Vol. 12, No. 2, 2025, Pages 146- 160

JIEMS
Journal of Industrial Engineering and Management Studies

journal homepage: www.jiems.icms.ac.ir

A Bi-Level Optimization for Supply Chains of Deteriorating Products: Integrating Cold Plasma Technology to Enhance Profitability and Reduce Emissions

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Received: Oct 2025-31/ Revised: Nov 2025-15/ Accepted: Dec 2025-25

Abstract

In this paper, a bi-level optimization model is developed to manage the supply chain of deteriorating products under the adoption of cold plasma technology. The proposed model simultaneously aims to maximize the profits of the manufacturer and retailer while reducing product waste and carbon emissions. Cold plasma technology plays a crucial role by extending product shelf life and lowering deterioration rates, which in turn reduces waste and improves economic performance. In addition, this technology contributes to mitigating greenhouse gas emissions across the supply chain, offering a sustainable environmental solution. Numerical results demonstrate that adopting cold plasma technology leads to a significant reduction in product waste and enhances the profitability of both supply chain members. The analysis further indicates that optimal supply chain decisions are sensitive to changes in deterioration rates, highlighting the need for adaptive management strategies. Overall, this study provides an integrated economic–environmental assessment of cold plasma technology and offers practical insights for its effective implementation in supply chains dealing with deteriorating products.

Keywords: Cold plasma Technology, Supply chain management, deteriorating items, Product waste, Reducing carbon emissions

Paper Type: Original Research

1. Introduction

Global challenges such as climate change, population growth, and the rising demand for safe and nutritious food have intensified concerns regarding food waste reduction. According to the Food and Agriculture Organization (FAO, 2011), approximately one-third of all food produced worldwide is lost due to deterioration and waste, resulting in substantial economic losses and severe environmental impacts (UNEP, 2021). Consequently, improving the management of supply chains for deteriorating products—such as fruits, vegetables, and dairy items with short shelf lives—has become a critical issue in the food and agricultural sectors. Deteriorating products are commonly characterized by two quality-related attributes: deterioration and freshness. Deterioration refers to the gradual loss of quality and safety caused by factors such as microbial growth, while freshness is associated with sensory characteristics including appearance, taste, and odor. Once deterioration begins, freshness declines, leading to reduced product quality and increased waste. Given the direct relationship between these factors and food loss, developing effective preservation strategies is of paramount importance (Ahvenainen, 1996). Various preservation technologies have been introduced to address this challenge, including pre-cooling, chemical preservatives, and specialized packaging. However, many of these methods are energy-intensive, costly, or raise concerns regarding environmental sustainability and product quality. In contrast, cold plasma technology has emerged as a promising non-thermal alternative for preserving deteriorating products. By exciting gas molecules at low temperatures, cold plasma effectively inhibits microbial growth, extends shelf life, and preserves nutritional and sensory qualities without chemical residues or high energy consumption. Motivated by these advantages, this study considers cold plasma technology as an innovative solution for reducing deterioration and improving product quality, particularly in dairy supply chains. Unlike conventional pre-cooling methods, which require substantial energy and may be ineffective for sensitive products, cold plasma can enhance shelf life without low-temperature requirements while maintaining product integrity. Its strong antimicrobial properties, combined with minimal environmental impact, make it especially suitable for high-value and quality-sensitive products such as dairy and meat.

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This paper investigates the role of cold plasma technology within a two-level supply chain consisting of a manufacturer and a retailer. A Stackelberg-based bi-level optimization model is proposed to analyze how the adoption of this technology affects pricing, production, and ordering decisions. Furthermore, the study evaluates the joint economic and environmental benefits of cold plasma by examining its impact on both carbon emission reduction and shelf-life extension. The results provide insights into how cold plasma adoption can enhance supply chain performance, reduce waste, and support sustainable operations. The remainder of the paper is organized as follows. Section 2 reviews the related literature and highlights the research gaps addressed in this study. Section 3 presents the model formulation and solution approach. Section 4 discusses the numerical results and sensitivity analyses. Finally, Section 5 concludes the paper and outlines directions for future research.

