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Research article

Differential game model and coordination model for green supply chain based on green technology research and development



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ABSTRACT

The purpose of this paper is to establish a green supply chain differential game model for green technology research and development based on a secondary green supply chain composed of a single manufacturer and a single retailer. It compares the differential game equilibrium solutions under centralized and decentralized decision-making. The green supply chain members are coordinated through the dynamic wholesale price mechanism, and numerical simulation is used as a methodology, to verify and explain the results. The study found that compared to decentralized decision-making, the level of green technology and the total profit of green channels are higher under centralized decision-making. When the coordination parameters are within a certain range, the dynamic wholesale price mechanism can coordinate the behavior of manufacturers and retailers. The result also discovers that under the dynamic wholesale price mechanism, with the increase of investment cost coefficient, or the increase of price sensitivity or the decrease of consumer's environmental awareness, the green technology level, product green degree, price, retailer's profit, and the total profit of green channel is decreased. In contrast, the wholesale price and manufacturer's profits are increased.

1. Introduction

Increasingly stringent international environmental regulations and consumer awareness of environmental protection or sustainable supply chain (Pahlevan et al., 2021) have urged suppliers of final products in the supply chain to implement green production to reduce environmental damage from production activities (Mohsin et al., 2020; Zhu et al., 2013; Li, 2008; Wang et al., 2017; Dai et al., 2015; Zhao and Sun, 2019; Babae Tirkolaee et al., 2017). Many countries and regions have successively issued relevant energy-saving and environmental protection laws and regulations, prompting enterprises to attach importance to green production (Hamedirostami et al., 2021; Do et al., 2020). For example, in 2006, the European Union began to implement the "Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment" (Jiang et al., 2019; So and Xu, 2016; Liu et al., 2019). In 2013, China issued the "Interpretation of the Supreme People's Court and the Supreme People's Procuratorate

on Several Issues Concerning the Application of Law in the Handling of Environmental Pollution Criminal Cases" (van Rooij, 2010). A green supply chain model that considers resource consumption and environmental impact based on the supply chain came into being in this context in the consumer economy (Mohsin et al., 2021). At present, most researches on green supply chain use static models or multi-stage dynamic game models (Liu, 2011; Zeng and Li, 2019; Xu et al., 2013a, 2013b; Li et al., 2020; Su et al., 2020). However, the above-mentioned game model's analysis method can only study the game behavior between the members of the discrete and intermittent supply chain. It cannot adapt to the continuous and real-time modeling needs, making the model's results deviate from the actual situation. The differential game theory is to study players' game behavior continuously, use differential equations to describe the system state's changing process continuously, and analyze players' strategic decisions in continuous time. It is powerful mathematics for studying the continuous decision-making of players. The model can effectively enhance the accuracy and timeliness of model analysis,

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thereby improving the manager's decision-making ability. Therefore, it is essential to analyze the differential game behavior between members of the green supply chain and coordinate the relationship between the two to realize the simultaneous increase in green technology and green supply chain members' profits. To justify the importance of the differential game theory, the key advantage is; researchers discovered the profit of all the parties involved in a particular business and the disadvantage is the self-interest of a particular party (Shekarian and Flapper, 2021). This paper introduces the differential game theory, considers the Research and Development (R&D) behavior of manufacturers, constructs a differential game model of green supply chain based on green technology R&D, and studies manufacturers' and retailers' game behavior green technology R&D strategies and their respective profits.

In recent years, the literature with the green supply chain as the research background has been relatively abundant with incentive mechanism (Wang et al., 2021). There are mainly two types of literature related to the research: research on green supply chain management decision-making; the other is the research on R&D decision-making (Wang et al., 2021). Research on green supply chain management decision-making, such as Zhang and Liu (2013), established a three-level green supply chain decision-making model, studied the game behaviors under four-game decisions, and on this basis adopted the revenue sharing contract, Sharpley Value method coordination mechanism, and asymmetric Nash negotiation mechanism to coordinate green supply chain issues. Ghosh and Shah (2012), considered a secondary supply chain consisting of a single manufacturer and a single retailer. The market price and the product's greenness jointly determined the market demand and used a two-part pricing contract to coordinate the relationship. Li et al. (2016), developed a two-channel green supply chain game model based on the Stackelberg game with a price strategy. They analyzed the equilibrium of the game under the decentralized (Li et al., 2016), decision, and the results show that:

- Manufacturers do not open direct sales channels when the green cost exceeds a certain threshold.
- Manufacturers will open dual-channel green supply chains (Li et al., 2016), when customer loyalty to traditional channels and green cost meet certain conditions.
- The price of goods in green supply chains under centralized decision (Li et al., 2016; Wang et al., 2021), is higher compared with the decentralized decision.

Cao and Zhang (2013), discussed the coordination strategy among green supply chain members under the Stackelberg game and cooperative strategy. A nonlinear pricing strategy based on the Nash negotiation model was proposed. Jiang and Ma (2014), comprehensively considered the game behaviors between manufacturers and retailers, established four game models of green supply chain, and used revenue-sharing contracts to coordinate the game behaviors between manufacturers and retailers. Zhang et al. (2020), studied closed-loop supply chain pricing decisions considering product greenness under fairness preference. They found that greenness and fairness preferences changed retail prices, wholesale prices, and scrap recycling rates and impacted the supply chain's total profit. Zhu et al. (2010), considered the diffusion process of green supply chain management under government price subsidies. They established a three-stage evolutionary game model based on the rational decision-making of enterprises and consumers. Feng and Tan (2019), established the influence of government subsidy mechanism on the game decision-making of upstream and downstream enterprises in the green supply chain. Increased government subsidies for green supply chain R&D innovation will damage the R&D investment of risk-averse manufacturers on green technology and increase risk-averse retailers' role in improving product greenness.

A review of the relevant literature reveals that in the study of green supply chain management decisions, regardless of the changes in the strength of the manufacturer or retailer channels, the strategy of the

game is price strategy, and the non-price strategies of the firm, such as R&D strategy and sales service, are rarely considered (Ali et al., 2020; Lee and Ha, 2020). For example, Lambertini and Mantovani (2009) argues that a firm's product research and development can improve its quality and thus enhance its monopoly power in the market. Therefore, it is of practical importance to study the impact of manufacturers' R&D decisions on green channel game decisions.

