_{P_r} \ \pi_r = \left(P_r - P_t - c_c - c_f\right)D_r \\ \text{s.t.} \ \ P_c \geq c_t + c_c, \ \ P_t \geq c_t, \ \ P_r \geq P_t + c_c + c_f, \ \ P_c \geq P_t + c_c, \ \ P_r \geq P_c + c_f, \ \ D_c, D_r \geq 0 \end{cases} \tag{Problem B}$$

Theorem 2. *The equilibrium pricing strategy in Nash II game is:*

$$\begin{cases} P_t{}^{NII} = \dfrac{\tau(a_r + \tau c_c) + \varphi(2a_c - (2\varphi - \tau)c_c + \tau c_f + 2(\varphi - \tau)c_t)}{(\varphi - \tau)(4\varphi + \tau)} \\ P_c{}^{NII} = \dfrac{\tau a_r + \varphi(2a_c + 2(\varphi - \tau)(c_t + c_c) + \tau c_f)}{(\varphi - \tau)(4\varphi + \tau)} \\ P_r{}^{NII} = \dfrac{(\tau + \varphi)a_c + (2\varphi - \tau)a_r + (\varphi^2 - \tau^2)(c_t + c_c) + \varphi(2\varphi - \tau)c_f}{(\varphi - \tau)(4\varphi + \tau)} \end{cases} \tag{9}$$

3.2. Stackelberg game

Under Stackelberg game, first, the leader player sets his decisions. Then, the follower player specifies his response based on the leader's decisions.

3.2.1. Stackelberg game under structure S1 (Stackelberg I game)

In Stackelberg I game developed under the structure S1, the collector as the leader declares the price of the collected bottles to the recycler at the first level. Then, at the second level, the cleaner and recycler as the followers respectively set the prices of the cleaned and recycled materials to suppliers independently and simultaneously. Stackelberg I game model is as follows:

$$\begin{cases} First\ level\text{:} \max\limits_{P_t} \ \pi_t{}^{S1} = (1-\gamma)(P_c - c_t - c_c)D_c + (P_t - c_t)D_r \\ Second\ level\text{:} \begin{cases} \max\limits_{P_c} \ \pi_c = \gamma(P_c - c_t - c_c)D_c \\ \max\limits_{P_r} \ \pi_r = \left(P_r - P_t - c_c - c_f\right)D_r \end{cases} \\ \text{s.t.} \ \ P_c \geq c_t + c_c, \ \ P_t \geq c_t, \ \ P_r \geq P_t + c_c + c_f, \ \ P_c \geq P_t + c_c, \ \ P_r \geq P_c + c_f, \ \ D_c, D_r \geq 0 \end{cases} \tag{Problem C}$$

Similar to the previous games, one can derive the following theorem:

Theorem 3. *The equilibrium pricing policy in Stackelberg I game is as follows:*

$$\begin{cases} P_t{}^{SI} = \dfrac{\tau B_2 a_c + 2\varphi B_3 a_r - B_4 c_c - B_5 c_f + B_6 c_t}{2B_1} \\ P_c{}^{SI} = \dfrac{\varphi B_7 a_c + 2\tau B_8 a_r + \varphi\big(B_9(c_t + c_c) + \tau B_{10} c_f\big)}{2B_1} \\ P_r{}^{SI} = \dfrac{\tau B_{11} a_c + \varphi\big(2B_8 a_r + B_{12}(c_t + c_c) + \varphi B_{10} c_f\big)}{B_1} \end{cases} \tag{10}$$

where,

$B_1 = 8\varphi^4 + \tau^4 - (7-\gamma)\tau^2\varphi^2$
$B_2 = 4(2-\gamma)\varphi^2 - \tau^2$
$B_3 = 4\varphi^2 - \gamma\tau^2$
$B_4 = \tau^4 - \tau^3\varphi + 2\gamma\tau^3\varphi - 8\tau^2\varphi^2 + 2\gamma\tau^2\varphi^2 - 4\gamma\tau\varphi^3 + 8\varphi^4$
$B_5 = \tau^4 - 8\tau^2\varphi^2 + 2\gamma\tau^2\varphi^2 + 8\varphi^4$
$B_6 = \tau^4 - 6\tau^2\varphi^2 + 4\gamma\tau\varphi^3 + 8\varphi^4 - 2\gamma\varphi\tau^3 + \varphi\tau^3$
$B_7 = 8\varphi^2 - 3\tau^2$
$B_8 = 3\varphi^2 - \tau^2$
$B_9 = -\tau^3 - 5\tau^2\varphi + 10\gamma\tau^2\varphi + 2\tau\varphi^2 + 8\varphi^3$
$B_{10} = 2\varphi^2 - \tau^2$
$B_{11} = (4-\gamma)\varphi^2 - \tau^2$
$B_{12} = -\tau^3 - \tau^2\varphi + 2\tau\varphi^2 + \gamma\tau\varphi^2 + 2\varphi^3$