2. Literature Review

This section reviews articles in the field of deteriorating goods supply chains with a focus on carbon emission-related topics. Sarkar et al. (2016) introduced an integrated inventory management model employing the Stackelberg game approach to optimize total costs between sellers and buyers. In this model, buyers identify defective items upon receiving shipments and return them to the seller in subsequent deliveries. Saha et al. (2017) analyzed a replenishment problem that integrates joint pricing strategies, dynamic investments in green operations, preservation technology, and optimal replenishment schedules for deteriorating items. Their findings reveal that continuous investments in green operations and preservation technology can significantly enhance the retailer's financial performance. Huang et al (2018) employed a Stackelberg game framework to analyze a three-level food supply chain comprising a retailer, seller, and supplier. The study examined three supply chain structures: decentralized, forward integration, and backward integration. Wang et al. (2018) investigated the effects of different carbon trading schemes (no trading, internal trading, and a mix of internal and external trading) on carbon permit prices, retail prices, and cold logistics service costs in the supply chain of fresh food products. Bai et al. (2019) examined a supply chain comprising one manufacturer and two competing retailers for perishable products under vendor-managed inventory. The study evaluated the effects of carbon emission reductions and implemented various carbon control methods, including cap-and-trade policies and investments in green technologies. Jamali and Rasti-Barzoki (2019) analyzed a sustainable supply chain with a focus on green transportation and delivery time. They employed a Stackelberg game model to evaluate three distinct scenarios in a supply chain comprising two manufacturers, one retailer, and a third-party logistics provider. The study assumes that consumers are aware of the significance of green transportation, which influences their purchasing decisions. Tiwari et al. (2019) developed a fuzzy green inventory model for non-instantaneously deteriorating products. Their work highlights how organizations can maximize total annual profits under various trade credit policies while minimizing carbon emissions, contributing to a cleaner environment. Lu et al. (2020) demonstrated that joint investment by buyers and sellers in carbon reduction technologies could simultaneously reduce greenhouse gas emissions and enhance the profitability of both parties. Their study employed the Stackelberg game approach to analyze buyer-seller interactions and determine optimal equilibrium strategies. Qin et al. (2020) examined the influence of advance payment financing on carbon emission reduction and production in a supply chain consisting of a manufacturer and a retailer. Two scenarios were analyzed: one without capital constraints and one with capital constraints. Manteghi et al. (2021) introduced three pricing models for a supply chain with two suppliers and one manufacturer aimed at improving consumer health and reducing greenhouse gas emissions. The models include a centralized structure and two decentralized structures. Zhao et al. (2021) studied a two-tier cold supply chain system involving a supplier and a retailer, emphasizing carbon labeling and the impact of random disruption factors on the supply chain. Dolat-abadi (2021) studied fresh agricultural product supply chains and the impact of market types (daily markets vs. bourse markets) and decision-making strategies (centralized vs. decentralized) on profits and waste management. Khorshidvand et al. (2021) proposed a hybrid method for closed-loop supply chain network design that coordinates greening and advertising decisions to maximize profit and minimize CO_2 emissions under uncertain demand, demonstrating the value of robust optimization. Also, Khorshidvand et al. (2021) introduced a two-stage approach combining optimal pricing/greening/advertising decisions with a fuzzy multi-objective MILP model, using Lagrangian relaxation to efficiently solve large-scale sustainable CLSC problems. Das et al. (2022) analyzed coordination in a two-stage supply chain for perishable products, consisting of a manufacturer and a retailer. Using the Stackelberg game framework, they examined the effects of deterioration rate, selling price, and freshness preservation policies. Liu et al. (2022) assessed the impact of investments in pre-cooling and carbon reduction technologies on the overall revenue of fresh food supply chains. Ranjan and Jha (2022) analyzed a dynamic pricing model for a two-level supply chain of deteriorating products, examining the impact of factors such as retail price and product freshness on demand. The model includes a manufacturer and a retailer managing deteriorating goods with a fixed shelf life. Demand in each period is influenced by retail price, on-hand inventory, reference price, and product freshness. The study also considers investment in preservation technology to reduce deterioration and carbon emissions.

Gautam et al. (2023) proposed a sustainable retail-based model where demand is represented as a function of pricing and greening efforts. Considering the deteriorating nature of items, the study demonstrates that preservation technology investment (PTI) yields better outcomes compared to traditional approaches. Khanlarzade and Farughi (2024) developed the Stackelberg game of deteriorating inventory within a two-level supply chain considering the concept of bounded rationality. Mahato and Mahata (2024) examined a two-level supply chain comprising a manufacturer and a retailer, with a focus on production disruption risks. In their model, the manufacturer relied on secondary markets to supply unmet demand. Customer demand was influenced by factors such as selling price, inventory levels, and product freshness. The study also incorporated investments in freshness-preservation technology to reduce deterioration rates and implemented carbon tax policies to mitigate carbon emissions. Hejazi and Khorshidvand (2024) proposed a multi-objective MILP model for CLSC that uses robust optimization to handle uncertainty and a novel scoring method for Pareto front selection, demonstrating trade-offs between economic, environmental, and social objectives. Zhou et al. (2024) studied the impact of corporate social responsibility on green supply chains and carbon emission reduction. Using a Stackelberg game model, the study analyzed how increasing consumer green preferences and trust contribute to reducing carbon emissions, although the high costs of green innovation were found to limit the rate of reduction Ma et al. (2024) explored joint decision-making in supply chains while considering carbon taxes and subsidies. Their model included technology selection, production quantity, wholesale pricing, and retail pricing, analyzed using the Stackelberg game framework and nested genetic algorithms. Khanlarzadeh (2024) examines the role of advanced technologies, such as cold plasma and blockchain, in improving the supply chain of deteriorating products, with a focus on milk. Based on the following summary table of the existing literature, cold plasma technology (particularly methods combining both carbon emission reduction and product shelf-life extension) has not yet been explored in the context of supply chains for deteriorating goods. Therefore, this study innovatively evaluates the application of this technology in the dairy supply chain for the first time. As one of the latest advancements in improving the quality and shelf-life of dairy products, cold plasma technology plays a significant role in enhancing supply chain sustainability by extending product shelf life, reducing waste, and lowering carbon emissions. Unlike previous research, which primarily focused on traditional approaches, this study develops a bilevel mathematical model to assess the impact of this technology on the decision-making processes of manufacturers and retailers. In contrast to previous studies that either focus on a single technology for one factor or use two technologies to address carbon reduction and product shelf life separately, this paper introduces cold plasma technology, which simultaneously impacts both factors. This innovation offers a more efficient approach by addressing both carbon emissions and product longevity with a single technology, making a significant contribution to supply chain sustainability. Another significant contribution of this research is a comprehensive analysis of the effects of three critical parameters: market size, customer price sensitivity, and the deterioration rate of products on waste reduction facilitated by cold plasma technology. Additionally, this study introduces, for the first time, a comprehensive utility metric for evaluating the economic feasibility of cold plasma technology. This metric incorporates a cost-benefit analysis of the technology, providing a detailed economic evaluation. The findings demonstrate that under specific conditions, the technology is not only environmentally beneficial but also economically advantageous for both manufacturers and retailers. This analysis offers valuable insights for implementing cold plasma technology in real-world scenarios. Despite the extensive body of literature on deteriorating product supply chains, several research gaps remain. Existing studies have largely focused either on traditional preservation or green technologies, or on strategic interactions modeled through Stackelberg game frameworks. However, limited attention has been paid to the simultaneous integration of an advanced preservation technology and a Stackelberg-based decision-making structure in deteriorating supply chains. In particular, the joint impact of a novel technology such as cold plasma on both product deterioration and carbon emissions within a bi-level Stackelberg framework has not been adequately explored. This study aims to fill this gap by providing an integrated economic–environmental analysis of cold plasma technology in a deteriorating goods supply chain. This study examines a two-level supply chain consisting of a manufacturer and a retailer, modeled using a Stackelberg game framework where the manufacturer acts as the leader. The manufacturer manufactures dairy products and adopts cold plasma technology at their own cost to improve product shelf life and reduce carbon emissions. By integrating this technology into the dairy supply chain, the proposed mathematical model identifies the conditions under which its use enhances supply chain performance, minimizes product waste, and reduces carbon emissions.

