OPSEARCH (2022) 59:786–808
https://doi.org/10.1007/s12597-021-00569-7

APPLICATION ARTICLE

Optimal sustainability investment and pricing decisions in a two-echelon supply chain with emissions-sensitive demand under cap-and-trade policy

Bibhas C. Giri[1] **· Ishani Ray**[1]

Accepted: 21 November 2021 / Published online: 15 January 2022

Abstract
With the alarming increase in global warming, business activities are being modified by green/sustainable initiatives through immense research. This paper considers a sustainable supply chain which consists of a supplier and a manufacturer. The market demand is emissions-sensitive besides dependent on the selling price and sustainability levels of the supplier and the manufacturer. To maintain the sustainability level of the whole supply chain, both the supply chain entities make investments. The decision behaviors of the centralized and the decentralized channels are compared and a two-part tariff contract is implemented to coordinate the supply chain under the cap-and-trade policy. It is found from the numerical study that the total profit in the centralized system is almost 10% higher than that of the decentralized system. Further, the two-part tariff contract leads to a perfect channel coordination. Sensitivity analysis is performed to examine the effects of key model-parameters on the optimal decisions.

Keywords Sustainable investment · Emissions-sensitive demand · Supply chain coordination · Cap-and-trade policy

1 Introduction

Sustainable development is a prime challenge in global practice today. In the World Summit on sustainable development in 2002, academicians and practitioners highlighted on people-planet-prosperity to emphasize that sustainable development is mainly based on balancing socioeconomic and environmental concerns

✉ Ishani Ray
ishani.jumath@gmail.com

Bibhas C. Giri
bcgiri.jumath@gmail.com

[1] Department of Mathematics, Jadavpur University, Kolkata, West Bengal 700032, India

[1]. In 2003, LMI Research Institute, a US-based (non-profit) government consulting institute, prepared a report which mentions two approaches that have been usually taken by the firms to greening their supply chains. The first one is an external examination of how its various suppliers supply raw materials. The suppliers have to undertake that their operations fulfill all environmental requirements. For example, Toyota and Ford are asked to provide evidence of ISO14001 certification. The second approach looks internally at a firm's manufacturing process which includes design, production and shipment of products [2]. Governments usually impose market-based strategies with more traditional command and control to diminish the activities that might harm the environment [3].

Carbon emission trading is one of the most effective market-based approaches to reduce greenhouse effect. In 2005, the European Union [4] launched an emission trading scheme, known as a *cap-and-trade policy* which allocates a predetermined amount of carbon emissions (a carbon cap) to a firm. If the firm exceeds the carbon cap, it can buy additional carbon emission rights from a carbon trading market and, in the reverse situation, the firm can sell its surplus carbon credit [5]. Recently, social media influences consumers to buy pollution-free furnishings, organic foods, and sustainable products that eventually lead to considerable pressure on firms to improve their impacts on the environment. The sustainability level of a product is something that helps to lessen environmental impacts throughout the life cycle and even after end-of-use. Sustainable (or green) investment is a process of incorporating more eco-friendly and environmentally responsible choices and fabricating lifestyles in the conventional ways for protecting the environmental balance and preserve natural resources for the future generation. It can be achieved in numerous ways which include recycling and remanufacturing, creating energy-efficient processes/products, reduction of environmental hazards, eco-friendly packaging and labeling, non-utilization of harmful substances and ozone-depleting materials, utilization of renewable ingredients, adoption of intelligent designs and manufacturing techniques, and so on. A survey on household electronic and electrical equipment reveals that approximately 70% of Ningbo respondents of China are willing to buy eco-friendly products [6]. Companies are taking an enthusiastic step to coordinate their supply chains by investing in sustainability under cap-and-trade regulation to get quick response from its customers. Big shot companies like Minnesota Mining and Manufacturing Corporation, Walmart, and China based Quanyou Household Company Limited came up with innovation and new strategies to establish sustainable operations [7, 8]. Sustainable supply chain management is mainly dependent on government regulations, market demand and requests of other stakeholders [9–11]. For instance, it is reported that Nike gave attention to the sustainability of its retail channel (NIKE, FY07-FY09). Coca Cola and its bottling franchisees declared that all of their new vending and cooling machines would be free from HFC (hydro-fluoro-carbon) by 2015. In order to minimize carbon emission during production, the fashion apparel companies like Levis, Marks & Spencer and H&M adopted many sustainable approaches [12]. Many prominent worldwide companies like Mercedes-Benz, Tesla, etc. are implementing sustainable practices in their supply chains. Mercedes-Benz uses fuel-efficient technology which is four-time more beneficial.

The sustainable approach of Tesla helps it in producing electric car which has an energy-efficient electric motor.

From marketing as well as operations perspectives, sustainable supply chain management has created several new challenges. In response to these challenges, several new streams of research have come up. Some prominent research streams in this field include green design [13], reverse logistics [14], product recovery [15], supply chain with environmentally aware consumer [16] or green-sensitive consumer [17] and so on. Advanced approaches and investment in newer technologies helped companies to get a better market image and an increase in total profit. The newer technologies must implement a balance between sustainable investment and total profit.

Based on the above background, this paper considers a two-echelon sustainable supply chain with emissions-sensitive demand under a cap-and-trade regulation. Here, we focus on the demand expansion effects of sustainability effort. The demand expansion effect describes a state of affair in which given two otherwise equivalent products, the customer prefers the product which is more sustainable. If we invest more in sustainability, the product cost will increase. On the other hand, the sustainability investment can bring a greener product to the customer resulting in expansion of the market demand which will eventually lead to greater sales revenue. Therefore, there is a stable relationship between sustainability level and total profit. The primary objectives of this study is to address the following research questions:

- Who should invest to maintain the sustainability of the supply chain? Should it be supplier or manufacturer or both?
- How the optimal decisions of the supply chain would change if the supply chain members invest in sustainability independently?
- Is it possible to coordinate the sustainable supply chain with a contract mechanism?

The main contributions of this paper are as follows. Firstly, we consider the problem of a single supplier who supplies raw materials to a single manufacturer under cap-and-trade regulation where the market demand is affected by the selling price and the sustainability levels of channel members. Secondly, we explore the relationship between the optimal sustainability levels of the manufacturer and the supplier. Furthermore, we analytically compare the optimal results of the decentralized and the centralized models for the following cases: (i) when only the supplier puts in effort to maintain sustainability, and (ii) when only the manufacturer puts in effort to maintain sustainability. Finally, we implement a two-part tariff contract to coordinate the supply chain.

The rest of the paper is organized as follows: Sect. 2 summarizes the related literature. In Sect. 3, notations and assumptions are provided and the proposed models are formulated. Section 4 analyses the optimal decisions of the decentralized and the centralized models. Section 5 deals with coordination of the supply chain. In Sect. 6, numerical results along with sensitivity analysis of key-parameters and managerial insights are presented. Finally, conclusions with some future research ideas are provided in Sect. 7.

2 Literature review

Environmental affairs are receiving significant deliberation from the public, escalating the development of a sustainable chain in operations management. Sustainable investment can provide a greener product and thereby expands market demand. Numerous researches have been carried out in the literature to reduce carbon emission and maximize supply chain profit under carbon cap-and-trade policy. In this section, we review the relevant literature based on two streams of research - sustainable (or green) investment in supply chain, and operational decisions under cap-and-trade policy.