3.2.2. Stackelberg game under structure S2 (Stackelberg II game)

Under Stackelberg II game, first, the collector as the leader makes the price of the collected bottles to the recycler and the price of the cleaned bottles to suppliers. Then, the recycler as the follower specifies the price of the recycled materials to suppliers. Stackelberg II game is formulated as follows:

$$\begin{cases} First\ level: \max\limits_{P_t,P_c} \pi_t{}^{S2} = (P_c - c_t - c_c)D_c + (P_t - c_t)D_r - K \\ Second\ level: \max\limits_{P_r} \pi_r = \big(P_r - P_t - c_c - c_f\big)D_r \\ \text{s.t.}\ \ P_c \geq c_t + c_c,\ \ P_t \geq c_t,\ \ P_r \geq P_t + c_c + c_f,\ \ P_c \geq P_t + c_c,\ \ P_r \geq P_c + c_f,\ \ D_c, D_r \geq 0 \end{cases}$$

(Problem D)

Theorem 4. *The equilibrium pricing strategy under Stackelberg II game is:*

$$\begin{cases} P_t{}^{SII} = \dfrac{\tau a_c + \varphi a_r + (\tau^2 - \varphi^2)(c_c + c_f - c_t)}{2(\varphi^2 - \tau^2)} \\ P_c{}^{SII} = \dfrac{\varphi a_c + \tau a_r + (\varphi^2 - \tau^2)(c_c + c_t)}{2(\varphi^2 - \tau^2)} \\ P_r{}^{SII} = \dfrac{2\tau\varphi a_c + (3\varphi^2 - \tau^2)a_r + (\varphi^2 - \tau^2)\Big((\tau + \varphi)(c_t + c_c) + \varphi c_f\Big)}{4\varphi(\varphi^2 - \tau^2)} \end{cases} \tag{11}$$

3.3. Centralized game

Under Centralized game, all players act in union and specify their decisions by maximizing the profit of the whole system.

3.3.1. Centralized game under structure S1 (Centralized I game)

In Centralized I game established under the structure S1, the collector, cleaner, and recycler agree to perform in union and specify the prices of the cleaned and recycled materials to suppliers jointly and simultaneously. Centralized I game model is as follows:

$$\begin{cases} \max\limits_{P_c,P_r} \pi_s{}^{S1} = \pi_t{}^{S1} + \pi_c + \pi_r = (P_c - c_t - c_c)D_c + \big(P_r - c_t - c_c - c_f\big)D_r \\ \text{s.t.}\ \ P_c \geq c_t + c_c,\ \ P_r \geq P_c + c_f,\ \ D_c, D_r \geq 0 \end{cases}$$

(Problem E)

Theorem 5. *In Centralized I game, the equilibrium prices of the cleaned and recycled materials to suppliers are obtained as follows:*

$$\begin{cases} P_c{}^{CI} = \dfrac{\varphi a_c + \tau a_r + (\varphi^2 - \tau^2)(c_c + c_t)}{2(\varphi^2 - \tau^2)} \\ P_r{}^{CI} = \dfrac{\tau a_c + \varphi a_r + (\varphi^2 - \tau^2)(c_c + c_f + c_t)}{2(\varphi^2 - \tau^2)} \end{cases} \tag{12}$$

Due to maximizing the profit value of the whole system under Centralized I game, this profit value is greater than under Nash I game in which the players compete to set their decisions, i.e., $\pi_s{}^{CI} \geq \pi_s{}^{NI} = \pi_t{}^{NI} + \pi_c{}^{NI} + \pi_r{}^{NI}$, where symbols *CI* and *NI* denote Centralized I and Nash I games, respectively. In this setting, the shares of the extra profit for the players obtained from the whole system cooperation under Centralized I game compared with Nash I game, the players' profits, and the price of the collected bottles set by the collector to the recycler are neglected in Centralized I game. Now, Nash bargaining process (Nash 1950) is applied to calculate these values in Centralized I game based on the negotiation powers of the players.