Table 1. Systematic review of related literature

Paper	Carbon Emission	Type of Technology	Technology features utilized		Product characteristics		Model Structure
			Carbon emission reduction	Product shelf-life extension (reduction of deterioration)	Freshness	Deterioration	
Sarkar et al., 2016	*						2-level SC
Saha et al., 2017		Green Operations and Preservation Technology		*		*	EOQ model
Huang et al., 2018		Preservation Technology Investment	*			*	3-level SC
Wang et al., 2018	*					*	2-level SC
Jamali and Rasti-Barzoki, 2019		Green Transportation	*				3-level SC
Tiwari et al., 2019	*					*	EOQ model
Bai et al., 2019		Green Technologies	*			*	2-level SC
Qin et al., 2020	*						2-level SC
Lu et al., 2020		Technological Investment in Reducing Carbon-emission	*			*	2-level SC
Dolat-Abadi, 2021		Freshness-Keeping Investment		*	*		3-level SC
Zhao et al., 2021		Carbon Footprint System	*			*	2-level SC
Das et al., 2022						*	2-level SC
Liu et al., 2022		Precooling and Carbon emission Reduction Technology	*		*		2-level SC
Ranjan and Jha, 2022		Preservation Technology Investment	*		*		2-level SC
Gautam et al., 2023		Preservation Technology Investment		*		*	EOQ model
Mahato and Mahata, 2024		Preservation Technology Investment		*	*	*	2-level SC
Zhou et al., 2024		Green Technology Innovation	*				2-level SC
Khanlarzade and Farughi, 2024						*	2-level SC
Ma et al., 2024		Green Technology	*				2-level SC
Khanlarzade, 2024		Block Chain		*		*	2-level SC
This research	*	Cold Plasma Technology	*	*		*	2-level SC

3. Methodology

3.1. Problem Statement

The study investigates a two-level supply chain consisting of a manufacturer and a retailer. The manufacturer produces dairy products and supplies them to the retailer, who then offers these products to end customers. The supply chain operates under a Stackelberg game framework, where the manufacturer acts as the leader and the retailer as the follower. The primary challenge is to address the environmental and operational issues associated with the production of deteriorating goods, particularly dairy products. The production process generates carbon emissions, and these emissions contribute to environmental degradation. Additionally, the deteriorating nature of dairy products leads to a limited shelf life, resulting in potential waste if not sold within the stipulated time. To address these challenges, the manufacturer adopts cold plasma technology. This innovative technology plays a dual role: it reduces carbon emissions and extends the shelf life of dairy products, including milk. Despite its advantages, implementing cold plasma technology incurs additional costs for the manufacturer. The objective of this study is to analyze the interplay between economic and environmental factors in this supply chain, focusing on maximizing profitability while minimizing carbon emissions and waste. Key questions include how the adoption of cold plasma technology influences demand, pricing, and profitability, and how the supply chain members can collaboratively optimize their operations to achieve these goals.

3.2. Model Description

The manufacturer implements and bears the cost of this technology during the production and processing stages. The problem is designed for a single decision-making period. The quantity of products produced by the manufacturer equals the retailer's demand. At the end of the replenishment period, the retailer's inventory level reaches zero. The demand for dairy products is price-sensitive and positively influenced by the adoption of cold plasma technology. This relationship is expressed as: $D = a - bp + \gamma e$ where a represents the market size, b is the price elasticity coefficient, p is the retail price, γ is the elasticity coefficient of carbon emission reduction, and e denotes the level of carbon emission reduction achieved through cold plasma technology. Additional notations used in the mathematical model are detailed in Table 2.

Table 2. Parameters and Decision variables

θ	Deterioration rate	Q	The production quantity of the manufacturer
Z	The fixed ordering cost of the retailer	h	The holding cost per unit per time unit at retailer
λ	The rate of reduction in Deterioration rate (or increase in product shelf life) due to the use of Cold plasma technology	$I_r(t)$	The inventory level at the retailer for $0 \le t \le T$
W	The wholesale price	T	The length of replenishment cycle
C	The unit production cost of the manufacturer	K	The Unit cost of reducing carbon emissions
π_r	Profit of the retailer	π_m	Profit of the manufacturer

The retailer's inventory decreases due to demand and product deterioration. Therefore:

$$\frac{dI_r(t)}{dt} = -(\theta - \lambda)I_r(t) - D \quad (1)$$

Considering $I(T) = 0$, the retailer's inventory level can be expressed as follows:

$$I_r(t) = \frac{(-1 + e^{(T-t)(\theta-\lambda)})D}{\theta-\lambda} \quad (2)$$

Additionally, since the quantity of goods produced by the manufacturer equals the retailer's inventory level at the beginning of the cycle, we have:

$$Q = I(0) = \frac{(-1+e^{T(\theta-\lambda)})D}{\theta-\lambda} \quad (3)$$

Therefore, the profit functions of the retailer and the manufacturer can be expressed as follows, respectively:

$$\pi_r = pD - \frac{1}{T}\left(Z + WQ + h\int_0^T I_r(t)\right) \quad (4)$$

$$\pi_m = \frac{1}{T}\left[(W - C)Q - \frac{1}{2}K(e^2 + \lambda^2)\right] \quad (5)$$

Q_{Np}^{w} and Q_{p}^{w} represent the amount of product waste in the absence of cold plasma and the amount of product waste when cold plasma is utilized, respectively. These values are determined using the following equations:

$$Q_{Np}^{w} = \theta\int_0^T I_r(t) \quad (6)$$

$$Q_{p}^{w} = (\theta - \lambda)\int_0^T I_r(t) \quad (7)$$

Additionally, ∇Q^{w} represents the reduction in product waste achieved through the use of cold plasma, which is calculated as follows:

$$\nabla Q^{w} = ((Q_{Np}^{w} - Q_{p}^{w})/Q_{Np}^{w}) * 100 \quad (8)$$

3.3. Solution Procedure

The leader-follower relationship between the manufacturer and the retailer is analyzed using the Stackelberg game framework, employing a backward induction approach, which is suitable for sequential decision-making. The presence of exponential terms introduces complexity to solving the problem. To simplify the model, a Taylor series approximation is applied as $e^{T(\theta-\lambda)} = 1 + T(\theta - \lambda) + \frac{(T(\theta-\lambda))^2}{2}$, which is used to simplify the profit functions. This approximation is valid due to the small magnitude of $T(\theta - \lambda)$.