In terms of R&D strategy, Kouvelis and Mukhopadhyay (1995), set product characteristics as a strategic decision for the firm and examined the impact of product R&D strategy on firm profits. Ouardighi and Tapiero (1998) argued that supply chain members should increase their R&D investment to increase consumer loyalty to that product. Furthermore, El Ouardighi and Kim (2010), developed a non-cooperative game model with a two-oligopolistic manufacturer and one supplier, and by comparing the optimal R&D decision of the manufacturer under revenue-sharing contract and wholesale price contract, they concluded that the monopoly supplier has a stronger incentive to invest in the manufacturer's R&D under revenue-sharing contract. Lin and Saggi (2002), studied the effect of different environments (Gounod competition and Bertrand competition) on firms' R&D strategies and showed that Bertrand competition provides stronger incentives for firms to develop their products. Battigalli et al. (2007), studied the effect of buyer power in the supply chain on manufacturers' product R&D decisions. They concluded that as buyer power increases, manufacturers will reduce their product R&D input. Nayeri et al. (2020), considered the R&D spillover effect and investigated the optimal R&D investment when the duopoly manufacturers do not cooperate. Wu et al. (2019), studied the R&D decision models of upstream and downstream firms in the supply chain under different channel potentials and examined the effects of different channel potentials and the spillover effects of R&D on the supply chain R&D decisions and their respective profits, respectively. The results show that if the manufacturer is more competitive, then the optimal R&D investment will rise with the spillover effect. Xu et al. (2013a, 2013b), studied the relationship between firm size and R&D investment and found a "V" shaped relationship between firm size and R&D investment intensity.

Although the literature has studied the influence of different game strategies on enterprises' R&D investment from different perspectives, certain shortcomings still exist. Firstly, they do not consider the game between manufacturers and retailers in continuous time. However, this will directly impact the game results among green supply chain members and further affect members' profits. Secondly, they do not consider the dynamic change process of product greenness, which may affect the green technology R&D decision of the green supply chain. In the real situation, the game behavior among the supply chain members is a continuous dynamic game process, and the differential game theory is a dynamic game model to study the competition and cooperation between two or more subjects in a continuous-time. Given this, this paper systematically considers the dynamic changes of the greenness of the products, uses the theory and method of differential game, studies the differential game problem among the green supply chain members, and finds out the equilibrium solution of the differential game under two strategies. On this basis, green supply chain members' behavior is coordinated through a dynamic wholesale price mechanism to provide a theoretical reference for the green supply chain management. The remaining sections include problem description, basic assumption, model analysis, conclusion and future research direction.

2. Problem description and basic assumptions

Consider a secondary single-channel green supply chain composed of a single risk-neutral manufacturer and a single retailer within a continuous time $t \in [0, +\infty)$. In this green supply chain, manufacturers develop green technologies to produce green products and sell them to retailers at wholesale prices $u(t)$. At the same time, the retailer sells the goods to the final consumer at the market price $p(t)$. When purchasing

a product, environmentally conscious consumers consider the market price $p(t)$ of the product and consider the degree of damage to the environment when the product is produced, that is, the greenness of the product. The goal of manufacturers and retailers is to maximize their profits. Based on the above analysis, this article makes the following assumptions:

Assumption 1. As consumers become more aware of environmental protection, manufacturers increase the research and development of green technology to improve the green technology level and thus the greenness of products (José, 2020). In contrast, with the rapid growth of green technology, the standard of product greenness is also increasing, and products with high greenness in the past may now have degraded to low greenness. It is considered to be the decline of product greenness over time (Guo et al., 2020). Therefore, the change process of product greenness can be expressed as:

$$\dot{g}(t) = k(t) - \delta g(t), k(0) = k_0, g(0) = g_0 \quad (1)$$

Where $g(t)$ denotes the greenness of the product, $g_0 > 0$ denotes the initial greenness; $k(t)$ denotes the green technology level, $k_0 > 0$ is the initial green technology level; $\delta > 0$ denotes the decline of the product greenness over time.

Assumption 2. The production of green products requires green technology research, vertical collaboration and development (Yu et al., 2021). It is assumed that the green investment cost $c(k(t))$ is related to the manufacturer's green technology level and satisfies $dc(k(t))/dk(t) > 0$, $d^2c(k(t))/d(k(t))^2 > 0$. For convenience, this article assumes that the green investment cost is: $c(k(t)) = \alpha k^2(t)/2$, where $\alpha > 0$ denotes the green investment cost coefficient (Song and Gao, 2018; Dou et al., 2018). At the same time, this article assumes that all green investment costs are borne by the manufacturer.

Assumption 3. Technology improvement costing for green products is under extreme challenge (Yang et al., 2021). The unit cost of the product produced by the manufacturer is c_0 . It is assumed that green technology does not affect the unit cost of manufacturers (Song and Gao, 2018).

Assumption 4. The retailer orders from the manufacturer at the wholesale price $w(t)$ and sells to the consumer at the retail price $p(t)$ (Brunner, 2013; De Giovanni and Zaccour, 2014) and assume that the retailer's cost of goods sold is 0 although the market price is not fixed.

Assumption 5. The market demand for a good is negatively related to the market price $p(t)$ and positively related to the greenness of the product $g(t)$ (Sexton, 2020; Zhou and Ju, 2015). Therefore, the market demand function can be expressed as:

$$D(t) = a - a_1 p(t) + a_2 g(t) \quad (2)$$

Where, $a > 0$ denotes total market demand, $a_1 > 0$ denotes price sensitivity, and $a_2 > 0$ is expressed as the overall consumer environmental awareness, reflecting consumer sensitivity to the product's greenness. Not being general, it is assumed that the good's market price is greater than the marginal cost, i.e., $p(t) > c_0$, so that there is: $a - a_1 c_0 > 0$.

3. Model analysis

This section will study the differential game model from two aspects: the centralized decision-making situation and the decentralized decision-making situation. Under centralized decision-making, manufacturers and retailers form a strategic group, the purpose of which is to find the best commodity prices and green technology levels to optimize the total profit of the green supply chain. Under decentralized decision-making, this article takes the manufacturer-led differential game model

as an example. The manufacturer and the retailer are two independent economies whose purpose is to optimize their respective profits. Finally, we compare and analyze the differential game equilibrium solutions under the two decisions.