Assume that λ_t, λ_c, and λ_r respectively are the negotiation powers of the collector, cleaner, and recycler and they respectively receive the shares $\Delta\pi_t{}^{CI} = \pi_t{}^{CI} - \pi_t{}^{NI}$, $\Delta\pi_c{}^{CI} = \pi_c{}^{CI} - \pi_c{}^{NI}$, and $\Delta\pi_r{}^{CI} = \pi_r{}^{CI} - \pi_r{}^{NI}$ of the increased profit obtained from the whole system cooperation under Centralized I game compared with Nash I game, i.e., $\Delta\pi_s{}^{CI} = \pi_s{}^{CI} - \pi_s{}^{NI}$. Applying Nash bargaining process, the following theorem can be given.

Theorem 6. *The shares of the extra profit for the players in Centralized I game are:*

$$\begin{cases} \Delta\pi_t{}^{CI} = \dfrac{\lambda_t}{\lambda_t + \lambda_c + \lambda_r} \Delta\pi_s{}^{CI} \\ \Delta\pi_c{}^{CI} = \dfrac{\lambda_c}{\lambda_t + \lambda_c + \lambda_r} \Delta\pi_s{}^{CI} \\ \Delta\pi_r{}^{CI} = \dfrac{\lambda_r}{\lambda_t + \lambda_c + \lambda_r} \Delta\pi_s{}^{CI} \end{cases} \tag{13}$$

The profit values of the players under Centralized I game are also calculated using following theorem.

Theorem 7. *The players' profits under Centralized I game are given as follows:*

$$\begin{cases} \pi_t{}^{CI} = \pi_t{}^{NI} + \dfrac{\lambda_t}{\lambda_t + \lambda_c + \lambda_r} \Delta\pi_s{}^{CI} \\ \pi_c{}^{CI} = \pi_c{}^{NI} + \dfrac{\lambda_c}{\lambda_t + \lambda_c + \lambda_r} \Delta\pi_s{}^{CI} \\ \pi_r{}^{CI} = \pi_r{}^{NI} + \dfrac{\lambda_r}{\lambda_t + \lambda_c + \lambda_r} \Delta\pi_s{}^{CI} \end{cases} \tag{14}$$

Furthermore, the price of the collected bottles specified by the collector to the recycler in Centralized I game is calculated by solving relation (3) with respect to P_t.

Theorem 8. *The price of the collected bottles set by the collector to the recycler under Centralized I game is:*

$$P_t{}^{CI} = \frac{\pi_t{}^{CI} - (1-\gamma)\left(P_c{}^{CI} - c_t - c_c\right)D_c{}^{CI}}{D_r{}^{CI}} + c_t \tag{15}$$

where, $D_c{}^{CI}$ *and* $D_r{}^{CI}$ *respectively are the suppliers' demands for the cleaned and recycled materials in Centralized I game.*

3.3.2. Centralized game under structure S2 (Centralized II game)

In Centralized II game, the collector and recycler cooperate and set the prices by maximizing the profit of the whole system under the structure S2. Centralized II game is formulated as follows:

$$\begin{cases} \max\limits_{P_c, P_r} \ \pi_s{}^{S2} = \pi_t{}^{S2} + \pi_c + \pi_r = (P_c - c_t - c_c)D_c + \left(P_r - c_t - c_c - c_f\right)D_r - K \\ \text{s.t.} \ \ P_c \geq c_t + c_c, \ \ P_r \geq P_c + c_f, \ \ D_c, D_r \geq 0 \end{cases}$$

(Problem F)

Comparing the problems considered in Centralized I and II games, one can derive that the selling prices to suppliers set in these games are the same.

Using Nash bargaining process, the shares of the increased profit for the players under Centralized II game compared with Nash II game, the players' profits, and the price of the collected bottles are calculated based on the negotiation powers of the collector and recycler.