Given that the retailer decides on the retail price and the replenishment cycle length, the first-order derivatives of the retailer's profit function with respect to the retail price and the replenishment cycle, respectively, are calculated as follows to determine the optimal decisions:

$$\frac{\partial \pi_r}{\partial p} = \frac{1}{2}\left[2a - 2bp + 2\gamma e + b\left(-2p + hT + w(2 + T\theta - T\lambda)\right)\right] \quad (9)$$

$\frac{\partial \pi_r}{\partial T} = \frac{1}{2}\left[\frac{2Z}{T^2} - eh\gamma - ew\gamma\theta - a\big(h + w(\theta - \lambda)\big) + bp\big(h + w(\theta - \lambda)\big) + ew\gamma\lambda\right]$ (10)

By simultaneously solving equations (9) and (10), the optimal values for the replenishment cycle are determined as follows:

$$T^* = \frac{\sqrt{2Z}}{\sqrt{(a-bp+e\gamma)(h+w(\theta-\lambda))}} \qquad (11)$$

Additionally, the following relationship is obtained:

$$a + e\gamma + \frac{1}{2}b\big(-4p + hT + w(2 + T\theta - T\lambda)\big) = 0 \qquad (12)$$

By substituting the expression obtained from Equation (11) into Equation (12), we derive:

$$a - 2bp + bw + e\gamma + \frac{b(h+w\theta-w\lambda)\sqrt{Z}}{\sqrt{2(a-bp+e\gamma)(h+w\theta-w\lambda)}} = 0 \qquad (13)$$

The optimal decisions of the manufacturer are determined by substituting the optimal decisions of the retailer into the manufacturer's objective function. Since determining the retail price from Equation (13) is not straightforward, we treat it as a constraint in the manufacturer's problem and identify the manufacturer's optimal decision considering the aforementioned constraint. Theorem 1. The retailer's profit function is concave, and the obtained values for the decision variables maximize the profit function and are unique.

Proof. To prove this theorem, assume that the retail and wholesale prices are given. Then, we have:

$$\frac{\partial^2 \pi_r}{\partial T^2} = \frac{-2Z}{T^3} \qquad (14)$$

The expression (14) is always negative.

Now, by substituting equation (11) into the retailer's profit function and calculating the second order derivative of the resulting function with respect to the retail price, we obtain:

$$\frac{\partial^2 \pi_r}{\partial p^2} = -2b \qquad (15)$$

Since the expression (15) is negative, the theorem is proven.▪

To solve the manufacturer's model, the following problem must be solved:

$$\begin{cases} Max\ \pi_m = \frac{1}{T}\left[(w-c)\left(\frac{a-bp+e\gamma}{\theta-\lambda}\right)\left(T(\theta-\lambda) + \frac{(T(\theta-\lambda))^2}{2}\right)\right] - \frac{1}{2}K(e^2+\lambda^2) \\ s.t. \quad a - 2bp + bw + e\gamma + \frac{b(h+w\theta-w\lambda)\sqrt{Z}}{\sqrt{2(a-bp+e\gamma)(h+w\theta-w\lambda)}} = 0 \end{cases} \qquad (16)$$

3.4. Solution Algorithm

The manufacturer's problem is a nonlinear problem; therefore, to solve the manufacturer's model and determine the optimal wholesale price, a heuristic algorithm is employed (Mahmoodi, 2021). This algorithm is outlined as follows.

Proposed Heuristic Algorithm

Step1) Set $w_1 = c$, resulting in $\pi_m^* = 0$.

Step2) Define the parameter $\varepsilon = 0.01$.

Step3) Set $i = 2$.

Step4) Set $w_i = w_{i-1} + \varepsilon$.

Step5) If $w_i < \frac{a+e\gamma}{b}$ (since $D > 0$ and $p > w$, it follows that $w < \frac{a+e\gamma}{b}$), proceed to step 6. Otherwise, set $w^* = w_{i-1}$ and calculate π_m^*.

Step6) Calculate the retail price and product sales period using equations (11) and (13), and then determine π_m^*.

Step7) If $\pi_m^*(w_i) > \pi_m^*(w_{i-1})$, set $w^* = w_i$ and $i = i + 1$, then return to step 4. Otherwise, set $w^* = w_{i-1}$.
Step8) End

4.Results and Discussion

To ensure a comprehensive understanding of the outcomes, sensitivity analysis was conducted to examine the effect of key parameters on supply chain performance metrics such as pricing, replenishment cycles, profits, and product waste. The sensitivity analysis explores how variations in parameters—such as market size, customer price sensitivity, and deterioration rates—impact the decisions and profitability of supply chain members. The results were interpreted by observing the trends and correlations between the parameters and the associated performance metrics. This approach highlights the interplay between economic and environmental considerations, helping to identify optimal strategies for improving supply chain efficiency while minimizing waste and costs. The insights gained from this analysis were used to propose strategies tailored to the specific conditions of the supply chain, ensuring practical and actionable recommendations. These findings provide a basis for further scenario-based evaluations, exploring innovative technologies and their implementation in dynamic market environments.

4.1. Initial Implementation of the Proposed Algorithm

Table 3 presents the parameters used for the implementation of the algorithm.