3.1. Centralized decision-making situation

Under centralized decision-making, the management of the green supply chain fully controls the decision-making behavior of manufacturers and retailers, and its instantaneous total profit function can be expressed as:

$$\pi(t) = D(t) [p(t) - c_0] - c(k(t)) \quad (3)$$

In this situation, the goal of the green supply chain management is to find the optimal price $p(t)$ and green technology level $k(t)$ within a continuous time $t \in [0, +\infty)$, so that the total profit the present value is maximized, then the objective function is:

$$\max_{p,k} \int_0^\infty \left\{ [p(t) - c_0] [a - a_1 p(t) + a_2 g(t)] - \frac{\alpha}{2} k^2(t) \right\} e^{-\rho t} dt \quad (4)$$

s.t. $\dot{g}(t) = k(t) - \delta g(t)$

Among them, $\rho > 0$ denotes the discount rate. Next, we study the optimal price and green technology level under the objective function maximization. The corresponding present value Hamilton function is:

$$H = [p(t) - c_0] [a - a_1 p(t) + a_2 g(t)] - \frac{\alpha}{2} k^2(t) + \lambda_1(t) [k(t) - \delta g(t)] \quad (5)$$

Where, $\lambda_1(t)$ denotes the shadow price of the state variable $g(t)$. The first-order condition for maximizing the present value Hamilton function and the common-mode equation is respectively,

$$\frac{\partial H}{\partial p(t)} = a - 2a_1 p(t) + a_2 g(t) + a_1 c_0 = 0 \quad (6)$$

$$\frac{\partial H}{\partial k(t)} = \lambda_1(t) - \alpha k(t) = 0 \quad (7)$$

$$\dot{\lambda}_1(t) = (\rho + \delta) \lambda_1(t) - a_2 [g(t) - c_0] \quad (8)$$

The pricing strategy of the green supply chain management under centralized decision making can be obtained from the first-order conditional equation (6), i.e.

$$p(g) = \frac{a + a_1 c_0 + a_2 g(t)}{2a_1} \quad (9)$$

From the pricing strategy equation (9), it can be seen that the market price of commodities increases with the greenness of the product, i.e., $dp(g)/dg > 0$. Next, this article studies the changing law of the green technology $k(t)$, find the derivative of the time t for the first-order conditional equation (7), and then bring the common state equation (8) into the above equation. After sorting, we can get:

$$\dot{k}(t) = (\rho + \delta) k(t) - \frac{a_2 [a - a_1 c_0 + a_2 g(t)]}{2\alpha a_1} \quad (10)$$

From equation (10), it can be seen that $\partial \dot{k}(t)/\partial g(t) < 0$. This inequality shows that the rate of green technology change decreases as the greenness of the product increases, which means that when the greenness of the product reaches the optimal level, the green technology will remain constant. The corresponding green investment is fixed, i.e., there exists $g(t) = g^*$, making $\partial k(t)/\partial g(t) = 0$.

The dynamic control system of the green channel management and further calculate the dynamic control system's equilibrium solution has given in the following. The dynamic control system of the green channel management under centralized decision making can be obtained by associating the dynamic equations (1) and (10).

$$\begin{cases} \dot{k}(t) = (\rho + \delta) k(t) - \frac{a_2 [a - a_1 c_0 + a_2 g(t)]}{2\alpha a_1} \\ \dot{g}(t) = k(t) - \delta g(t) \end{cases} \quad (11)$$

When the dynamic control system is equilibrated, i.e., $\dot{k}(t) = \dot{g}(t) = 0$, the equilibrium solution of the dynamic control system Eq. (11) can be obtained as $\{k^c, g^c\}$. Among them, $k^c = \frac{\delta a_2(a-a_1c_0)}{2\alpha\delta a_1(\rho+\delta)-a_2^2}$, $g^c = \frac{a_2(a-a_1c_0)}{2\alpha\delta a_1(\rho+\delta)-a_2^2}$. Here, we assume $2\alpha\delta a_1(\rho+\delta) > a_2^2$, otherwise the equilibrium solution will have no economic meaning.

Substituting the equilibrium solution g^c into equation (9) can get the wholesale price p^c when the system is in equilibrium, which is $p^c = \frac{\alpha\delta(\rho+\delta)(a+a_1c_0)-c_0a_2^2}{2\alpha\delta a_1(\rho+\delta)-a_2^2}$. Furthermore, the market demand D^c and the total profit of green supply chain π_f^c , at the equilibrium of the system can be obtained, which is $D^c = \frac{\alpha\delta a_1(\rho+\delta)(a-a_1c_0)}{2\alpha\delta a_1(\rho+\delta)-a_2^2}$ and, $\pi_f^c = \frac{\alpha\delta^2(a-a_1c_0)^2[2a_1\alpha(\rho+\delta)^2-a_2^2]}{2[2\alpha\delta a_1(\rho+\delta)-a_2^2]^2}$.

Here, the equilibrium solutions of the dynamic control system Eq. (11) for each control and state variables under the stability condition has obtained. Next, we will prove the stability of the equilibrium solution of the dynamic control system equation (11). Let, $J^c = \frac{\partial(k(t), g(t))}{\partial(k(t), g(t))}$ Jacobian matrix representing the dynamic control system equation (11), then: $J^c = \begin{bmatrix} \rho+\delta & -\frac{a_2^2}{2\alpha a_1} \\ 1 & -\delta \end{bmatrix}$.

Let E be the second-order unit matrix and r_i^c ($i = 1, 2$) be the eigenvalues corresponding to the Jacobian matrix J^c . Calculating the characteristic equation $|J^c - r_i^c E| = 0$, the eigenvalues values are obtained as,

$$r_1^c = \frac{\rho\alpha a_1 + \sqrt{\alpha a_1 \{ \alpha a_1 \rho^2 + 2[2\alpha\delta a_1(\rho+\delta) - a_2^2] \}}}{2\alpha a_1},$$

$$r_2^c = \frac{\rho\alpha a_1 - \sqrt{\alpha a_1 \{ \alpha a_1 \rho^2 + 2[2\alpha\delta a_1(\rho+\delta) - a_2^2] \}}}{2\alpha a_1}.$$

Since $2\alpha\delta a_1(\rho+\delta) > a_2^2$, it follows that there are: $r_1^c > 0, r_2^c < 0$. Referring to Lambertini (2009) and Pan and Li (2016), the above analysis can be summarized as Proposition 1.