Theorem 9. *Under Centralized II game, the shares of the increased profit for the players are as follows:*

$$\begin{cases} \Delta\pi_t^{CII} = \dfrac{\lambda_t}{\lambda_t + \lambda_r} \Delta\pi_s^{CII} \\ \Delta\pi_r^{CII} = \dfrac{\lambda_r}{\lambda_t + \lambda_r} \Delta\pi_s^{CII} \end{cases} \tag{16}$$

where, $\Delta\pi_s^{CII} = \pi_s^{CII} - \pi_s^{NII}$ *is the extra profit of the whole system under Centralized II game compared with Nash II game.*

Theorem 10. *The players' profits in Centralized II game are:*

$$\begin{cases} \pi_t^{CII} = \pi_t^{NII} + \dfrac{\lambda_t}{\lambda_t + \lambda_r} \Delta\pi_s^{CII} \\ \pi_r^{CII} = \pi_r^{NII} + \dfrac{\lambda_r}{\lambda_t + \lambda_r} \Delta\pi_s^{CII} \end{cases} \tag{17}$$

Theorem 11. *Under Centralized II game, the price of the collected bottles determined by the collector to the recycler is as follows:*

$$P_t^{CII} = \frac{\pi_t^{CII} - \left(P_c^{CII} - c_t - c_c\right)D_c^{CII} + K}{D_r^{CII}} + c_t \tag{18}$$

where, D_c^{CII} *and* D_r^{CII} *are the suppliers' demands under Centralized II game.*

Due to various interactions among the players, different games can be established to price the collected, cleaned, and recycled bottles in the market. If the players compete to set the prices independently with similar decision powers, they can make decisions under Nash game. When the decision power of the collector is higher than of the others, they can specify the prices under Stackelberg game. Moreover, Centralized game can be developed to determine the prices by maximizing the profit value of whole system.

4. Results and discussion

In this section, the obtained decisions are discussed and the results are revealed.

4.1. Comparisons of the obtained strategies under the developed games

To answer to Research Question 2 introduced in Section 1, under the established games, it is investigated which of the structures S1 or S2 can be more beneficial from the collector's point of view?

Result 1. *Comparing the collector's profits given by the games developed under the structures S1 and S2, one can derive that:*

(i) $\pi_t^{NI} < \pi_t^{NII}$ $\quad if\ K < K^N$
(ii) $\pi_t^{SI} < \pi_t^{SII}$ $\quad if\ K < K^S$
(iii) $\pi_t^{CI} < \pi_t^{CII}$ $\quad if\ K < K^C$

where, symbols K^N, K^S, *and* K^C *are defined in Appendix A* (*in electronic companion*).

Managerial Insight 1. *Under Nash, Stackelberg, and Centralized games, it is more beneficial for the collector to establish the bottles cleaning technology himself, if the setup cost of this technology is lower than* K^N, K^S, *and* K^C, *respectively.*

Below, to answer to Research Question 3, the given decisions are compared under the investigated games. Note that the provided results can be straightforwardly derived using assumptions (3)-(5) and after some manipulations.

Result 2. *The following relations hold among the prices obtained from the games:*

(i) $\begin{cases} P_t^{CI} \le P_t^{NI} \le P_t^{SI} & under\ structure\ S1 \\ P_t^{CII} \le P_t^{NII} \le P_t^{SII} & under\ structure\ S2 \end{cases}$

(ii) $\begin{cases} P_c^{NI} \le P_c^{SI} \le P_c^{CI} & under\ structure\ S1 \\ P_c^{NII} \le P_c^{SII} \le P_c^{CII} & under\ structure\ S2 \end{cases}$

(iii) $\begin{cases} P_r^{CI} \le P_r^{NI} \le P_r^{SI} & under\ structure\ S1 \\ P_r^{CII} \le P_r^{NII} \le P_r^{SII} & under\ structure\ S2 \end{cases}$

Managerial Insight 2. *Under the structures S1 and S2, Centralized and Stackelberg games respectively give the lowest and the highest prices for the collected bottles and the recycled materials, while the lowest and the highest prices for the cleaned bottles are obtained under Nash and Centralized games, respectively.*

Result 3. *The following relations can be given for the suppliers' demands:*

(i) $\begin{cases} {D_c}^{CI} \leq {D_c}^{NI} \leq {D_c}^{SI} & under\ structure\ S1 \\ {D_c}^{CII} \leq {D_c}^{NII} \leq {D_c}^{SII} & under\ structure\ S2 \end{cases}$

(ii) $\begin{cases} {D_r}^{SI} \leq {D_r}^{NI} \leq {D_r}^{CI} & under\ structure\ S1 \\ {D_r}^{SII} \leq {D_r}^{NII} \leq {D_r}^{CII} & under\ structure\ S2 \end{cases}$

Managerial Insight 3. *Centralized and Stackelberg games respectively lead to the shortest and the greatest demands for the cleaned bottles under structures S1 and S2. This inference is reversed for the demands of the recycled materials.*

Suppliers are price sensitive. Thus, higher prices lead to lower demands. Consequently, it can be stated that Managerial Insight 3 is obtained from Managerial Insight 2.