Table 3. Parameters used in the model

a	b	c	λ	θ	e	γ	h	k	z
1000	1	100	0.005	0.3	0.25	1.6	10	50	200

To further analyze the results, various examples have been defined as shown in Table 4, and the corresponding solution results are provided. In each example, the values of all parameters are selected as in Table 3, with only the value of the modified parameter being specified for each respective example.

Table 4. Model evaluation under different parameter conditions

Examples	Value of parameters	w^*	T^*	p^*	π_m^*	π_r^*	Q_p^w
Exp.1	$a = 500$	292	0.204736	401.172	19635.7	8879.48	0.6135
Exp.2	$a = 1000$	542.4	0.1023	775. 8	100884	48513.5	0.346699
Exp.3	$a = 1500$	792.5	0.06849	1150.67	244665	119423	0.241344
Exp.4	$a = 2000$	1042.5	0.0515053	1525.59	450955	221610	0.185787
Exp.5	$b = 0.5$	1039.5	0.0729401	1525.97	225471	110012	0.186309
Exp.6	$b = 1.5$	376.9	0.12483	525.749	59740.4	28318.7	0.486752
Exp.7	$b = 2$	294.3	0.1441	400.79	39470.9	18397.5	0.609201
Exp.8	$b = 3$	211.5	0.1786	275.767	19825.1	8885.71	0.814677
Exp.9	$\theta = 0.15$	544.7	0.141445	775.747	100949	49077.7	0.325659
Exp.10	$\theta = 0.2$	543.8	0.1238	775.744	100928	48878.4	0.33571
Exp.11	$\theta = 0.45$	540.7	0.084308	775.883	100822	48058.5	0.355072
Exp.12	$\gamma = 0.8$	542.3	0.10236	775.651	100839	48491.4	0.347027
Exp.13	$\gamma = 1$	542.3	0.1023	775.675	100850	48502.6	0.34704
Exp.14	$\gamma = 2.4$	542.5	0.102322	775.95	100929	48535.6	0.346777
Exp.15	$\gamma = 3$	542.6	0.102307	776.076	100963	48546.5	0.346861

According to Table 4, with an increase in market size, prices have significantly risen, which is due to the greater ability to cover costs as demand increases. The replenishment cycle has decreased, likely due to the faster sales pace in larger markets. The increase in profit also indicates an improvement in the economic efficiency of the supply chain in larger markets. Additionally, due to better sales time management, product waste has decreased. Due to increased customer price sensitivity, prices have dropped, and this lower price has led to reduced revenue for the members. Product waste has increased due to the shorter replenishment cycle and lower demand. With an increase in the deterioration rate, the significant reduction in the replenishment cycle highlights the necessity of accelerating the sales of deteriorating goods. Prices have remained relatively stable, indicating that the deterioration rate has more of a direct impact on the reduction of the replenishment cycle than on prices. On the other hand, the economic pressure from the increased deterioration rate has led to reduced profits for the members. The increase in product waste further emphasizes the need for advanced deterioration reduction technologies or additional investment in existing technologies. By examining the data in the Table 4, it can be stated that the increase in the carbon emission reduction elasticity coefficient has no significant effect on prices, as the reduction in emissions does not directly impact production and consumption costs. The members' profits slightly increase because the costs associated with carbon emission reduction in production have been better managed. On the other hand, the product waste shows little difference but has a slight decrease, indicating that emission reduction technology does not have a significant impact on product deterioration.

4.1.1. Strategic Economic Insights and Supply Chain Optimization

Based on the results of the model and the analyses conducted, several economic strategies can be proposed to improve supply chain performance. These analyses have been carried out considering various factors such as market size, product deterioration rates, customer price sensitivity, and the impact of innovative technologies in the supply chain. The first solution pertains to pricing strategy. Reducing customer price sensitivity contributes to higher profits for both manufacturers and retailers. In markets with price-sensitive customers, the pricing strategy should focus on balancing profitability and demand. Implementing a hybrid pricing model (Fixed + Dynamic) for products with high deterioration rates is a method that helps adjust prices gradually based on time and market conditions. Additionally, offering periodic discounts or purchase incentives to reduce inventory before expiration can be effective. Managing product deterioration can be the second strategy. An increase in product deterioration decreases profitability and increases waste. In such cases, replenishment periods should be shortened to reduce deterioration. To achieve this, investments in other deterioration-reduction technologies, such as active packaging that extends product shelf life, should be made. Furthermore, implementing demand forecasting models using artificial intelligence for better inventory and transportation planning, along with faster distribution through optimized transport routes, can be beneficial. A larger market leads to reduced product waste and higher profitability. However, in smaller markets, profit growth is limited. In such cases, expanding the target market by exporting to new regions or increasing advertising in current markets, as well as establishing local sales networks for faster product delivery and reduced distribution costs, can improve the situation. The increased use of green technologies does not have a direct impact on profits but influences brand image and customer satisfaction. Therefore, increasing supply chain transparency through blockchain to inform customers about sustainability efforts and offering government incentives to reduce the costs of implementing green technologies can be proposed as a solution. In cases where the retailer's profit exceeds that of the manufacturer, to prevent dissatisfaction from the manufacturer, it is recommended to implement profit-sharing mechanisms to balance profitability between the manufacturer and retailer, as well as to establish long-term contracts and define clear roles within the supply chain.