2.1 *Sustainable (or green) investment in supply chain*

Customer's environmental awareness has a significant impact on business practice. So, more and more researchers have begun to focus on sustainable supply chain management. The sustainable investment or use of green technology reduces the carbon emission per unit product. Zhang et al. [13] proposed a sustainable approach by considering environmentally conscious design and manufacturing whose benefits include improved quality of product at a lower cost, reduced environment and health threat, cleaner and safer business units, reduced disposal cost and higher productivity. Gungor and Gupta [15] developed a sustainable design through environmentally conscious manufacturing and product recovery, which was driven by continuous environmental deterioration. Beamon [18] introduced environmental management strategies for the supply chain, which are based on the development of a basic procedure towards achieving sustainability. Sarkis [19] presented a strategic decision framework about green practices, which mainly focuses on the components and elements of a sustainable supply chain. Green supply chain management (GSCM) has been used as a key parameter by business bodies to become more sustainable environmentally. Zhu et al. [20] evaluated GSCM drivers and described green practices among different manufacturing organizations in China. Srivastava [21] gave a more precise review of the literature on green supply chain management (GrSCM). The convergence of supply chain and sustainability has been provided by Linton et al. [22] by focusing on environmental management. Wu and Pagell [23] presented a green supply chain model and explained how to make decisions and balance short-term profitability and long-term environmental sustainability. Ghosh and Shah [24] proposed game-theoretic models with greening policies and showed the impact of various channel structures on supply chain decisions including greening levels, prices and profits. A two-echelon supply chain has been demonstrated by Swami and Shah [25], in which both the manufacturer and the retailer invest for greening their operations without considering any carbon emission regulation. They also considered a two-part tariff contract to coordinate the supply chain. Ghosh and Shah [26] analyzed supply chain operations under green-sensitive customer demand and showed the effect of consumer sensitivity on green products. Li et al. [27] discussed the greening policies for the members of a dual-channel supply chain under a consistent pricing strategy. The pricing and greening strategies for a closed-loop green supply chain were derived by Mondal et al [28]. Dey and Giri [29] investigated a closed-loop supply chain problem by maintaining sustainability through re-manufacturing the used products.

2.2 Operational decisions under cap-and-trade policy

Traditional operation decisions under cap-and-trade regulation can be categorized into two groups: operational decisions of a single firm and operational decisions of a supply chain. With increasing attention on carbon cap-and-trade regulation, extensive research is carried out focusing on operation decisions that eventually reduce carbon emissions and maximize profit. Dobos [30] discussed the impact of cap-and-trade policy on the production and inventory decisions of a firm. Jiang and Klabjan [31] focused on firm's profit and emission reduction by analysing the manufacturer's joint production and investment decisions under command-and-control and cap-and-trade regulations. He et al. [32] examined a firm's production lot-sizing issues under two regulations – cap-and-trade and carbon tax. They also compared the optimal carbon emissions of the firm under these two regulations. To protect the environment by reducing emissions, the European Union Emissions Trading System (EU-ETS) has been proposed by Jaber et al. [33] in supply chain management. Du et al. [34] developed a two-echelon emission-dependent supply chain in the cap-and-trade system via the Stackelberg game. This model is composed of an emission permit supplier and an emission-dependent manufacturer. Further, Du et al. [35] investigated the operation decision of each member in an emission-dependent supply chain, which is based on the newsvendor model. Coordination problem of a supply chain consisting of a manufacturer and a retailer, where the manufacturer can invest in emission reduction under the cap-and-trade policy was described by Yang [36]. Dong et al. [12] considered various contracts to coordinate a two-echelon supply chain under cap-and-trade regulation. Considering the market demand dependent on selling price and sustainability level, Xu et al. [37] evaluated the optimal production quantities and sustainability investment for the centralized and the decentralized systems under cap-and-trade regulation. Drake et al. [38] showed uncertainty in emission price that ultimately resulted in higher profit than that for the case of constant rate of an emission tax scheme. Xu et al. [39] discussed the supply chain coordination problem under cap-and-trade mechanism, and investigated that the supply chain coordination can be achieved by both the wholesale price and the cost-sharing contracts. Liu et al. [40] investigated the impact of the carbon price and consumer environmental preference on optimal decisions of a supply chain with emissions-sensitive demand. Under cap-and-trade policy, Xu et al. [41] proposed a two-echelon supply chain, and showed that the customer's awareness and the initial amount of carbon emission have a negative impact on the selling price, whereas the trading price of carbon cap has a positive impact on the selling price. Qian et al. [42] presented a coordination problem in a two-echelon sustainable supply chain which incorporates a socially responsible manufacturer and a fair-minded retailer. The optimal pricing and carbon emission strategies in a two-stage supply chain was demonstrated by Zhang and Tao [43]. Further, Chen and Gu [44] considered a two-echelon supply chain where the manufacturer invests in sustainability. By comparing with the sustainable investment only in the upstream, they showed that investment in both upstream and downstream is more sustainable as well as profitable.

From the above literature review, it is observed that several works have been done considering the key factors such as emission-sensitive demand, sustainable (or green) investment, cap-and-trade policy, two-part tariff contract, etc. However, most of the previous studies considered these factors separately. The idea of this study is to investigate the optimal supply chain strategy considering all these factors together in one model. A comparison of the proposed model with some related existing models is given in Table 1.

Inspired by the research works mentioned above, this paper considers a sustainable supply chain with emissions-sensitive demand in a deterministic (make-to-order) setting, and analyzes the optimal sustainability investment and pricing decisions. The primary objective is to study the sustainable development by considering efforts from both the supplier and the manufacturer to coordinate the supply chain and maximize the sustainability.

3 Model formulation

We consider a two-echelon supply chain which consists of a supplier and a manufacturer. In a make-to-order setting, the supplier supplies the raw material to the manufacturer at a wholesale price, and the manufacturer makes the product and sells it to customers. Both the channel partners are responsible for carbon emissions. To reduce carbon emissions during production, both the supplier and the manufacturer make investments to improve their sustainability levels. The supplier makes decisions on the wholesale price and the effort to maintain sustainability level, while the manufacturer decides the selling price

Table 1 A comparison of the proposed model with existing models

Author(s)	Emissions-sensitive demands	Sustainable (green) investment by		Cap-and-trade policy
		Manufacturer	Other player	
Swami and Shah [25]	×	✓	✓	×
Yang [36]	✓	✓	×	×
Xu et al. [37]	×	✓	×	✓
Xu et al. [39]	×	✓	×	✓
Liu et al. [40]	✓	×	×	✓
Xu et al. [41]	✓	✓	×	✓
This paper	✓	✓	✓	✓

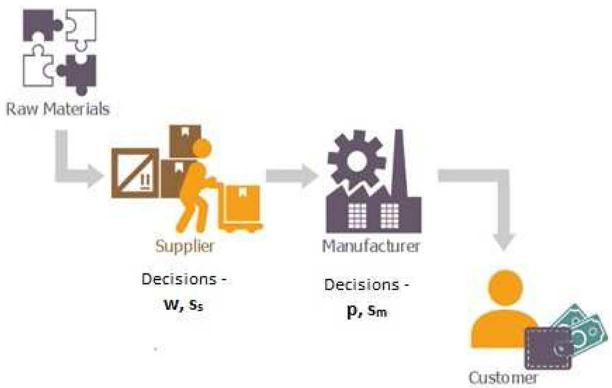

Fig. 1 Structure of the supply chain considered

Table 2 List of notations

Notation	Explanation
w	unit wholesale price.
p	manufacturer's unit selling price.
s_s	supplier's sustainability level.
s_m	manufacturer's sustainability level.
$D_0(>0)$	potential market demand.
$D(s_s, s_m, p)$	market demand function.
α_s	coefficient of sustainability effect on market demand for the supplier.
α_m	coefficient of sustainability effect on market demand for the manufacturer.
β	coefficient of price effect on market demand.
k	coefficient of market sensitivity.
e_s	carbon emission due to raw materials processing at the supplier.
e_m	carbon emission due to manufacturing process.
$e(=e_s + e_m)$	total carbon emission.
b_s	coefficient of sustainability effect on reducing emission for the supplier.
b_m	coefficient of sustainability effect on reducing emission for the manufacturer.
e_{cap}	carbon emission cap.
c_e	unit carbon emission trading price.
c_s	sustainability investment coefficient for the supplier.
c_m	sustainability investment coefficient for the supplier.
c	ordering cost per order.
F	fixed costs charged by the supplier under two-part tariff contract.
$\Pi_S(s_s, w)$	supplier's profit in the decentralized system.
$\Pi_M(s_m, p)$	manufacturer's profit in the decentralized system.
$\Pi_C(s_s, s_m, p)$	total profit of the centralized system.
$\Pi_{S/tt}$	supplier's profit under two-part tariff contract.
$\Pi_{M/tt}$	manufacturer's profit under two-part tariff contract.

and its corresponding sustainability level. The structure of the proposed supply chain model is depicted in Fig. 1. The notations used throughout the paper are given in Table 2.