Result 4. *The following inferences can be derived for the profits:*

(i) $\begin{cases} \begin{cases} {\pi_t}^{NI} \leq {\pi_t}^{SI} \leq {\pi_t}^{CI} & if\ F_1 \geq 0 \\ {\pi_t}^{NI} \leq {\pi_t}^{CI} < {\pi_t}^{SI} & otherwise \end{cases} & under\ structure\ S1 \\ \begin{cases} {\pi_t}^{NII} \leq {\pi_t}^{SII} \leq {\pi_t}^{CII} & if\ F_2 \geq 0 \\ {\pi_t}^{NII} \leq {\pi_t}^{CII} < {\pi_t}^{SII} & otherwise \end{cases} & under\ structure\ S2 \end{cases}$

(ii) $\begin{cases} {\pi_c}^{NI} \leq {\pi_c}^{SI} \leq {\pi_c}^{CI} & if\ F_1 \geq 0 \\ {\pi_c}^{NI} \leq {\pi_c}^{CI} < {\pi_c}^{SI} & otherwise \end{cases}$

(iii) $\begin{cases} {\pi_r}^{SI} \leq {\pi_r}^{NI} \leq {\pi_r}^{CI} & under\ structure\ S1 \\ {\pi_r}^{SII} \leq {\pi_r}^{NII} \leq {\pi_r}^{CII} & under\ structure\ S2 \end{cases}$

(iv) $\begin{cases} {\pi_s}^{SI} \leq {\pi_s}^{NI} \leq {\pi_s}^{CI} & under\ structure\ S1 \\ {\pi_s}^{SII} \leq {\pi_s}^{NII} \leq {\pi_s}^{CII} & under\ structure\ S2 \end{cases}$

Managerial Insight 4. *Nash game leads to the lowest profits for the collector and cleaner. Moreover, the highest and the lowest profits for the recycler and the whole system are respectively obtained under Centralized and Stackelberg games.*

Regarding Theorems 7 and 10, the profit values under Centralized game are greater than under Nash game. In Stackelberg game, the collector acts as the leader and the recycler is considered as the follower. Thus, it is expected that the collector's profit given by Stackelberg game is higher than by Nash game. This inference holds for the cleaner's profit by giving a share of the collector's profit to the cleaner under the structure S1. Furthermore, this conclusion is reversed for the profit values of the recycler and the whole system.

Result 5. *Under Centralized games, one can derive that* ${\pi_s}^{CII} = {\pi_s}^{CI} - K$.

Managerial Insight 5. *From the whole system's point of view, it is more beneficial to clean the collected bottles via the cleaner by giving a share of the profit obtained from selling in this channel to him.*

4.2. Numerical example

In this section, a real case is presented to well illustrate the research problem. Consider an instance with the parameters values given in Table 1. Note these values have been estimated under a supply chain structure similar to that investigated on the current study in a market of textile industry in Iran. The results obtained from the developed games for this example are summarized in Table 2.

Table 1. The values of the parameters in the numerical example

Parameter	c_t	c_c	c_f	a_c	a_r	φ	τ	K	γ
Value	100	20	40	2000	4000	6.0	0.3	100000	0.4

Table 2. The results obtained from the investigated games for the numerical example

Games	Prices			Demands	
	P_t	P_c	P_r	D_c	D_r
Nash I	218.63	238.63	478.62	711.79	1199.90
Nash II	221.72	241.72	480.23	693.78	1191.11
Stackelberg I	361.23	240.42	549.96	722.49	772.36
Stackelberg II	362.52	243.79	550.69	702.45	769.00
Centralized I	-	243.79	422.52	664.00	1538.00
Centralized II	-	243.79	422.52	664.00	1538.00

	Profits			
	π_t	π_c	π_r	π_s
Nash I	193011.26	33776.55	239959.47	466747.28
Nash II	129420.00	-	236457.61	365877.62
Stackelberg I	253966.56	34799.84	99424.36	388190.76
Stackelberg II	188838.43	-	98560.17	287398.60
Centralized I	-	-	-	485958.76
Centralized II	-	-	-	385958.76

Let the negotiation powers of the collector, cleaner, and recycler respectively are equal to $\lambda_t = 0.5$, $\lambda_c = 0.2$, and $\lambda_r = 0.3$. In this situation, the shares of the extra profit for the players obtained from the whole system cooperation, the players' profits, and the price of the collected bottles set by the collector to the recycler under Centralized games are calculated using Nash bargaining process. The related values are provided in Table 3.