4.2. Waste Reduction Trends Relative to Parameters

In this subsection, the effects of key supply chain parameters—market size, customer price sensitivity, and product deterioration rate—on the effectiveness of cold plasma technology in reducing waste are analyzed. The goal is to understand how variations in these parameters influence the level of waste reduction achievable in different market and customer conditions. Figure 1 illustrates the variation in waste reduction levels when using cold plasma technology in relation to market size, customer price sensitivity, and deterioration rate parameters. A reduction in market size has a positive impact on waste reduction. This could be due to lower demand and a stronger focus on optimizing storage and preventing deterioration. In this case, as the market shrinks, demand decreases, and manufacturers are more likely to rely on waste reduction technologies such as cold plasma to extend the saleable life of their products. A 50% increase in market size slightly reduces waste reduction. The larger demand volume may put additional pressure on the supply chain, even with the use of cold plasma. As the market expands, manufacturers may feel less pressure to use cold plasma technology to minimize waste, and such technologies might be used at a lower intensity. In this situation, increased competition leads to higher product demand, and sales time increases. In smaller markets, competition is lower, and manufacturers need more control over their inventories. Overall, the market size curve exhibits less variation because market size has an indirect effect on waste reduction. A 50% decrease in customer price sensitivity has a significant impact on waste reduction. When customers are less sensitive to price, it is reasonable for manufacturers to prefer more sophisticated and expensive technologies like cold plasma to reduce waste and keep their products in the market longer without having to lower prices. This suggests that when customer price sensitivity is lower, manufacturers can maintain higher prices and benefit more from cold plasma technology in reducing waste. Conversely, a 50% increase in customer price sensitivity reduces the effectiveness of cold plasma technology, as pricing becomes more flexible, and the need for such technologies diminishes. Price-sensitive customers tend to prefer cheaper products, prompting manufacturers to lower prices instead of relying heavily on cold plasma technology, reducing the impact of this technology. As a result, the extent of waste reduction using cold plasma technology also decreases.

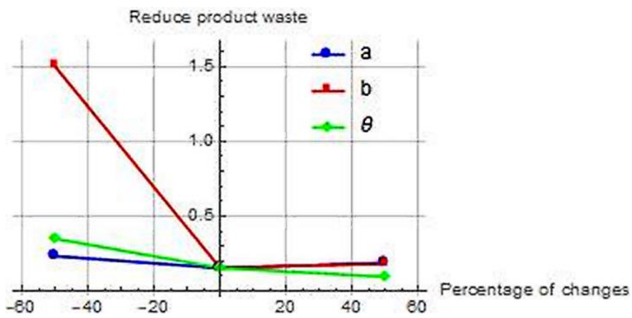

Figure 1. Analysis of the changes in waste reduction with cold plasma technology in relation to key supply chain parameters

A lower deterioration rate results in a more pronounced effect of cold plasma technology in extending product shelf life. In contrast, a higher deterioration rate limits the effectiveness of cold plasma and leads to a smaller reduction in product waste. Therefore, when the deterioration rate decreases, the use of cold plasma technology will have a more significant positive impact on waste reduction. Based on the data and analyses conducted, it can be concluded that cold plasma technology has the greatest impact under conditions where the market size is small, customer price sensitivity is low, and the deterioration rate is high. Conversely, when the market size is large, customer price sensitivity is high, and the deterioration rate is low, the impact of cold plasma technology diminishes.

4.2.1. Optimizing Cold Plasma Technology for Waste Reduction

This subsection analyzes strategies for optimizing the use of cold plasma technology to minimize product waste in the supply chain. It focuses on how market characteristics, customer price sensitivity, and product deterioration rates influence the effectiveness and economic feasibility of cold plasma implementation. Manufacturers and retailers can adopt various strategies to optimize the use of cold plasma technology, depending on market characteristics and product features. One such solution is the optimal use of cold plasma in small markets. In smaller markets, where demand for the product is lower, the application of cold plasma can be highly effective in reducing waste. This approach may be cost-effective for manufacturers facing low demand. Furthermore, in markets where price sensitivity is high, the use of technologies like cold plasma may not be economically feasible. In these situations, manufacturers should focus on optimizing pricing strategies and using discounts to boost demand. For products with high deterioration rates, the application of cold plasma can significantly help in reducing waste. This technology should be particularly considered for products with short shelf lives to prevent deterioration and waste.

4.3. Cold Plasma Technology Cost Analysis

In this subsection, the economic implications of adopting cold plasma technology are examined. The objective is to assess whether the investment in this technology is justified by its effects on product shelf-life extension, waste reduction, and indirect contributions to carbon emission mitigation. The cost of utilizing plasma technology, as a critical parameter, can indicate whether the use of this technology is economically justifiable. This technology is specifically designed to extend the shelf life and preserve the quality of products, particularly food items. Therefore, the more advanced and costly the technology, the greater its impact on prolonging product shelf life. Cold plasma technology indirectly contributes to reducing carbon emissions by reducing product waste and, as a result, minimizing overproduction. Since its direct impact on carbon reduction is typically more limited than its effect on extending shelf life, for the cost analysis, we assume that with a unit increase in the cost of cold plasma, the reduction in carbon emissions and the increase in product shelf life will each increase by 5% and 15%, respectively. The baseline values for the technology parameters are considered as follows:

$$k_0 = 50, \lambda_0 = 0.05, e_0 = 0.25$$

Table 5 presents the defined scenarios based on this, and subsequently, the changes in member profits and product waste levels for all scenarios will be analyzed.

Table 5. Different scenarios and corresponding parameter values in cold plasma technology

Scenarios	λ	e	k	Scenarios	λ	e	k
Scenario1	0.0575	0.2625	51	Scenario8	0.1527	0.3689	58
Scenario2	0.0661	0.2756	52	Scenario9	0.1756	0.3873	59
Scenario3	0.076	0.2893	53	Scenario10	0.2019	0.4066	60
Scenario4	0.0874	0.3037	54	Scenario11	0.2321	0.4269	61
Scenario5	0.1005	0.3188	55	Scenario12	0.2669	0.4482	62
Scenario6	0.1155	0.3347	56	Scenario13	0.3069	0.4706	63
Scenario7	0.1328	0.3514	57	Scenario14	0.3529	0.4941	64

4.3.1 Economic Analysis: Impact of Cold Plasma on Manufacturer's Profitability

This subsection examines how the adoption of cold plasma technology affects the profitability of the manufacturer. The analysis considers the influence of extended product shelf life and reduced deterioration costs on revenue and overall financial performance. This section explores the impact of cold plasma technology on manufacturer profitability. The results in Fig. 2 indicate that as the shelf life of products increases due to cold plasma, the manufacturer's profit improves significantly. This is because extended shelf life reduces the likelihood of product deterioration, allowing manufacturers to sell a higher proportion of their inventory. In addition, reduced deterioration costs help offset the initial investment in cold plasma technology, further enhancing the manufacturer's profitability. For higher deterioration rates, the impact of cold plasma technology is more pronounced, as it directly mitigates the rapid deterioration of products. At lower deterioration rates, the profit improvement is less dramatic but still significant. Manufacturers can further enhance their profitability by implementing complementary measures such as optimized packaging and faster distribution networks.