The customers' environmental awareness results in higher demand of low carbon products. Thus the market demand increases as the sustainability investment increases. Higher emissions at the supplier and the manufacturer certainly affect the market demand. In fact, the market demand is affected by total carbon emissions ($e = e_s + e_m$). We assume that the market demand at the manufacturer end is a function of the selling price p and the sustainability efforts s_s and s_m made by the supplier and the manufacturer, respectively.

Hence, the market demand function can be modeled as

$$D(s_s, s_m, p) = D_0 + \alpha_s s_s + \alpha_m s_m - \beta p - ke \tag{1}$$

where D_0 is the market potential; α_s and α_m denote respectively the coefficients of sustainability efforts by the supplier and the manufacturer; β denotes the coefficient of the price effect on decreasing demand; k represents the coefficient of market sensitivity effect on decreasing market demand.

We define the carbon emissions per unit product at the supplier end as $e_s - b_s s_s$ and at the manufacturer end as $e_m - b_m s_m$, where b_s and b_m denote the coefficients of the sustainability effect on reducing emissions for the supplier and the manufacturer, respectively. As we cannot cease carbon emission completely, therefore, we have $0 \leq s_s \leq \frac{e_s}{b_s}$ and $0 \leq s_m \leq \frac{e_m}{b_m}$.

3.1 Model assumptions

The following assumptions are made to develop the proposed models:

Assumption 1 The sustainability investments of the manufacturer and the supplier are quadratic functions of their respective sustainability levels [37]. We define the sustainability investment function as $\frac{1}{2}c_s s_s^2$ for the supplier and $\frac{1}{2}c_m s_m^2$ for the manufacturer.

Assumption 2 The carbon permits are always available for buying and selling in the carbon trading market [4].

Assumption 3 To guarantee the non-negative values of wholesale price, selling price and sustainability levels, we assume that the following conditions hold:

(i) $c_s c_m (D_1 + \beta\theta) > \lambda_1 \psi_1 + \lambda_2 \psi_2$
(ii) $D_1 > \beta\theta$
(iii) $c_m > 2b_m c_e \alpha_m$ and $c_s > 2b_s c_e \alpha_s$

(iv) $\psi_i < 0, i = 3, 4, 5$
(v) $\Delta_i < 0, i = 1, 2.$

Assumption 4 To ensure the feasibility of the sustainability levels, we assume that the following conditions hold:

(i) $\frac{c_m\psi_1(\beta\theta-D_1)}{c_m\psi_1^2+2c_s\psi_3^2} < \frac{e_s}{b_s}$
(ii) $\frac{c_s\psi_2(\beta\theta-D_1)}{c_m\psi_1^2+2c_s\psi_3^2} < \frac{e_m}{b_m}$

In addition to the list of parameters given in Table 2, we also define the following parameters for modelling simplicity:
$D_1 = D_0 - ke,\ \theta = c + c_e e = c + c_e(e_s + e_m),\ \psi_1 = \alpha_s + b_s c_e \beta,\ \psi_2 = \alpha_m + b_m c_e \beta$, $\psi_3 = \psi_2^2 - 2c_m\beta,\quad \psi_4 = \psi_1^2 - 2c_s\beta,\quad \psi_5 = \psi_1^2 - 4c_s\beta,\quad \lambda_1 = c_m(b_s c_e D_1 + \theta\alpha_s)$, $\lambda_2 = c_s(b_m c_e D_1 + \theta\alpha_m),\ \Delta_1 = c_m\psi_1^2 + 2c_s\psi_3,\quad \Delta_2 = c_m\psi_1^2 + c_s\psi_3.$

4 Model development and analysis

4.1 Decentralized model

In the decentralized scenario, the supplier and the manufacturer take their decisions individually to maximize their own profits. Here we consider the supplier-Stackelberg game in which the supplier acts as the leader and the manufacturer as the follower. The profit functions of the supplier and the manufacturer are given by

$$\Pi_S(s_s, w) = (w - c)D - c_e[(e_s - b_s s_s)D - e_{cap}] - \frac{1}{2}c_s s_s^2 \tag{2}$$

$$\Pi_M(s_m, p) = (p - w)D - c_e[(e_m - b_m s_m)D - e_{cap}] - \frac{1}{2}c_m s_m^2 \tag{3}$$

Proposition 1 *In the supplier-Stackelberg game, there exist unique optimal wholesale price w^*, optimal selling price p^* and optimal sustainability levels s_s^* and s_m^* where*

$$w^* = \frac{c_s(D_1 + \theta\beta)\psi_3 + \beta\psi_1\lambda_1}{\beta\Delta_1} - e_m c_e \tag{4}$$

$$p^* = \frac{\beta[\lambda_1\psi_1 + \lambda_2\psi_2 - c_m c_s(D_1 + \beta\theta)] + c_s D_1\psi_3}{\beta\Delta_1} \tag{5}$$

$$s_s^* = \frac{c_m \psi_1(\beta\theta - D_1)}{\Delta_1} \tag{6}$$

$$s_m^* = \frac{c_s \psi_2(\beta\theta - D_1)}{\Delta_1} \tag{7}$$

Proof In the supplier-Stckelberg game, we use the backward sequential decision-making approach to derive the optimal solutions of the supply chain entities. We first substitute Eq. (1) into Eqs. (2) and (3) and then solve $\frac{\partial \Pi_M(s_m,p)}{\partial p} = 0$ and $\frac{\partial \Pi_M(s_m,p)}{\partial s_m} = 0$ to get the values of p and s_m. Taking the second partial derivatives of $\Pi_M(s,p)$ with respect to s_m and p, we get

$$\frac{\partial^2 \Pi_M(s_m,p)}{\partial s_m^2} = -c_m + 2b_m c_e \alpha_m < 0, \quad \frac{\partial^2 \Pi_M(s_m,p)}{\partial p^2} = -2\beta < 0$$
$$\text{and} \quad \frac{\partial^2 \Pi_M(s_m,p)}{\partial s_m \partial p} = \alpha_m - b_m c_e \beta.$$

Then, we calculate

$$\frac{\partial^2 \Pi_M(s_m,p)}{\partial s_m^2} \cdot \frac{\partial^2 \Pi_M(s_m,p)}{\partial p^2} - \left(\frac{\partial^2 \Pi_M(s_m,p)}{\partial s_m \partial p}\right)^2 = 2\beta c_m - \psi_2^2 = -\psi_3 > 0$$

which implies that the profit of the manufacturer $\Pi_M(s_m,p)$ is a joint concave function of s_m and p. □

Now, substituting the values of p and s_m in Eqn. (2) and solving $\frac{\partial \Pi_S(s_s,w)}{\partial w} = 0$ and $\frac{\partial \Pi_S(s_s,w)}{\partial s_s} = 0$, we get the optimal values of w and s_s as given in Eqs. (4) and (6). Taking the second partial derivatives of $\Pi_S(s_s,w)$ with respect to s_s and w, we get

$$\frac{\partial^2 \Pi_S(s_s,w)}{\partial s_s^2} = -c_s - \frac{2b_s c_e c_m \alpha_s \beta}{\psi_3} < 0, \quad \frac{\partial^2 \Pi_S(s_s,w)}{\partial w^2} = \frac{2c_m \beta^2}{\psi_3} < 0$$
$$\text{and} \quad \frac{\partial^2 \Pi_S(s_s,w)}{\partial s_s \partial w} = -\frac{c_m \beta(\alpha_s - b_s c_e \beta}{\psi_3}.$$

Now, we obtain

$$\frac{\partial^2 \Pi_S(s_s,w)}{\partial s_s^2} \cdot \frac{\partial^2 \Pi_S(s_s,w)}{\partial w^2} - \left(\frac{\partial^2 \Pi_S(s_s,w)}{\partial s_s \partial w}\right)^2 = -\frac{c_m \beta^2 \Delta_1}{\psi_3^2} > 0$$

This shows that the profit of the supplier $\Pi_S(s_s,w)$ is a joint concave function of s_s and w. Therefore, the optimal wholesale price w^* and the sustainability level s_s^*

for the supplier are uniquely determined by Eqs. (4) and (6), respectively. Finally, substituting the optimal values of w and s_s in the expressions of p and s_m as derived earlier, we obtain the optimal selling price p^* and the sustainability level s_m^* for the manufacturer as given in Eqs. (5) and (7), respectively.