Proposition 1. In the centralized decision case, the equilibrium solution $\{k^c, g^c\}$ of the dynamic control system (11) is saddle-point equilibrium.

3.2. Decentralized decision-making situation

In the decentralized decision scenario, we assume that the manufacturer is the leader of the green channel. The sequence of the game between the manufacturer and the retailer is as follows: first, the manufacturer decides the level of green technology and the wholesale price of the goods, and then, the retailer decides the market price of the goods on this basis. The model is solved by the inverse induction method.

Let $\pi_m(t)$ and $\pi_r(t)$ denote the manufacturer's instantaneous profit functions and the retailer under the differential game model, respectively. From Assumptions 1-5, we can get:

$$\pi_m(t) = [w(t) - c_0] [a - a_1 p(t) + a_2 g(t)] - \frac{\alpha}{2} k^2(t) \quad (12)$$

$$\pi_r(t) = [p(t) - w(t)] [a - a_1 p(t) + a_2 g(t)] \quad (13)$$

Because manufacturers are the green supply chain leaders, they must anticipate the market price of goods beforehand before deciding on the level of green technology and the wholesale price of goods. Therefore, the market price of the commodity is found first. By finding the first-order partial derivative of the market price of the commodity for equation (13) and making the first-order partial derivative equal to 0, it can be solved as follows:

$$p(g, w) = \frac{a + a_2 g(t) + a_1 w(t)}{2a_1} \quad (14)$$

From equation (14) we have: $\partial p(g, w)/\partial g > 0$, $\partial p(g, w)/\partial w > 0$. The above two inequalities show that the market price of good increases with the increase in the good's greenness or the wholesale price of the good. The objective function of the manufacturer is given next. The manufacturer's objective is to find the optimal level of greenness and wholesale price of the commodity in continuous time $t \in [0, +\infty)$ that maximizes the discounted value of its profit. Therefore, by bringing equation (14) into equation (12) and then associating the dynamic equation (1), the manufacturer's objective function is obtained, which is:

$$\max_{k, w} \int_0^\infty \pi_m(t) e^{-\rho t} dt \quad (15)$$

s.t. $\dot{g}(t) = k(t) - \delta g(t)$

The objective function equation (15) corresponds to the present value Hamiltonian function as:

$$H_m = \frac{[w(t) - c_0] [a + a_2 g(t) - a_1 w(t)]}{2} - \frac{\alpha}{2} k^2(t) + \lambda_2(t) [k(t) - \delta g(t)] \quad (16)$$

Where $\lambda_2(t)$ is the shadow price of the state variable $g(t)$, the first-order condition and the covariance equation for maximizing the present-value Hamiltonian function are given by expressions (17)–(19), respectively.

$$\frac{\partial H_m}{\partial w(t)} = \frac{a + a_2 g(t) - 2a_1 w(t) + a_1 c_0}{2} = 0 \quad (17)$$

$$\frac{\partial H_m}{\partial k(t)} = -\alpha k(t) + \lambda_2(t) = 0 \quad (18)$$

$$\dot{\lambda}_2(t) = (\rho + \delta) \lambda_2(t) - \frac{a_2 [w(t) - c_0]}{2} \quad (19)$$

From the first-order conditional equation (17), the wholesale price of the commodity can be obtained as:

$$w(g) = \frac{a + a_1 c_0 + a_2 g(t)}{2a_1} \quad (20)$$

From equation (20), we get: $\partial w(g)/\partial g > 0$. This inequality indicates that the wholesale price of goods increases as the greenness of the product increases. It is because higher product greenness means that manufacturers invest more in research and development of green technologies. Therefore, manufacturers should charge a higher wholesale price of goods to maximize their profits. Next, the variation law of the green technology $k(t)$ is studied. Find the derivative of the time t for the first-order conditional equation (18), and then put the common-mode equation (19) into the above equation, after sorting, we get:

$$\dot{k}(t) = (\rho + \delta) k(t) - \frac{a_2 [a + a_2 g(t) - a_1 c_0]}{4\alpha a_1} \quad (21)$$

From equation (21) we get: $\partial \dot{k}(t)/\partial g(t) < 0$. This inequality shows that the rate of change of green technology $\dot{k}(t)$ decreases with increased product greenness under decentralized decision making. Simultaneous dynamic equations (1) and (21) can get the manufacturer's dynamic control system:

$$\begin{cases} \dot{k}(t) = (\rho + \delta) k(t) - \frac{a_2 [a + a_2 g(t) - a_1 c_0]}{4\alpha a_1} \\ \dot{g}(t) = k(t) - \delta g(t) \end{cases} \quad (22)$$

When the dynamic control system equation (22) is equilibrium, that is, $\dot{k}(t) = \dot{g}(t) = 0$, the equilibrium solution of the dynamic control system can be solved as $\{k^d, g^d\}$, where $k^d = \frac{\delta a_2(a-a_1c_0)}{4\alpha\delta a_1(\rho+\delta)-a_2^2}$, $g^d = \frac{a_2(a-a_1c_0)}{4\alpha\delta a_1(\rho+\delta)-a_2^2}$. Here, we assume $4\alpha\delta a_1(\rho+\delta) > a_2^2$, otherwise, the equilibrium solution would not make economic meaning.

Incorporating the equilibrium solution g^d into equation (20), the dynamic control system (22) can obtain the wholesale price w^d of the

goods in equilibrium, which is $w^d = \frac{2\alpha\delta(\rho+\delta)(a+a_1c_0)-c_0a_2^2}{4\alpha\delta a_1(\rho+\delta)-a_2^2}$. Furthermore, we can obtain the market price p^d , the market demand D^d , the manufacturer profit π_m^d , the retailer profit π_r^d , and the total green supply chain profit π_f^d , as follows:

$$\begin{aligned} p^d &= \frac{\alpha\delta(\rho+\delta)(3a+a_1c_0)-c_0a_2^2}{4\alpha\delta a_1(\rho+\delta)-a_2^2}, \\ D^d &= \frac{\alpha\delta a_1(\rho+\delta)(a-a_1c_0)}{4\alpha\delta a_1(\rho+\delta)-a_2^2}, \\ \pi_m^d &= \frac{\alpha\delta^2(a-a_1c_0)^2[4\alpha a_1(\rho+\delta)-a_2^2]}{2[4\alpha\delta a_1(\rho+\delta)-a_2^2]^2}, \\ \pi_r^d &= \frac{a_1\alpha^2\delta^2(\rho+\delta)^2(a-a_1c_0)}{[4\alpha\delta a_1(\rho+\delta)-a_2^2]^2} \quad \text{and} \\ \pi_f^d &= \frac{\alpha\delta^2(a-a_1c_0)^2[6\alpha a_1(\rho+\delta)-a_2^2]}{2[4\alpha\delta a_1(\rho+\delta)-a_2^2]^2}. \end{aligned}$$