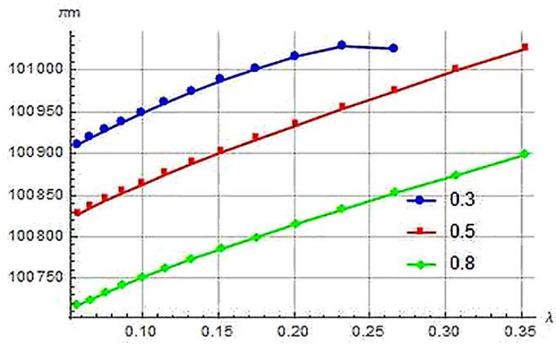

Figure 2. The impact of deterioration rate on producer profit in the defined scenarios

4.3.2 Retailer Profit Dynamics Under Varying Deterioration Rates

Here, we analyze the retailer's profitability under different product deterioration rates and the effect of shelf-life improvements due to cold plasma technology. According to Fig. 3 retailer profits depend on deterioration rates and shelf-life improvements from cold plasma technology. At lower deterioration rates, the extended shelf life allows retailers to maintain lower inventory levels and reduce waste, which positively impacts profitability. As the deterioration rate increases, retailers face higher deterioration risks, and the profitability gains from using cold plasma diminish. The results also show that dynamic pricing strategies can help retailers manage the risks associated with high deterioration rates. For example, offering discounts closer to the expiration date can stimulate demand and minimize waste. Additionally, retailers may benefit from collaborative agreements with manufacturers to share the costs and benefits of adopting advanced preservation technologies.

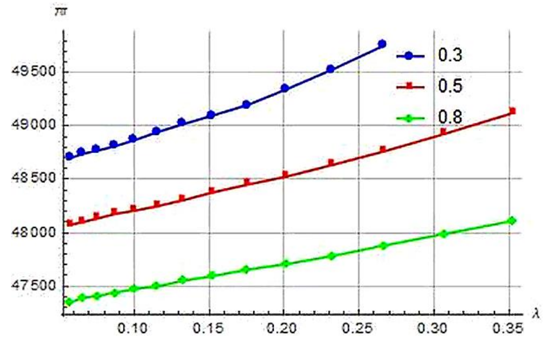

Figure 3. The impact of deterioration rate on retailer profit in the defined scenarios

4.3.3 Pricing Strategies: Adjusting Retail Prices for Perishable Goods

This subsection explores how cold plasma technology influences retail pricing decisions for perishable goods, considering both cost changes and shelf-life improvements. The use of cold plasma technology introduces new dynamics in pricing strategies for perishable goods, influencing how retailers adjust prices based on costs and shelf-life improvements (Fig. 4). Retail prices tend to fluctuate based on the additional costs incurred for extending shelf life and controlling deterioration. For products with lower deterioration rates, retail prices remain relatively stable, as the preservation costs are lower. However, for products with higher deterioration rates, retailers are compelled to set higher prices to cover the increased preservation costs. To maximize revenue, retailers can adopt hybrid pricing models that combine fixed and dynamic pricing. This approach allows for gradual price adjustments based on market conditions and product shelf life, ensuring profitability while maintaining competitive pricing.

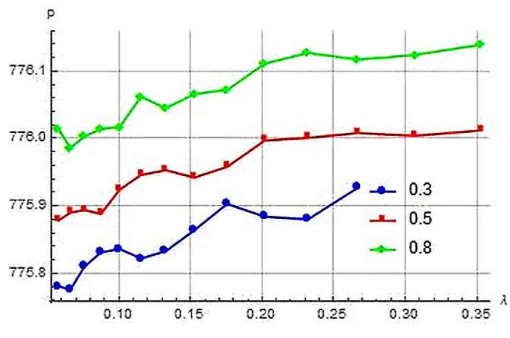

Figure 4. The impact of deterioration rate on retail price in the defined scenarios

4.3.4 Wholesale Pricing Insights: Balancing Costs and Benefits

In this part, the focus is on wholesale pricing strategies and how manufacturers can balance the costs of cold plasma adoption with the benefits of extended shelf life to optimize supply chain performance. Wholesale prices reflect the cost implications of adopting cold plasma technology. According to Fig 5 products with lower deterioration rates typically command higher wholesale prices due to their extended shelf life and reduced risk of deterioration. On the other hand, for products with higher deterioration rates, manufacturers may lower wholesale prices to encourage retailers to stock these items despite the higher deterioration risks.The analysis reveals that balancing the costs of preservation with the benefits of extended shelf life is critical. Manufacturers should consider flexible pricing strategies, such as offering discounts on bulk purchases or lower prices for high-deterioration products, to optimize their supply chain performance and strengthen retailer partnerships.

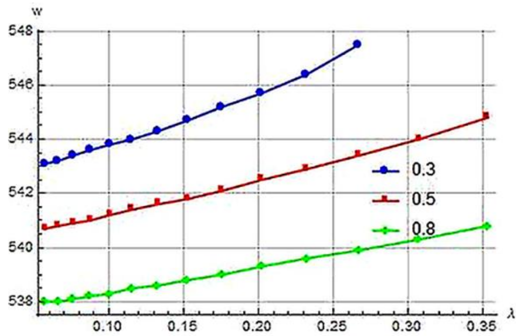

Figure 5. The impact of deterioration rate on wholesale price in the defined scenarios

Figures 4 and 5 demonstrate that both retail and wholesale prices behave differently depending on the role and objectives of each segment of the supply chain, as well as the level of deterioration risk. These behaviors align with the literature on supply chains for deteriorating goods and Stackelberg decision-making models. The manufacturer focuses on increasing sales to the retailer, while the retailer adjusts pricing strategies based on customer behavior. At higher deterioration rates, the manufacturer is compelled to lower the wholesale price to incentivize the retailer to purchase, as the increased risk of deterioration reduces the retailer's willingness to pay a premium price. In turn, the retailer increases retail prices to compensate for the reduced demand and to cover the risk of potential losses. However, at lower, as the higher deterioration risk discourages the retailer from paying a premium price rate, the manufacturer understands that an extended shelf life reduces, as the higher deterioration risk discourages the retailer from paying a premium price risk for the retailer, making the retailer willing to pay a higher price for the product. As a result, the manufacturer raises the wholesale price to capture a greater share of the profit. The natural shelf life of the product is higher, and the retailer does not need to drastically increase prices since customers are more likely to purchase the product. Therefore, the deterioration risk is lower, demand remains higher, and the retailer has less need to substantially increase prices.