Substituting the optimal values given in Eqs. (4), (5) and (6) into Eqs. (2) and (3), we obtain the supplier's optimal profit Π_S^* and the manufacturer's optimal profit Π_M^*. The optimal total profit of the decentralized system is then

$$\Pi_D^* = \Pi_S^* + \Pi_M^*$$

4.2 Centralized model

In the centralized scenario, the supplier and the manufacturer are considered as an integrated business unit. They cooperatively decide the optimal selling price and sustainability levels to maximize the total profit of the supply chain. The profit function of the centralized system is given by

$$\begin{aligned}\Pi_C(s_s, s_m, p) =&(p-c)D - c_e[(e_s + e_m - b_s s_s - b_m s_m)D - 2e_{cap}] \\ &- \frac{1}{2}(c_s s_s^2 + c_m s_m^2)\end{aligned} \tag{8}$$

Proposition 2 *There exist unique optimal selling price p^* and sustainability levels s_s^* and s_m^* which maximize the total profit of the centralized channel, where*

$$p^* = \frac{\lambda_1\psi_1 + \lambda_2\psi_2 - c_s c_m(D_1 + \beta\theta)}{\Delta_2} \tag{9}$$

$$s_s^* = \frac{c_m\psi_1(\beta\theta - D_1)}{\Delta_2} \tag{10}$$

$$s_m^* = \frac{c_s\psi_2(\beta\theta - D_1)}{\Delta_2} \tag{11}$$

Proof From the first order conditions $\frac{\partial\Pi_C}{\partial p} = 0$, $\frac{\partial\Pi_C}{\partial s_s} = 0$ and $\frac{\partial\Pi_C}{\partial s_m} = 0$, we obtain the optimal selling price and sustainability levels for both the supplier and the manufacturer as given in Eqs. (9), (10) and (11), respectively. Taking the second partial derivatives of $\Pi_C(s_s, s_m, w)$ with respect to p, s_m and s_s, we obtain the corresponding Hessian matrix as

$$\mathbf{H}_{3\times3} = \begin{bmatrix} \frac{\partial^2 \Pi_C}{\partial p^2} & \frac{\partial^2 \Pi_C}{\partial p s_m} & \frac{\partial^2 \Pi_C}{\partial p s_s} \\ \frac{\partial^2 \Pi_C}{\partial s_m p} & \frac{\partial^2 \Pi_C}{\partial s_m^2} & \frac{\partial^2 \Pi_C}{\partial s_m s_s} \\ \frac{\partial^2 \Pi_C}{\partial s_s p} & \frac{\partial^2 \Pi_C}{\partial s_s s_m} & \frac{\partial^2 \Pi_C}{\partial s_s^2} \end{bmatrix} = \begin{bmatrix} -2\beta & (\alpha_m - b_m c_e \beta) & (\alpha_s - b_s c_e \beta) \\ (\alpha_m - b_m c_e \beta) & (-c_m + 2 b_m c_e \alpha_m) & c_e(b_s \alpha_m + b_m \alpha_s) \\ (\alpha_s - b_s c_e \beta) & c_e(b_s \alpha_m + b_m \alpha_s) & (-c_s + 2 b_s c_e \alpha_s) \end{bmatrix}$$

□

Now we have,

$$\mathbf{D}_1 = -2\beta < 0,$$

$$\mathbf{D}_2 = \begin{vmatrix} -2\beta & (\alpha_m - b_m c_e \beta) \\ (\alpha_m - b_m c_e \beta) & (-c_m + 2 b_m c_e \alpha_m) \end{vmatrix} = -\psi_3 > 0$$

$$\mathbf{D}_3 = \begin{vmatrix} -2\beta & (\alpha_m - b_m c_e \beta) & (\alpha_s - b_s c_e \beta) \\ (\alpha_m - b_m c_e \beta) & (-c_m + 2 b_m c_e \alpha_m) & c_e(b_s \alpha_m + b_m \alpha_s) \\ (\alpha_s - b_s c_e \beta) & c_e(b_s \alpha_m + b_m \alpha_s) & (-c_s + 2 b_s c_e \alpha_s) \end{vmatrix} = \Delta_2 < 0$$

Since $\mathbf{D}_1, \mathbf{D}_3 < 0$ and $\mathbf{D}_2 > 0$, therefore, the Hessian matrix $\mathbf{H}$ is negative definite. Hence Π_C is a strictly concave function of s_s, s_m and p.

Proposition 3 *In both the centralized and the decentralized systems, the optimal sustainability levels s_s^* and s_m^* are connected by the relation*

$$\frac{s_s^*}{s_m^*} = \frac{\frac{(\alpha_s + b_s c_e \beta)}{(\alpha_m + b_m c_e \beta)}}{\left(\frac{c_s}{c_m}\right)} \tag{12}$$

Proof The result can obtained straightforwardly either from Eqns. (6) and (7) or from Eqns. (10) and (11). □

A comparison of the optimal results of the centralized and the decentralized models is shown in Table 3.

We now discuss some special cases where supply chain members put effort independently to improve sustainability.

Table 3 A comparison of the optimal results for the decentralized and the centralized channels

Comparison measure	Decentralized channel	Centralized channel
Wholesale price	$\frac{c_s(D_1+\theta\beta)\psi_3+\beta\psi_1\lambda_1}{\beta\Delta_1} - e_m c_e$	–
Selling price	$\frac{\beta[\lambda_1\psi_1+\lambda_2\psi_2-c_m c_s(D_1+\beta\theta)]+c_s D_1\psi_3}{\beta\Delta_1}$	$\frac{\lambda_1\psi_1+\lambda_2\psi_2-c_s c_m(D_1+\beta\theta)}{\Delta_2}$
Supplier's sustainability level	$\frac{c_m\psi_1(\beta\theta-D_1)}{\Delta_1}$	$\frac{c_m\psi_1(\beta\theta-D_1)}{\Delta_2}$
Manufacturer's sustainability level	$\frac{c_s\psi_2(\beta\theta-D_1)}{\Delta_1}$	$\frac{c_s\psi_2(\beta\theta-D_1)}{\Delta_2}$

Case (i): When only the supplier invests in sustainability (i.e. when $s_m = 0$)

Proposition 4 *When only the supplier invests in sustaianability, the optimal values of wholesale price, selling price, sustainability level and profit of the whole supply chain in the decentralized model are obtained as*

$$
\begin{aligned}
w_s^* &= \frac{(b_s c_e D_1 + \theta\alpha_s)\psi_1 - 2c_s(D_1 + \beta\theta)}{\psi_5} - e_m c_e \\
p_s^* &= \frac{(b_s c_e D_1 + \theta\alpha_s)\psi_1 - c_s(3D_1 + \beta\theta)}{\psi_5} \\
s_s^* &= \frac{\psi_1(\beta\theta - D_1)}{\psi_5} \\
\Pi_D^* &= 2c_e e_{cap} - \frac{c_s(\psi_1^2 - 6c_s\beta)(\beta\theta - D_1)^2}{2\psi_5^2}
\end{aligned}
$$

Proof In the decentralized scenario, the supplier decides the wholesale price and the sustainability investment while the manufacturer sets the selling price. The profit functions of the supplier and the manufacturer are given by

$$\Pi_S(s_s, w) =(w - c)D(s_s, p) - c_e[(e_s - b_s s_s)D(s_s, p) - e_{cap}] - \frac{1}{2}c_s s_s^2 \tag{13}$$

$$\Pi_M(p) =(p - w)D(s_s, p) - c_e[e_m D(s_s, p) - e_{cap}] \tag{14}$$

Then proceeding similarly as in Proposition 1 the results of Proposition 4 can be obtained. □