We have calculated the game equilibrium solution of the dynamic control system equation (22) under the stability condition, and next, we study the stability of the equilibrium solution of the dynamic control system equation (22). Let, $J^d = \frac{\partial(k(t), \dot{g}(t))}{\partial(k(t), g(t))}$ denote the Jacobian matrix of the dynamic control system (22), then:

$$J^d = \begin{bmatrix} \rho+\delta & -\frac{a_2^2}{4\alpha a_1} \\ 1 & -\delta \end{bmatrix}$$

Let E be the second-order identity matrix and r_i^d ($i=1,2$) be the eigenvalues corresponding to the Jacobian matrix J^d . Calculating the characteristic equation $|J^d - r_i^d E| = 0$, the characteristic value can be obtained:

$$\begin{aligned} r_1^d &= \frac{\rho\alpha a_1 + \sqrt{\alpha a_1[\alpha a_1\rho^2 + 4\alpha\delta a_1(\delta+\rho) - a_2^2]}}{2\alpha a_1}, \\ r_2^d &= \frac{\rho\alpha a_1 - \sqrt{\alpha a_1[\alpha a_1\rho^2 + 4\alpha\delta a_1(\delta+\rho) - a_2^2]}}{2\alpha a_1}. \end{aligned}$$

Since $4\alpha\delta a_1(\rho+\delta) > a_2^2$, we get: $r_1^d > 0, r_2^d < 0$. The above analysis is summarized in Proposition 2 (Lambertini and Mantovani, 2009; Lin, 2007; Li, 2017; Pan and Li, 2016).

Proposition 2. In the decentralized decision case, the equilibrium solution $\{k^d, g^d\}$ of the dynamic control system equation (22) is a saddle-point equilibrium.

3.3. Result analysis

In subsections 3.1 and 3.2, we have calculated the optimal level of green technology and total green channel profit under centralized and decentralized decision making. This subsection will conduct a comparative analysis of the optimal level of green technology and total green channel profit.

3.3.1. Optimal R&D decision analysis

Comparing the optimal level of green technology under centralized and decentralized decision-making leads to Proposition 3.

Proposition 3. The optimal level of green technology satisfies: $k^c > k^d$.

Proof.

$$k^c = \frac{\delta a_2(a-a_1c_0)}{2\alpha\delta a_1(\rho+\delta)-a_2^2}$$

and

$$\begin{aligned} \pi_f^c - \pi_f^d &= \frac{a_1\alpha^2\delta^2(a-a_1c_0)^2(\rho+\delta)\{\alpha\delta a_1(\rho+\delta)[2\alpha\delta a_1(\rho+\delta)^2 + a_2^2(2\rho-\delta)] - \rho a_2^4\}}{[2\alpha\delta a_1(\rho+\delta)-a_2^2]^2[4\alpha\delta a_1(\rho+\delta)-a_2^2]^2} \end{aligned}$$

Because, $\alpha\delta a_1(\rho+\delta)^2 > \alpha\delta^2 a_1(\rho+\delta)$ and $2\alpha\delta a_1(\rho+\delta) - a_2^2 > 0$, we can obtain $k^d = \frac{\delta a_2(a-a_1c_0)}{4\alpha\delta a_1(\rho+\delta)-a_2^2}$, $k^c - k^d = \frac{2\alpha\delta^2 a_1 a_2(\rho+\delta)(a-a_1c_0)}{[2\alpha\delta a_1(\rho+\delta)-a_2^2][4\alpha\delta a_1(\rho+\delta)-a_2^2]}$, and since $2\alpha\delta a_1(\rho+\delta) - a_2^2 > 0$, $4\alpha\delta a_1(\rho+\delta) - a_2^2 > 0$, $a - a_1c_0 > 0$, all of which can be obtained as $k^c > k^d$. The proof is complete. \square

Proposition 3 shows that the optimal level of green technology under centralized decision making is higher than the decentralized decision-making scenario. The manufacturer's R&D decisions depend on the expected benefits and R&D costs of R&D. Under the decentralized decision, it can be seen from $\partial k(t)/\partial g(t) > 0$ that for each unit increase in product greenness, the difficulty of green technology R&D will increase. Then, the corresponding R&D cost will also increase. Therefore, the manufacturer will reduce the R&D investment in green technology accordingly to save cost. And in the centralized model, the manufacturer and the retailer work closely together to improve green technology.

3.3.2. Optimal green channel total profit analysis

Proposition 4. The optimal total profit of the green channel satisfies: $\pi_f^c > \pi_f^d$.

Proof.

$$\pi_f^c = \frac{\alpha\delta^2(a-a_1c_0)^2[2a_1\alpha(\rho+\delta)^2 - a_2^2]}{2[2\alpha\delta a_1(\rho+\delta) - a_2^2]^2}$$

and

$$\pi_f^d = \frac{\alpha\delta^2(a-a_1c_0)^2[6\alpha a_1(\rho+\delta)^2 - a_2^2]}{2[4\alpha\delta a_1(\rho+\delta) - a_2^2]^2}$$

We get: $2\alpha\delta a_1(\rho+\delta)^2 + a_2^2(2\rho-\delta) > 2\rho a_2^2$. Furthermore: $2\rho\alpha\delta a_1(\rho+\delta)a_2^2 - \rho a_2^4 > 0$, therefore, it is proved that $\pi_f^c - \pi_f^d > 0$. The proof is complete (Lambertini, 2009). \square

Proposition 4 shows that the green supply chain's total profit under centralized decision-making is higher than that under decentralized decision-making. Under decentralized decision-making, each member of the green supply chain's goal is to maximize their profits. This kind of abuse of buyer or seller power may strive for greater profits for the supply chain in the short term, but in the long run, this is not conducive to expanding the sales market of products and will ultimately reduce the total profit of the green supply chain.

The above analysis shows that the total profit of green channel as well as the level of green technology under decentralized decision is not optimal. In order to promote further cooperation of green supply chain members and converge to the centralized control model, in the next section, a cooperative coordination model will be designed.