Regarding the results, under Nash and Stackelberg games, it is more beneficial for the collector to clean the collected bottles via the cleaner by giving a share of the profit to him, whereas the collector receives higher profit under Centralized game, if he establishes the bottles cleaning technology himself by paying a setup cost.

Table 3. The results of Nash bargaining process for the numerical example

Centralized I game				
Shares of the extra profit	$\Delta\pi_s$	$\Delta\pi_t$	$\Delta\pi_c$	$\Delta\pi_r$
	19211.49	9605.74	3842.30	5763.45
Profits	π_t	π_c	π_r	
	202617.00	37618.85	245722.92	
Price of the collected bottles	P_t			
	199.67			
Centralized II game				
Shares of the extra profit	$\Delta\pi_s$	$\Delta\pi_t$	$\Delta\pi_r$	
	120081.15	75050.72	45030.43	
Profits	π_t	π_r		
	204470.72	281488.04		
Price of the collected bottles	P_t			
	114.48			

4.3. Sensitivity analysis

Now, to answer to Research Question 4, the effects of the parametric changes are investigated on the demands and profits given by the developed games.

4.3.1. *Effects of the negotiation powers of the players*

Changes of the profits with respect to the negotiation powers of the players are specified regarding Theorems 7 and 10.

Managerial Insight 6. *The more the negotiation power of a player, the more profit for him and the less profits for the others.*

It is difficult to recognize how the profits are affected by changing γ, φ, and τ. Thus, a sensitivity analysis is applied using the numerical example presented in Section 4.2.

4.3.2. *Effects of the share of the profit given by the collector to the cleaner*

Changes in the demands and profits with γ are shown in Fig. 1. Since γ is considered under the structure S1, its effects are only investigated on the profits related to this structure.