Proposition 5 *When only the supplier invests in sustainability, the optimal values of selling price, sustainability level and profit of the whole supply chain in the centralized model are obtained as*

$$
\begin{aligned}
p_s^* &= \frac{(b_s c_e D_1 + \theta\alpha_s)\psi_1 - c_s(D_1 + \beta\theta)}{\psi_4} \\
s_s^* &= \frac{\psi_1(\beta\theta - D_1)}{\psi_4} \\
\Pi_C^* &= 2c_e e_{cap} - \frac{c_s(\beta\theta - D_1)^2}{2\psi_4}
\end{aligned}
$$

Proof In the centralized scenario, the profit function of the whole supply chain is given by

$$
\begin{aligned}
\Pi_C(s_s, p) = (p - c)D(s_s, p) - c_e[(e_s + e_m - b_s s_s)D(s_s, p) - 2e_{cap}] \\
- \frac{1}{2}c_s s_s^2
\end{aligned} \tag{15}
$$

Then proceeding similarly as in Proposition 2, the results of Proposition 5 can be obtained. □

Case (ii): When only the manufacturer invests in sustainability (i.e. when $s_s = 0$)

Proposition 6 *When only the manufacturer invests in sustainability, the optimal values of wholesale price, selling price, sustainability level and the profit of the whole supply chain in the decentralized model are obtained as follows:*

$$w_m^* = \frac{D_1 + \beta\theta}{2\beta} - e_m c_e$$

$$p_m^* = \frac{D_1}{2\beta} + \frac{(b_m c_e D_1 + \theta\alpha_m)\psi_2 - c_m(D_1 + \beta\theta)}{2\psi_3}$$

$$s_m^* = \frac{\psi_2(\beta\theta - D_1)}{2\psi_3}$$

$$\Pi_D^* = 2c_e e_{cap} - \frac{3c_m(\beta\theta - D_1)^2}{8\psi_3}$$

Proof In the decentralized scenario, the manufacturer sets the selling price and the sustainability investment, and the manufacturer decides the wholesale price of the supply chain. The profit functions of the supplier and the manufacturer are as follows:

$$\Pi_S(w) = (w - c)D(s_m, p) - c_e[e_s D(s_m, p) - e_{cap}] \tag{16}$$

$$\Pi_M(s_m, p) = (p - w)D(s_m, p) - c_e[(e_m - b_m s_m)D(s_m, p) - e_{cap}] \tag{17}$$

$$-\frac{1}{2}c_m s_m^2 \tag{18}$$

Proceeding similarly as in Proposition 1, the results of Proposition 6 can be obtained. □

Proposition 7 *When only the manufacturer invests in sustainability, the optimal values of selling price, sustainability level and the profit of the whole supply chain in the centralized model are obtained as follows:*

$$p_m^* = \frac{(b_m c_e D_1 + \theta\alpha_m)\psi_2 - c_m(D_1 + \beta\theta)}{\psi_3}$$

$$s_m^* = \frac{\psi_2(\beta\theta - D_1)}{\psi_3}$$

$$\Pi_C^* = 2c_e e_{cap} - \frac{c_m(\beta\theta - D_1)^2}{2\psi_3}$$

Proof In the centralized scenario, the profit function of the whole supply chain is given by

$$\Pi_C(s_m, p) = (p - c)D(s_m, p) - c_e[(e_s + e_m - b_m s_m)D(s_m, p) - 2e_{cap}] - \frac{1}{2}c_m s_m^2 \tag{19}$$

The rest of this proof is omitted as it is similar to that of Proposition 2. □

We now summarize the optimal results of the special cases in Table 4. From Tables 3 and 4, we have the following two propositions.

Proposition 8 *The relationships between the optimal sustainability levels and the selling prices in the two channels (centralized and decentralized) are as follows:*

(i) $s_s^C > s_s^D$ *and* $s_m^C > s_m^D$
(ii) $p^D > p^C$.

Proof The proof is omitted as it can be easily verified. □

Proposition 9 *The optimal total profits in the centralized and the decentralized channels satisfy the relation* $\Pi_D < \Pi_C < \frac{4}{3}\Pi_D$.

Proof To simplify the calculation, one can take $\alpha_s = \alpha_m$, $\beta_s = \beta_m$ and $c_s = s_m$, and easily prove the proposition using Assumption 2. □

Table 4 A comparison of the optimal results for the decentralized and the centralized channels under different cases

Comparison measure	Decentralized channel	Centralized channel
Under supplier's sustainable investment		
Wholesale price	$\frac{(b_s c_e D_1+\theta\alpha_s)\psi_1-2c_s(D_1+\beta\theta)}{\psi_5} - e_m c_e$	-
Selling price	$\frac{(b_s c_e D_1+\theta\alpha_s)\psi_1-c_s(3D_1+\beta\theta)}{\psi_5}$	$\frac{(b_s c_e D_1+\theta\alpha_s)\psi_1-c_s(D_1+\beta\theta)}{\psi_4}$
Supplier's sustainability level	$\frac{\psi_1(\beta\theta-D_1)}{\psi_5}$	$\frac{\psi_1(\beta\theta-D_1)}{\psi_4}$
Total profit	$2c_e e_{cap} - \frac{c_s(\psi_1^2-6c_s\beta)(\beta\theta-D_1)^2}{2\psi_5^2}$	$2c_e e_{cap} - \frac{c_s(\beta\theta-D_1)^2}{2\psi_4}$
Under manufacturer's sustainable investment		
Wholesale price	$\frac{D_1+\beta\theta}{2\beta} - e_m c_e$	-
Selling price	$\frac{D_1}{2\beta} + \frac{(b_m c_e D_1+\theta\alpha_m)\psi_2-c_m(D_1+\beta\theta)}{2\psi_3}$	$\frac{(b_m c_e D_1+\theta\alpha_m)\psi_2-c_m(D_1+\beta\theta)}{\psi_3}$
Manufacturer's sustainability level	$\frac{\psi_2(\beta\theta-D_1)}{2\psi_3}$	$\frac{\psi_2(\beta\theta-D_1)}{\psi_3}$
Total profit	$2c_e e_{cap} - \frac{3c_m(\beta\theta-D_1)^2}{8\psi_3}$	$2c_e e_{cap} - \frac{c_m(\beta\theta-D_1)^2}{2\psi_3}$

5 Supply chain coordination

We now employ a two-part tariff contract to coordinate the proposed sustainable supply chain. In this contract, there are both price and non-price variables. A unit wholesale price w is charged by the supplier, and the manufacturer makes a lump-sum payment F to the supplier. The profit functions of the supplier and manufacturer under this contract are given by

$$\Pi_{S/tt} =(w-c)D - c_e[(e_s - b_s s_s)D - e_{cap}] - \frac{1}{2}c_s s_s^2 + F \tag{20}$$

$$\Pi_{M/tt} =(p-w)D - c_e[(e_m - b_m s_m)D - e_{cap}] - \frac{1}{2}c_m s_m^2 - F \tag{21}$$

Proposition 10 *The two-part tariff contract between the supplier and the manufacturer coordinates the supply chain with the supplier's wholesale price*

$$w^* = \frac{(c + c_e e_s)(c_m \alpha_s \Psi_1 + c_s \Psi_3) + c_e c_m \Psi_1 b_s (D_1 - c_e e_m \beta)}{\Delta_2}$$

and the manufacturer's selling price p^* equal to the optimal selling price in the centralized channel.

Proof The proof of Proposition 10 is similar to that of Proposition 1. It can be shown that the total profit of the supply chain under two-part tariff contract is equal to that of the centralized system. This means that the supply chain is perfectly coordinated. □

6 Numerical analysis

In this section, we present a numerical example to demonstrate the theoretical results. The following parameter-values are chosen for the numerical study (most of the data are similar to those of Xu et al. [37]):

$c = 150$, $D_0 = 500$, $\alpha_s = 0.2$, $\alpha_m = 0.4$, $\beta = 0.8$, $e_s = 6$, $e_m = 8$, $b_s = 0.3$, $b_m = 0.2$, $c_e = 12$, $c_s = 30$, $c_m = 25$, $e_{cap} = 300$ and $k = 12$.