4. Cooperation and coordination model

Centralized decision-making requires green supply chain management to make a unified strategy. Still, it is difficult for the green supply chain management to create a suitable decision when manufacturers and retailers are independent economic entities. Therefore, it is necessary to establish a cooperation and coordination mode among the green supply chain members. Under this model, the goal of green supply chain members is to maximize the total profit of the green channel and to ensure that the profit of each member is not less than the profit of each member under decentralized decision-making, so as to encourage each member to have the motivation to participate in the cooperative coordination mode.

Table 1. Parameter assignment table.

α	δ	ρ	a	a_1	a_2	c_0
1	0.18	0.2	1	0.16	0.08	0.01

4.1. Cooperative coordination mode-dynamic wholesale price

From the analysis in Section 3, it can be seen that both manufacturers and retailers have not reached the optimal state under decentralized decision-making, and the centralized decision-making situation is difficult to achieve. Therefore, we will design a dynamic wholesale price mechanism to coordinate the behavior of manufacturers and retailers. In this coordination mode, the manufacturer and the retailer reach a commitment that the retailer's wholesale price is related to the retailer's sales volume, which is not general. We assume that the wholesale price is a decreasing function of the sales volume. The change form can be expressed as follows:

$$w(t) = c_0 + \theta / D(t) \quad (23)$$

Where $\theta > 0$ is the coordination parameter, $D(t)$ denotes consumers' instantaneous demand at moment t . From Assumptions 1–5, the manufacturer's expressions and retailer's instantaneous profits at dynamic wholesale prices can be obtained, respectively:

$$\pi_m^E(t) = [w(t) - c_0] [a - a_1 p(t) + a_2 g(t)] - \frac{\alpha}{2} k^2(t) \quad (24)$$

$$\pi_r^E(t) = [p(t) - w(t)] [a - a_1 p(t) + a_2 g(t)] \quad (25)$$

Where $\pi_m^E(t)$ and $\pi_r^E(t)$ denote the manufacturer's instantaneous profits and the retailer at dynamic wholesale prices, respectively. Due to the space limitation, the differential game's equilibrium solution, in this case, is only given, and the calculation procedure is similar to that in Section 3. The equilibrium solution, in this case, is given by:

$$k^E = \frac{\delta a_2 (a - a_1 c_0)}{2\alpha\delta a_1(\rho + \delta) - a_2^2}, \quad g^E = \frac{a_2 (a - a_1 c_0)}{2\alpha\delta a_1(\rho + \delta) - a_2^2},$$

$$p^E = \frac{\alpha\delta(\rho + \delta)(a + a_1 c_0) - c_0 a_2^2}{2\alpha\delta a_1(\rho + \delta) - a_2^2},$$

$$\pi_r^E(\theta) = \frac{a_1 \alpha^2 \delta^2 (\rho + \delta)^2 (a - a_1 c_0)^2}{[2\alpha\delta a_1(\rho + \delta) - a_2^2]^2} - \theta,$$

$$\pi_m^E(\theta) = \theta - \frac{\alpha \delta^2 a_2^2 (a - a_1 c_0)^2}{2[2\alpha\delta a_1(\rho + \delta) - a_2^2]^2}.$$

After coordination by the dynamic wholesale price mechanism, it is necessary to ensure that the retailer and the manufacturer's profit is not less than the profit before negotiation, namely: $\pi_r^E \geq \pi_r^d$, $\pi_m^E \geq \pi_m^d$. Further we can calculate the value range of the coordination parameter θ , namely: $\theta \in [\underline{\theta}, \bar{\theta}]$. Among them:

$$\underline{\theta} = \frac{a_1 \alpha^2 \delta^2 (\rho + \delta)(a - a_1 c_0)^2 \{(\rho + \delta)[2\alpha\delta a_1(\rho + \delta) - a_2^2]^2 + \delta a_2^2 [3\alpha\delta a_1(\rho + \delta) - a_2^2]\}}{[2\alpha\delta a_1(\rho + \delta) - a_2^2]^2 [4\alpha\delta a_1(\rho + \delta) - a_2^2]^2},$$

$$\bar{\theta} = \frac{4a_1^2 \alpha^3 \delta^3 (\rho + \delta)^3 (a - a_1 c_0)^2 [3\alpha\delta a_1(\rho + \delta) - a_2^2]}{[2\alpha\delta a_1(\rho + \delta) - a_2^2]^2 [4\alpha\delta a_1(\rho + \delta) - a_2^2]^2}.$$

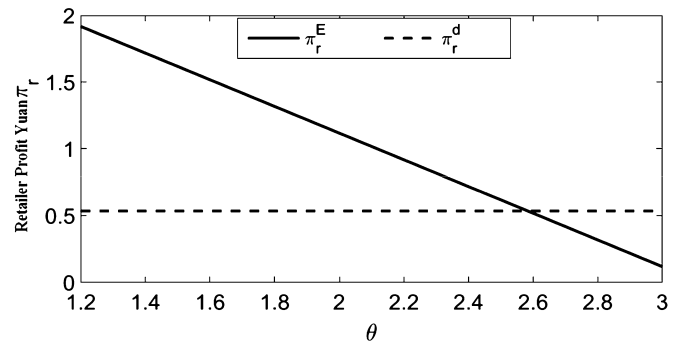
4.2. Numerical simulation

In order to verify the correctness of the proposed model, numerical simulations are performed for the equilibrium solution under the dynamic wholesale price mechanism. The assignment of parameters is given in Table 1.

From the range of values of the coordination parameter $\theta \in [\underline{\theta}, \bar{\theta}]$ and the values of the parameter given in Table 1, we can obtain: $1.4991 \leq \theta \leq 2.5765$. Further, the profits of the manufacturer and retailer, as well

Table 2. The relationship between the maximum or minimum parameter value θ and retailer's profit, manufacturer's profit, and total profit of green channel.

θ	π_r^E / π_r^d	π_m^E / π_m^d	π_r^E / π_r^d
1.4991	1.6115/0.5341	1.0683/1.0683	2.6798/1.6024
2.5765	0.5341/0.5341	2.1457/1.0683	2.6798/1.6024

**Fig. 1.** The influence of parameter θ on retailer's profit.

as the green channel in different scenarios, can be obtained when the maximum and minimum values of θ are taken, as shown in Table 2.