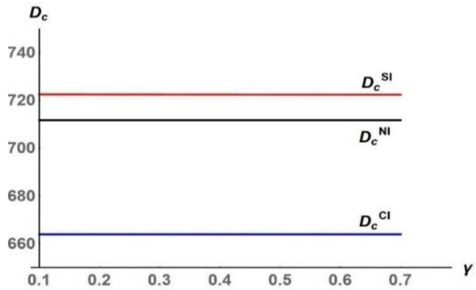

Fig. 1(a). Changes of D_c with γ

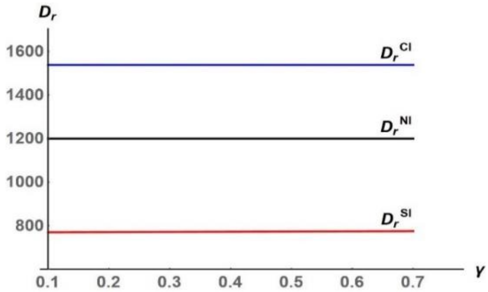

Fig. 1(b). Changes of D_r with γ

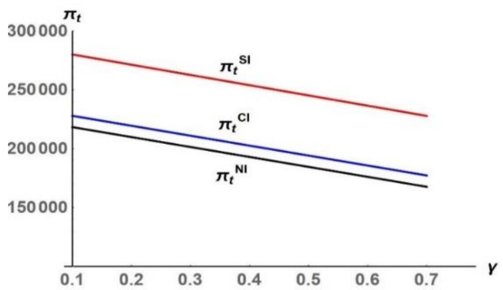

Fig. 1(c). Changes of π_t with γ

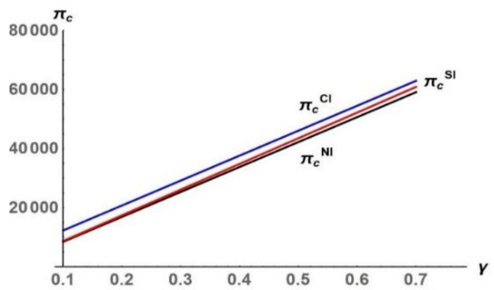

Fig. 1(d). Changes of π_c with γ

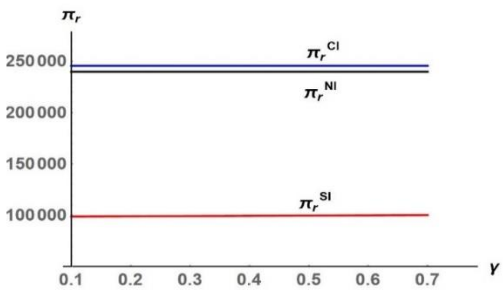

Fig. 1(e). Changes of π_r with γ

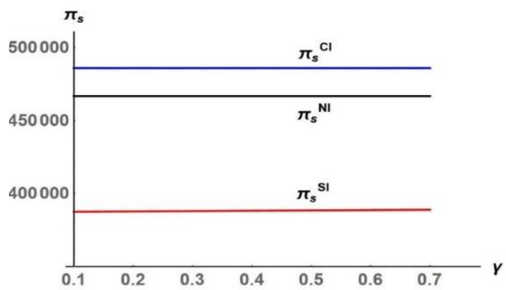

Fig. 1(f). Changes of π_s with γ

Fig. 1. Changes of the demands and profits with γ

Managerial Insight 7. *Under the structure S1, by increasing the share of the profit obtained from selling the cleaned bottles given by the collector to the cleaner, the collector's profit decreases, while the cleaner's profit increases, obviously. Moreover, changing this parameter does not affect the demands and profits of the recycler and whole system.*

4.3.3. *Effects of the self-price and cross-price sensitivities of the demands*

Changes of the demands and profits obtained from the investigated games with respect to φ and τ are exhibited in Fig. 2, simultaneously.