For this set of parameter-values, the concavity property of profit functions of the supplier and the manufacturer is graphically shown in Fig. 2. The optimal results of the decentralized and the centralized models for different cases, and the model with two-part tariff contract are shown in Table 5.

From Table 5, we observe that the optimal profits of the decentralized and the centralized channels are 9120.10 and 10017.88, respectively, which implies that the profit in the centralized channel is notably higher than that in the decentralized channel. In particular, in the centralized channel, the cooperation between the supplier and the manufacturer results in a 9.84% profit increase. In the

Table 5 Optimal results for different models

Model	w^*	p^*	s_s^*	s_m^*	Supplier's profit	Manufacturer's profit	Total profit
Decentralized	265.06	385.65	3.25	2.93	4827.33	4292.77	9120.10
Centralized	-	347.61	7.46	6.74	-	-	10017.88
Only supplier's effort							
Decentralized	265.87	388.78	2.76	-	4644.07	4179.28	8823.35
Centralized	-	365.10	6.21	-	-	-	9545.31
Only manufacturer's effort							
Decentralized	271.43	389.64	-	2.09	4676.63	4138.32	8814.95
Centralized	-	362.41	-	4.18	-	-	9353.27
Two-part tariff contract							
$F = 2000$	195.16	347.61	7.46	6.74	4766.06	5251.82	10017.88
$F = 2100$	195.16	347.61	7.46	6.74	4866.06	5151.82	10017.88
$F = 2300$	195.16	347.61	7.46	6.74	5066.06	4951.82	10017.88
$F = 2500$	195.16	347.61	7.46	6.74	5266.06	4751.82	10017.88
$F = 2700$	195.16	347.61	7.46	6.74	5466.06	4551.82	10017.88
$F = 2900$	195.16	347.61	7.46	6.74	5666.06	4351.82	10017.88
$F = 3000$	195.16	347.61	7.46	6.74	5766.06	4251.82	10017.88

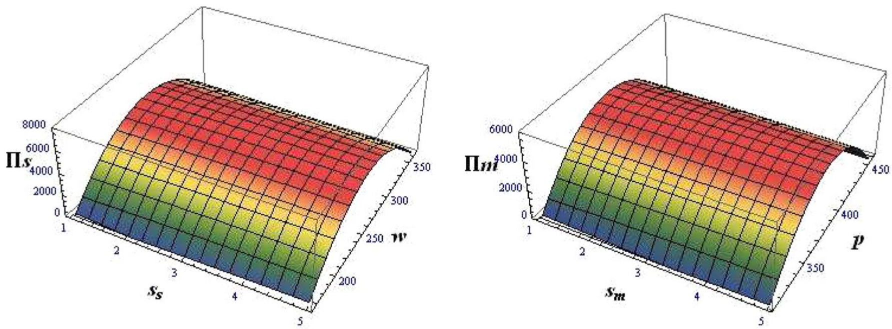

Fig. 2 Concavity of the profit functions of the supplier and the manufacturer

decentralized model, the individual profits for the supplier and the manufacturer are 4827.33 and 4292.77, respectively. Further, Table 5 shows that the selling price 385.65 in the decentralized channel decreases to 347.61 in the centralized channel, whereas the sustainability level for the supplier increases from 3.25 to 7.46 and for the manufacturer, it rises from 2.93 to 6.74. Comparing the optimal results of the decentralized and the centralized channels, we can say that a higher sustainability level for both the parties can coexist with a lower selling price and higher total profit.

When only the supplier puts effort to maintain sustainability, the decentralized and the centralized profits are obtained as 8823.35 and 9545.31, respectively.

Similarly, when only the manufacturer makes sustainable investment, the decentralized and the centralized profits are obtained as 8814.35 and 9535.27, respectively. From Table 5, we find that the individual profits as well as the whole supply chain's profit in the decentralized and the centralized scenarios decrease if the supply chain members decide to invest in sustainability independently. Table 5 also reveals that the simultaneous efforts of the supply chain members strengthen their respective sustainability levels.

Under the two-part tariff contract, we observe that, as F increases, the supplier's profit increases whereas the manufacturer's profit decreases. At $F = 2000$, the supplier's profit becomes less than that of the decentralized channel while the manufacturer's profit becomes less than that of the decentralized channel when $F = 3000$. For other values of F between 2100 and 2900, we see that a win-win outcome is attained.

To investigate the effects of parameters α_s, α_m, b_s, b_m, c_s and c_m on the optimal decisions as well as the profits of the supplier and the manufacturer and the whole supply chain, we perform a sensitivity analysis for the model under two-part tariff

Table 6 Sensitivity analysis under two-part tariff contract with $F = 2500$

Parameter	Value (% change)	w^*	p^*	s_s^*	s_m^*	$\Pi^*_{S/tt}(s_s^*, w)$	$\Pi^*_{M/tt}(s_m^*, p^*)$	Total profit
$\alpha_s(= 0.2)$	0.24(+20)	194.60	347.49	7.61	6.79	5230.87	4808.98	10039.85
	0.22(+10)	194.88	347.55	7.53	6.77	5248.65	4780.14	10028.79
	0.18(-10)	195.43	347.67	7.38	6.71	5283.13	4724.00	10007.13
	0.16(-20)	195.71	347.73	7.30	6.69	5299.85	4696.67	9996.52
$\alpha_m(= 0.4)$	0.48(+20)	194.77	347.47	7.56	7.07	5241.98	4816.31	10058.29
	0.44(+10)	194.97	347.54	7.51	6.90	5254.25	4783.52	10037.77
	0.36(-10)	195.34	347.68	7.40	6.58	5277.44	4721.17	9998.61
	0.32(-20)	195.52	347.76	7.36	6.42	5288.38	4691.53	9979.91
$b_s(= 0.3)$	0.36(+20)	178.50	338.72	10.07	7.67	4579.08	5826.85	10405.93
	0.33(+10)	187.73	343.65	8.65	7.15	4976.40	5214.77	10191.17
	0.27(-10)	201.20	350.82	6.42	6.40	5481.69	4394.97	9876.66
	0.24(-20)	206.13	353.44	5.51	6.12	5644.75	4116.16	9760.91
$b_m(= 0.2)$	0.24(+20)	193.07	342.96	8.04	8.47	5131.18	5106.06	10237.24
	0.22(+10)	194.19	345.47	7.72	7.56	5204.97	4914.30	10119.27
	0.18(-10)	195.99	349.43	7.22	5.99	5316.94	4613.65	9930.59
	0.16(-20)	196.70	350.97	7.03	5.30	5359.45	4495.96	9855.41
$c_s(= 30)$	36(+20)	200.68	350.48	5.92	6.42	5468.85	4416.57	9885.42
	33(+10)	198.24	349.21	6.60	6.56	5381.08	4562.97	9944.06
	27(-10)	191.16	345.53	8.57	6.97	5109.32	5004.37	10113.69
	24(-20)	185.77	342.73	10.06	7.28	4884.35	5358.67	10243.02
$c_m(= 25)$	30(+20)	196.03	349.25	7.21	5.43	5319.38	4606.95	9926.33
	27.5(+10)	195.64	348.52	7.32	6.02	5295.80	4671.40	9967.20
	22.5(-10)	194.54	346.45	7.63	7.66	5227.43	4854.98	10082.41
	20(-20)	193.73	344.92	7.85	8.87	5175.24	4992.11	10167.35