Table 2 shows that when $\theta = 1.4991$, the manufacturer's profit under cooperative coordination and decentralized decision-making is the same, but the retailer's profit under cooperative coordination is greater than the profit of the retailer under decentralized decision-making. Therefore, when the coordination parameter takes the minimum value, when $\theta = 1.4991$, the green supply chain members choose when $\theta = 2.5765$, the profits of retailers under cooperative coordination and decentralized decision making are the same, but the profits of manufacturers under cooperative coordination are greater than the profits of manufacturers under decentralized decision making. Therefore, in this case, members of the green supply chain can also get Pareto improvements when cooperating and coordinating (Lambertini and Mantovani, 2009; Lin, 2007; Li, 2017; Pan and Li, 2016).

By analyzing the game's equilibrium solutions under the centralized decision and the dynamic wholesale price mechanism, we can find that the green technology, product greenness, and commodity price under the dynamic wholesale price mechanism reach the situation of the centralized model. In order to study more intuitively the impact of the change in θ on the wholesale price mechanism on the profitability of retailers and manufacturers, numerical simulations can be obtained in Figs. 1 and 2. The impact of the parameters θ on the retailer's respective profits and the manufacturer is reflected in Figs. 1 and 2.

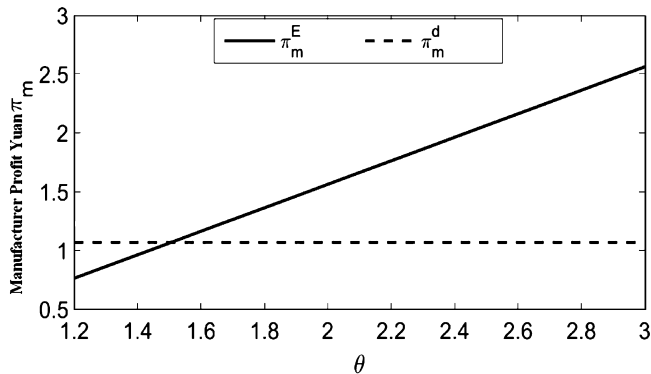
Fig. 1 shows that the retailer's profit decreases as the parameter θ increases. Fig. 2, shows that the manufacturer's profit increases as the parameter θ increases. But in any case, when the parameter $\theta \in [\underline{\theta}, \bar{\theta}]$, the respective profits of green channel members under cooperative coordination are not smaller than the respective profits under decentralized decision making. Therefore, it can be assumed that the dynamic wholesale price mechanism can coordinate this type of green supply chain (Lambertini and Mantovani, 2009; Lin, 2007; Li, 2017; Pan and Li, 2016).

4.3. Sensitivity analysis

To further investigate the influence of the green investment cost coefficient α , consumer price sensitivity a_1 , and consumer environmental awareness a_2 on the differential game's equilibrium solution under this coordination mode, we use sensitivity analysis, referring to the parameter values given in Table 1 and assume that the negotiation parameter $\theta = 2$.

Table 3. The influence of green investment cost coefficient on the equilibrium solution of differential game.

Parameter	k^E	g^E	p^E	w^E	π_r^E	π_m^E	π_f^E
α							
0.8	1.2940	7.1889	4.9272	2.5521	1.8687	1.3302	3.1989
0.9	1.0810	6.0058	4.6314	2.7148	1.4172	1.4741	2.8913
1	0.9283	5.1570	4.4193	2.8449	1.1106	1.5692	2.6798
1.1	0.8133	4.5185	4.2596	2.9514	0.8895	1.6362	2.5257
1.2	0.7237	4.0206	4.1352	3.0402	0.7227	1.6857	2.4084

**Fig. 2.** The influence of parameter θ on manufacturer's profit.

4.3.1. The impact of green investment cost coefficient on the equilibrium solution of differential game

The green investment cost coefficient α is an important parameter for this study, because it affects the manufacturer's green technology investment cost, and thus affects the greenness and price of the product. Therefore, we use $\alpha = 1$ as the benchmark and sequentially change $\pm 10\%$ and $\pm 20\%$ to study the influence of different cost coefficient α values on the equilibrium solution of the differential game.

Table 3 reflects the effect of green investment cost coefficients such as environmental regulations on the equilibrium solution of the differential game. It can be found that as the cost coefficient α increases, the level of green technology, product greenness, commodity price, retailer's profit, and total green channel profit decrease, while the wholesale price and manufacturer's profit increase. The reason is that when the cost coefficient α increases, the manufacturer will reduce the investment in green technology research and development, thus reducing the level of green technology. Furthermore, the greenness of the product will also decrease. From the price expression $p = \frac{a+a_1c_0+a_2g}{2a_1}$, it can be seen that the decrease in the greenness of the product will reduce the price of the good. Since the decline in product greenness leads to a decrease in demand that exceeds a decrease in prices, which leads to an increase in demand ($\Delta D = -a_1\Delta p + a_2\Delta g < 0$), the demand for goods will decline. From the dynamic expression $w = c_0 + \theta/D$, it can be seen that the decline in demand will cause manufacturers to charge higher wholesale prices of goods, thereby reducing retailers' profits. The increase in manufacturer's profit is caused by the reduction of green technology R&D investment, which can be seen from the manufacturer's profit expression ($\pi_m^E = \theta - \alpha k^2/2$).

4.3.2. The impact of consumer price sensitivity on the equilibrium solution of the differential game

One of the most critical parameters in the model is price sensitivity because it impacts the demand for goods and the green supply chain's profit. Therefore, this paper uses $a_1 = 0.16$ as the benchmark and sequentially changes $\pm 10\%$ and $\pm 20\%$ to study the influence of different price sensitivity $1a$ on the differential game's equilibrium solution.

Table 4 reflects the impact of price sensitivity on the equilibrium solution of the differential game. It can be found that as price sensitivity increases, the level of green technology, product greenness, commodity prices, retailers' profits, and the total profits of green channels decreases. The wholesale prices of commodities and the profits of

manufacturers have increased. The reason is that the increase of a_1 will reduce the demand of consumers, and the retailer will reduce the price to maintain the original sales volume, but from the demand function $D = a - a_1p + a_2g$ and Table 4, we can get: $\Delta D = -p\Delta a_1 - a_1\Delta p + a_2\Delta g < 0$, that is, the price sensitivity a_1 increases and the decrease in demand will exceed the increase in price and the increase in demand, so the demand is falling.