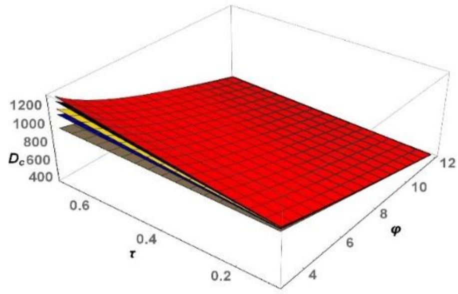

Fig. 2(a). Changes of D_c with φ and τ

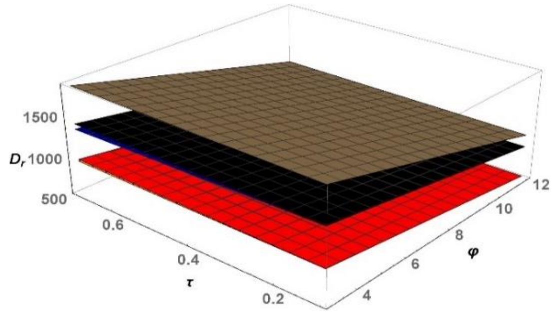

Fig. 2(b). Changes of D_r with φ and τ

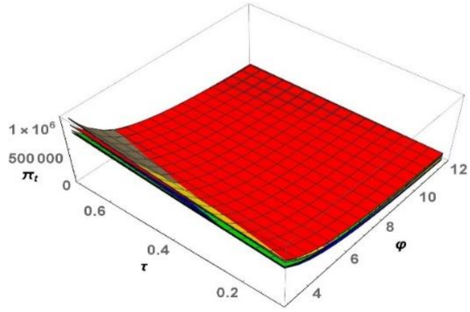

Fig. 2(c). Changes of π_t with φ and τ

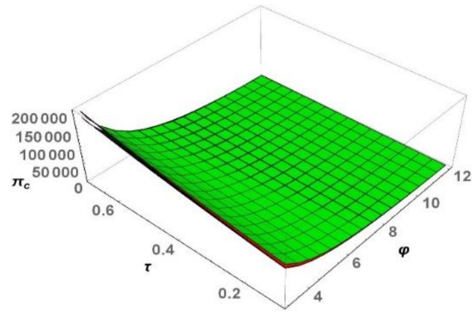

Fig. 2(d). Changes of π_c with φ and τ

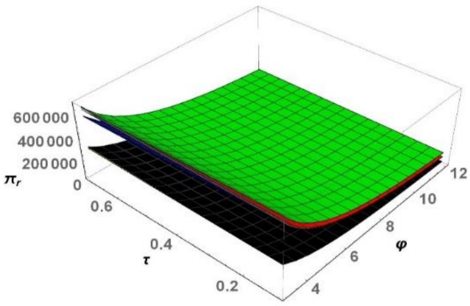

Fig. 2(e). Changes of π_r with φ and τ

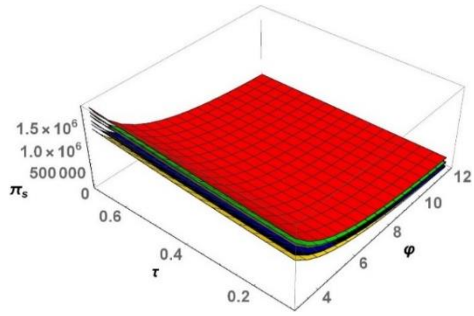

Fig. 2(f). Changes of π_s with φ and τ

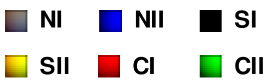

Fig. 2. Changes of the demands and profits with φ and τ

Managerial Insight 8. *The demands and profits decrease by increasing the self-price sensitivity of the suppliers' demands. Furthermore, the more the cross-price sensitivity of the suppliers' demands, the more demands and profits under the investigated games.*

By increasing φ, the suppliers' demands decrease and this leads to lower profits obtained from the developed games. This insight is reversed as τ increases.

Managerial Insight 9. *Policies that lead to decreasing the self-price and increasing the cross-price sensitivities of the suppliers' demands increase the volume of PET plastic bottles collected to be recycled and reused in textile industry. Therefore, these strategies can make the environment friendlier.*

5. Summary and conclusions

In this paper, a sustainable supply chain consisting of the collector, cleaner, and recycler was established to collect, clean, and fragment PET plastic bottles and then reuse them in textile industry as appropriate substitutable for virgin materials. Some suppliers of textile industry purchase the cleaned and non-fragmented bottles and then they fragment them, whereas others procure the recycled materials (i.e., the cleaned and fragmented bottles). The collector collects the used plastic bottles. To meet demand of the recycled materials, the collector transfers a portion of the collected bottles to the recycler and then the recycler cleans and fragments them. Furthermore, to meet demand of the cleaned bottles, the collector cleans another portion of the collected bottles himself or via the cleaner. In this setting, two different structures were considered for transferring the cleaned bottles to suppliers. In the first structure, the collector cleans the collected bottles via the cleaner by giving a share of the profit to him, while he is equipped with the bottles cleaning technology by paying a setup cost in the second structure.

To make the decisions, the game-theoretic models including Nash, Stackelberg, and Centralized were developed under two considered structures.

Then, to analyze the effects of the investigated games on the given decisions, they were compared under these games. The obtained results are as follows:

- It is more beneficial for the collector to establish the bottles cleaning technology himself, if the setup cost of this technology is lower than a threshold.
- The lowest and the highest prices for the collected bottles and the recycled materials are respectively given by Centralized and Stackelberg games, while Nash and Centralized games respectively lead to the lowest and the highest prices for the cleaned bottles.
- The shortest and the greatest demands for the cleaned bottles are respectively obtained from Centralized and Stackelberg games and this inference is reversed for the demand of the recycled materials.
- From the collector's and cleaner's point of view, it is more beneficial to establish Centralized game among the members, if a threshold is met. Moreover, the highest profits received by the recycler and whole system are given under Centralized game.
- From the whole system's point of view, it is beneficial to clean the collected bottles through a cleaner by giving a share of the profit to him.

Finally, a sensitivity analysis is done on the considered parameters. The inferences are summarized as follows:

- More negotiation powers give higher profits for the members.
- Higher the self-price/cross-price sensitivity of the suppliers' demands gives lower/higher profits to the members and whole system.
- Strategies that decrease the self-price and increase the cross-price sensitivities of the suppliers' demands make the environment friendlier.

There are some possible directions for future researches. To coordinate the members, various contracts can be investigated on the considered research problem. In this paper, the suppliers' demands were obtained based on the prices. Other types of the demand functions can be considered in future studies. Moreover, the game-theoretic models were established under a deterministic scenario. One can investigate the disruption concepts under the considered supply chain applying the stochastic models.

6. Declarations

6.1. Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

6.2. Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6.3. Availability of data and material

Not applicable

6.4. Code availability

Not applicable

Appendix A. Proofs and notations

Supplementary materials associated with the proofs of theorems and the defined notations can be found in the online version at ….

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