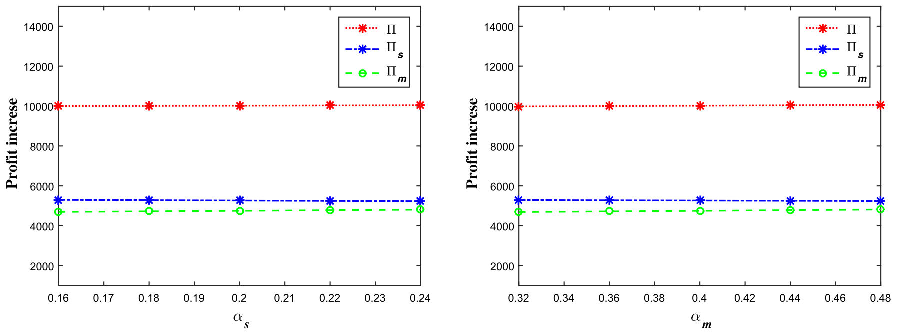

Fig. 3 Effects of α_s and α_m on profit

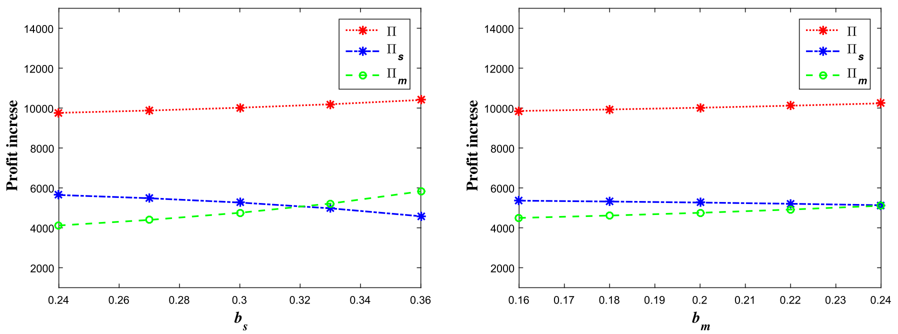

Fig. 4 Effects of b_s and b_m on profit

contract by considering a fixed value $F = 2500$. We change the parameter-values one at a time by +20%, +10%, -10% and -20% and keep the other parameter-values unchanged. The computational results are presented in Table 6. From Table 6, we have the following observations:

- As α_s and α_m decrease, the optimal wholesale price and selling price increase while the sustainability levels for both the parties decrease. Moreover, as both α_s and α_m increase, the supplier's profit decreases but the manufacturer's profit and the whole supply chain's profit increase, see Fig. 3. From the figure, we see that the impacts of the sensitivity factors α_s and α_m on profit are almost the same.
- Under the two-part tariff contract, the optimal wholesale price and selling price decrease, and the sustainability levels for both the parties increase as b_s and b_m increase. Further, the manufacturer's profit and the supply chain's profit decrease as one of b_s and b_m shrinks, but the supplier's profit rises when b_s and b_m decrease, which is reflected in Fig. 4. The numerical results in Table 6 and Fig. 4 show that the contract is highly sensitive to the parameter b_s.
- With higher values of c_s (c_m), the optimal wholesale price, the selling price and the supplier's profit increase whereas the sustainability levels for both the

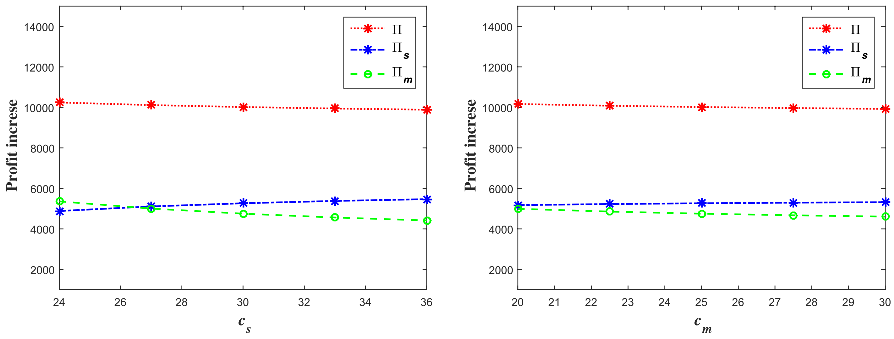

Fig. 5 Effects of c_s and c_m on profit

supply chain members, the manufacturer's profit, as well as the total profit are getting bigger with lower values of c_s (c_m). From Fig. 5, we observe that the profits under the two-part tariff contract are affected by the changes in the sustainability investment coefficients. Comparing the results given in Table 6, it can be easily concluded that c_s is much more sensitive than c_m.

6.1 Managerial insights

Some significant managerial insights for the proposed supply chain are outlined in the following:

(i) The centralized policy is the best choice for the improvement of the sustainability of the supply chain. However, this policy may not be beneficial to all the channel members. A cooperative agreement among all channel members needs to be discussed and practiced to gain the desired sustainability and thus benefits.

(ii) It will not be beneficial if only one of the supply chain members invests in sustainability. If it is possible to develop a circumstance in which the channel members always agree to work jointly on sustainability, then it will help to increase the overall profit.

(iii) The cap-and-trade policy lowers emissions during production and increases the sustainability of the product. Although the policy reduces the wholesale price, the cost of the product increases with the increase in sustainability. This problem can be managed by making consumers aware of the environment and the benefits of the sustainable product. Consumers today are more inclined to products with high sustainability. They can share feedback which can provide new ways in sustainable improvement.

The responsible supply chain managers can procure real-time knowledge and analytical information from the effects on product pricing, profitability and production emission by using green marketing, sustainable products and cap-and-trade policy and by arising environmental awareness among consumers. They can use the gained knowledge to get optimal decisions for economic and environmental benefits.

7 Conclusions

This paper considers carbon footprint in a two-echelon supply chain system which executes emissions-sensitive demand under a make-to-order setting with one supplier and one manufacturer. The sustainability level of the supply chain is maintained by both the supplier and the manufacturer who can invest to buy extra carbon emission permits. The market demand is dependent on two factors – the sustainability level and the selling price, and also affected by normal carbon emission. We have derived the optimal decisions for the decentralized and the centralized models under cap-and-trade regulation. We have also studied the cases, where the supplier and the manufacturer work independently to upgrade sustainability. The comparison of different circumstances reveals that the joint effort of the supplier and the manufacturer to enhance the sustainability of the supply chain maximizes the total profit of the supply chain. Also, the individual profit of the supply chain members escalates if they work on sustainable investment simultaneously. By carefully analyzing the corporation incentives of the supplier and the manufacturer, we have developed a two-part tariff contract to coordinate the two-echelon supply chain. The upper limit of F has been found as a result of the constraint that the manufacturer has to make a non-zero profit. This negotiation process would make sure that both the supplier and the manufacturer 'share the pie' appropriately. Precisely, the comparison of the decentralized channel with the centralized one showed that cooperation between the supplier and the manufacturer can yield at most 33% increase in profit. The present model also reveals that the selling price in the centralized system is less than that in the decentralized system, while the optimal sustainability levels for both the supplier and the manufacturer in the centralized system are greater than that in the decentralized system. Further, it is established that a higher sustainability level can coexist with a lower selling price and a higher total profit of the supply chain.

Eventually, the above conclusions open up a wide range of new areas to focus. Firstly, we consider the supply chain coordination with a single supplier and a single manufacturer under cap-and-trade policy. In real scenarios, the interactions are among multiple competing suppliers or multiple competing manufacturers under different carbon reduction policies. So future research can find effective contracts to coordinate more complex systems under different carbon regulations, and to observe the impact of competition among manufacturers or retailers on contract efficiency. Secondly, a deterministic demand is assumed in our model, which can be extended by considering stochastic demand. Thirdly, consideration of various model-parameters uncertain could provide useful insights of the model.

Author Contributions IR involved in model constructing and carried out the numerical studies, and also wrote the paper. BCG contributed in discussion, gave valuable suggestions, and revised the whole paper. Both the authors read and approved the final manuscript.