Further, it can be obtained that the wholesale price of the commodity is increased ($w = c_0 + \theta/D$). Since the commodity's demand and price are decreasing and the commodity's wholesale price is increasing, then the retailer's profit will be falling ($\pi_r^E = (p - w)D$).

The increase in the manufacturer's profit can be explained by the fact that the manufacturer's interregional green technology R&D investment (Pan et al., 2021) depends on the expected benefits of R&D and the R&D cost. When the expected R&D revenue is high, the manufacturer is willing to invest more R&D funds. With the increase of price sensitivity $1a$, consumers' uncertainty about the product's consumption will also increase, which will reduce the manufacturer's expected R&D income, thereby reducing the green technology R&D investment, thereby increasing the manufacturer's profit.

4.3.3. The impact of consumers' environmental awareness on the equilibrium solution of differential games

Different consumers have different environmental awareness, so we use $a_2 = 0.08$ as the benchmark and change it by $\pm 10\%$ and $\pm 20\%$ to investigate the effect of various environmental awareness on the differential game's equilibrium solution.

Table 5 reflects the effect of consumers' environmental awareness on the equilibrium solution of the differential game. It can be found that when consumers' environmental awareness increases, the level of green technology, greenness, commodity prices, retailers' profits, and total profits of the green channel increase. At the same time, the wholesale price of goods and manufacturers' profits decrease (Taleizadeh et al., 2021). The rise of a_2 indicates that consumers' environmental awareness increases, which means that consumers tend to buy greener goods so that manufacturers will increase their R&D investment in green technology to meet these consumers' needs, thus increasing green technology and product greenness. Due to a_2 , there will be two effects on commodity demand. The increase of consumers' environmental awareness will increase the consumption of green goods. With the increase of consumers' environmental awareness and the increase in products, the degree of greenness increases commodities' price, reducing the demand for commodities. But from the demand function and Table 5, we can get: $\Delta D = -a_1\Delta p + g\Delta a_2 + a_2\Delta g > 0$, which means that the increase in environmental awareness caused by the rise in demand will exceed the increase in price and the decrease in demand. Therefore, the demand for goods will increase with the rise of a_2 . It can be further obtained that with the increase of a_2 , the wholesale prices have fallen, while retailers' profits have increased.

5. Conclusions, recommendations and future research

This paper comprehensively considers the manufacturer's green technology level, product greenness, and game behavior among the green supply chain members. Also, it establishes a differential game model of green supply chain considering green technology R&D and compares the differential game equilibrium solutions under centralized

Table 4. The influence of consumer price sensitivity on the equilibrium solution of differential game.

Parameter	k^E	g^E	p^E	w^E	π_r^E	π_m^E	π_f^E
a_1	0.128	1.2944	7.1912	6.1585	2.5513	2.8389	1.1622
	0.144	1.0812	6.0067	5.1458	2.7143	1.7981	1.4155
	0.16	0.9283	5.1570	4.4193	2.8449	1.1106	1.5692
	0.176	0.8132	4.5177	3.8727	2.9519	0.6260	1.6694
	0.192	0.7235	4.0193	3.4465	3.0412	0.2675	1.7383

Table 5. The influence of consumers' environmental awareness on the equilibrium solution of differential game.

Parameter	k^E	g^E	p^E	w^E	π_r^E	π_m^E	π_f^E
a_2	0.064	0.6464	3.5914	3.8483	3.2667	0.3572	1.7911
	0.072	0.7746	4.3034	4.0983	3.0675	0.6742	1.7000
	0.08	0.9283	5.1570	4.4193	2.8449	1.1106	1.5692
	0.088	1.1181	6.2118	4.8382	2.5989	1.7299	1.3749
	0.096	1.3615	7.5636	5.3991	2.3295	2.6468	1.0732

and decentralized decision making. And on this basis, a new cooperation coordination model-dynamic wholesale price mechanism is designed to provide a theoretical reference for coordinating the relationship between manufacturers and retailers. Finally, numerical simulation is used to verify the effectiveness of the cooperative coordination mechanism. Also, the differential game equilibrium solutions under centralized or decentralized decision are saddle point equilibrium. Compared with decentralized decision, centralized decision has higher green technology level, product greenness, and total green channel profit with lower market price. Compared with decentralized decision, under cooperative coordination model, when the coordination parameter $\theta \in [\underline{\theta}, \bar{\theta}]$, the profits of both manufacturers and retailers can be Pareto improved, and the level of green technology, product greenness, and the market price of goods all reach the situation under the centralized model, so the dynamic wholesale price mechanism can coordinate well between manufacturers and retailers. From the perspective of sensitivity analysis, in the cooperative coordination model, when the green investment cost coefficient α increases, the green technology level, product greenness, commodity price, retailers' profit and total green channel profit are decreased, while the wholesale price and manufacturers' profit are increased; when the price sensitivity a_1 increases, the green technology level, product greenness, commodity price, retailer's profit, and total green channel profit are decreasing while wholesale price and manufacturer's profit are increasing; When consumer's environmental awareness a_2 increases, green technology level, greenness, commodity price, retailer's profit, and total green channel profit are increasing while wholesale price and manufacturer's profit are decreasing.

From the investigation, the authors recommend to upstream and downstream companies in the green supply chain should abandon the traditional game thinking and maintain cooperative commitment effectiveness even if they cannot adopt the centralized management model. Because in the cooperative model, when negotiating parameters $\theta \in [\underline{\theta}, \bar{\theta}]$, the respective profits of green channel members are not smaller than the individual profits under decentralized decision making. The government should try to cultivate to improve consumers' environmental awareness because when consumers' environmental awareness increases, the greenness of products will increase. Therefore, there will have a better ecological environment in the long run. Since this paper considers the differential game model with complete information, the differential game model with information asymmetry is not considered. The next study can take information asymmetry into account in the model. Also, the green supply chain consisting of a single manufacturer and a single retailer is considered in this paper, but the situation of the dual-channel green supply chain is not considered, so this will also be the direction of future research.

Declarations

Author contribution statement

AKM Mohsin: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Sayed Far Abid Hossain and Hasanuzzaman Tushar: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Mohammed Masum Iqbal and Alamgir Hossain: Analyzed and interpreted the data; Wrote the paper.

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Data will be made available on request.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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