Funding Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

1. White, L., Lee, G.J.: Operational research and sustainable development: tackling the social dimension. Eur. J. Oper. Res. **193**(3), 683–692 (2009)
2. LMI Report: GreenSCOR: developing a green supply chain analytical tool. Report LG101T4 (2003). https://postconflict.unep.ch/humanitarianaction/documents/02_08-04_05-11.pdf
3. Aidt, T.S., Dutta, J.: Transitional politics: emerging incentive-based instruments in environmental regulation. J. Environ. Econ. Manag. **47**(3), 458–479 (2004)
4. European Commission: Questions and answers on emissions trading and national allocation plans (2005). https://ec.europa.eu/commission/presscorner/detail/en/MEMO_05_84
5. Hua, G., Cheng, T.C.E., Wang, S.: Managing carbon footprints in inventory management. Int. J. Prod. Econ. **132**(2), 178–185 (2011)
6. Huang, P., Zhang, X., Deng, X.: Survey and analysis of public environmental awareness and performance in Ningbo, China: a case study on household electrical and electronic equipment. J. Clean. Prod. **14**(18), 1635–1643 (2006)
7. Penfield, P.C.: Sustainability within the supply chain. *US Department of States Bureau of International Information Programs, March, 12* (2008)
8. Plambeck, E.L.: Reducing greenhouse gas emissions through operations and supply chain management. Energy Econ. **34**, S64–S74 (2012)
9. Seuring, S., Müller, M.: From a literature review to a conceptual framework for sustainable supply chain management. J. Clean. Prod. **16**(15), 1699–1710 (2008)
10. Testa, F., Iraldo, F.: Shadows and lights of GSCM (Green Supply Chain Management): determinants and effects of these practices based on a multi-national study. J. Clean. Prod. **18**(10–11), 953–962 (2010)
11. Kumar, S., Teichman, S., Timpernagel, T.: A green supply chain is a requirement for profitability. Int. J. Prod. Res. **50**(5), 1278–1296 (2012)
12. Dong, C., Shen, B., Chow, P.S., Yang, L., Ng, C.T.: Sustainability investment under cap-and-trade regulation. Ann. Oper. Res. **240**(2), 509–531 (2016)
13. Zhang, H.C., Kuo, T.C., Lu, H., Huang, S.H.: Environmentally conscious design and manufacturing: a state-of-the-art survey. J. Manuf. Syst. **16**(5), 352–371 (1997)
14. Fleischmann, M., Bloemhof-Ruwaard, J.M., Dekker, R., Van der Laan, E., Van Nunen, J.A., Van Wassenhove, L.N.: Quantitative models for reverse logistics: a review. Eur. J. Oper. Res. **103**(1), 1–17 (1997)
15. Gungor, A., Gupta, S.M.: Issues in environmentally conscious manufacturing and product recovery: a survey. Comput. Ind. Eng. **36**(4), 811–853 (1999)
16. Giri, B.C., Bardhan, S.: Coordinating a two-echelon supply chain with environmentally aware consumers. Int. J. Manag. Sci. Eng. Manag. **11**(3), 178–185 (2016)
17. Giri, B.C., Mondal, C., Maiti, T.: Analysing a closed-loop supply chain with selling price, warranty period and green sensitive consumer demand under revenue sharing contract. J. Clean. Prod. **190**, 822–837 (2018)
18. Beamon, B.M.: Designing the green supply chain. *Logistics information management* (1999)
19. Sarkis, J.: A strategic decision framework for green supply chain management. J. Clean. Prod. **11**(4), 397–409 (2003)
20. Zhu, Q., Sarkis, J., Geng, Y.: Green supply chain management in China: pressures, practices and performance. Int. J. Oper. Prod. Manag. (2005)

21. Srivastava, S.K.: Green supply chain management: a state-of-the-art literature review. Int. J. Manag. Rev. **9**(1), 53–80 (2007)
22. Linton, J.D., Klassen, R., Jayaraman, V.: Sustainable supply chains: an introduction. J. Oper. Manag. **25**(6), 1075–1082 (2007)
23. Wu, Z., Pagell, M.: Balancing priorities: decision-making in sustainable supply chain management. J. Oper. Manag. **29**(6), 577–590 (2011)
24. Ghosh, D., Shah, J.: A comparative analysis of greening policies across supply chain structures. Int. J. Prod. Econ. **135**(2), 568–583 (2012)
25. Swami, S., Shah, J.: Channel coordination in green supply chain management. J. Oper. Res. Soc. **64**(3), 336–351 (2013)
26. Ghosh, D., Shah, J.: Supply chain analysis under green sensitive consumer demand and cost sharing contract. Int. J. Prod. Econ. **164**, 319–329 (2015)
27. Li, B., Zhu, M., Jiang, Y., Li, Z.: Pricing policies of a competitive dual-channel green supply chain. J. Clean. Prod. **112**, 2029–2042 (2016)
28. Mondal, C., Giri, B. C., Maiti, T.: Pricing and greening strategies for a dual-channel closed-loop green supply chain. *Flexible Services and Manufacturing Journal*, 1-38 (2019)
29. Dey, S. K., Giri, B. C.: Coordination of a sustainable reverse supply chain with revenue sharing contract. J. Ind Manag. Opt. (2020)
30. Dobos, I.: The effects of emission trading on production and inventories in the Arrow–Karlin model. Int. J. Prod. Econ. **93**, 301–308 (2005)
31. Jiang, Y., Klabjan, D.: Optimal Emissions Reduction Investment Under Green House Gas Emissions Regulations. Northwestern University, Evanston (2012)
32. He, P., Zhang, W., Xu, X., Bian, Y.: Production lot-sizing and carbon emissions under cap-and-trade and carbon tax regulations. J. Clean. Prod. **103**, 241–248 (2015)
33. Jaber, M.Y., Glock, C.H., El Saadany, A.M.: Supply chain coordination with emissions reduction incentives. Int. J. Prod. Res. **51**(1), 69–82 (2013)
34. Du, S., Zhu, L., Liang, L., Ma, F.: Emission-dependent supply chain and environment-policy-making in the ‘cap-and-trade‘system. Energy Policy **57**, 61–67 (2013)
35. Du, S., Ma, F., Fu, Z., Zhu, L., Zhang, J.: Game-theoretic analysis for an emission-dependent supply chain in a ‘cap-and-trade‘ system. Ann. Oper. Res. **228**(1), 135–149 (2015)
36. Yang, X.: Supply chain coordination contract with carbon emissions sensitive demand and green technology investments. Metall. Min. Ind. (9) (2015)
37. Xu, J., Chen, Y., Bai, Q.: A two-echelon sustainable supply chain coordination under cap-and-trade regulation. J. Clean. Prod. **135**, 42–56 (2016)
38. Drake, D.F., Kleindorfer, P.R., Van Wassenhove, L.N.: Technology choice and capacity portfolios under emissions regulation. Prod. Oper. Manag. **25**(6), 1006–1025 (2016)
39. Xu, X., He, P., Xu, H., Zhang, Q.: Supply chain coordination with green technology under cap-and-trade regulation. Int. J. Prod. Econ. **183**, 433–442 (2017)
40. Liu, Y., Huang, C., Song, Q., Li, G., Xiong, Y.: Carbon emissions reduction and transfer in supply chains under a cap-and-trade system with emissions-sensitive demand. Syst. Sci. Control Eng. **6**(2), 37–44 (2018)
41. Xu, L., Xie, F., Yuan, Q., Chen, J.: Pricing and carbon footprint in a two-echelon supply chain under cap-and-trade regulation. Int. J. Low Carbon Technol. **14**(2), 212–221 (2019)
42. Qian, X., Chan, F.T., Zhang, J., Yin, M., Zhang, Q.: Channel coordination of a two-echelon sustainable supply chain with a fair-minded retailer under cap-and-trade regulation. J. Clean. Prod. **244**, 118715 (2020)
43. Zhang, X., Tao, Z.: Two-stage supply chain optimization with consumers’ environmental awareness under cap-and-trade regulation. *Chinese Control And Decision Conference (CCDC)*, IEEE , pp. 1584–1589 (2020)
44. Chen, Y., Gu, J.: Sustainability Investment of a Two-Echelon Supply Chain under Cap-and-Trade Regulation. *6th International Conference on Social Sciences and Economic Development (ICSSED 2021)* (pp. 222-226). Atlantis Press (2021)