4.3.5 Reducing Product Waste: Evaluating Cold Plasma Effectiveness

This subsection investigates the effectiveness of cold plasma technology in reducing product waste and identifies which product categories benefit the most from this intervention. Cold plasma technology has proven to be an effective solution for reducing product waste in supply chains. According to Fig. 6, the analysis shows that its impact is most significant for products with lower deterioration rates, where the extended shelf life leads to considerable waste reduction. For products with higher deterioration rates, while the technology still helps, its effectiveness diminishes, requiring complementary solutions such as advanced packaging or optimized transportation systems. Investments in cold plasma technology should therefore be prioritized for products where its waste reduction potential is maximized. Combining this technology with other preservation methods can further enhance its effectiveness and provide comprehensive solutions for waste management.

4.3.6 Optimizing Replenishment Cycles for Deteriorating Goods

Here, the impact of cold plasma technology on replenishment cycle decisions is analyzed, with attention to how extended shelf-life influences inventory planning and logistics. Cold plasma technology also affects replenishment cycle decisions in the supply chain. According to Fig. 7, for products with low deterioration rates, the extended shelf life allows for longer replenishment cycles, reducing logistical costs and enhancing efficiency. However, for products with high deterioration rates, the technology has limited impact on cycle length, necessitating more frequent replenishment to prevent deterioration. The findings suggest that supply chain managers should adopt tailored replenishment strategies based on the deterioration characteristics of their products. For instance, leveraging technologies like artificial intelligence to predict demand and optimize inventory levels can further enhance the benefits of cold plasma technology. Additionally, fast and efficient distribution networks can complement the technology's impact, especially for high-deterioration products.

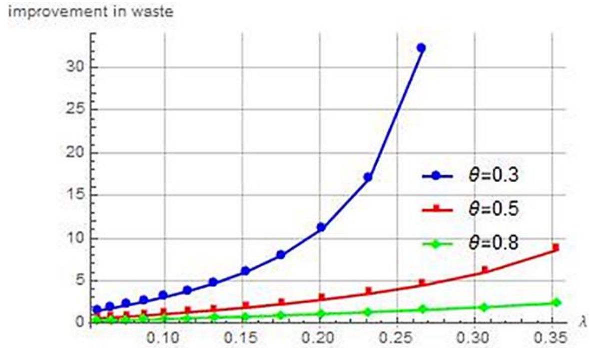

Figure 6. The impact of deterioration rate on product waste reduction in the defined scenarios

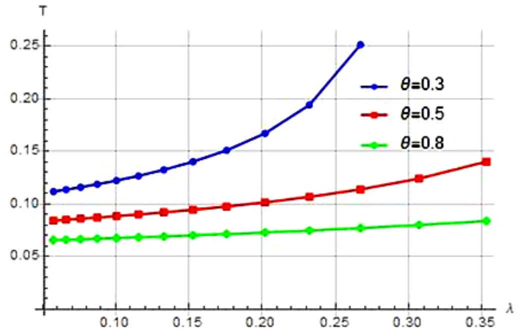

Figure 7. The impact of deterioration rate on the replenishment period in the defined scenarios

4.4. Overall Utility Metric

This section introduces the overall utility metric, which combines product waste reduction and carbon emission reduction to provide a comprehensive assessment of cold plasma technology's performance across the supply chain. To evaluate the effectiveness of cold plasma technology, a combined utility metric (OUM) was developed to account for both product waste reduction and carbon emission reduction. This composite index provides a comprehensive comparison between scenarios with and without cold plasma technology. The metric is defined as:

$$OUM = w_1\left(\frac{G}{H}\right) + w_2\left(\frac{E}{F}\right)$$

Here, the first term represents the ratio of product waste reduction relative to the no-cold plasma scenario, while the second term reflects the carbon emission reduction. The weights (w_1 and w_2) vary across three scenarios:

- In Scenario A: Product waste (0.3), Carbon emissions (0.7).
- In Scenario B: Equal weights for both metrics (0.5 each).
- In Scenario C: Product waste (0.7), Carbon emissions (0.3).

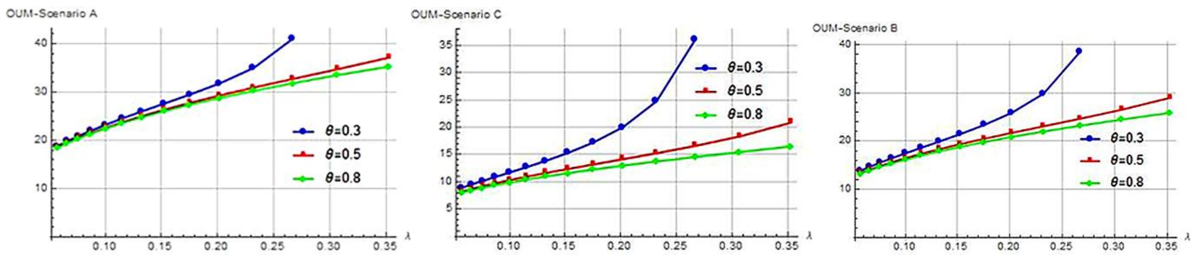

Figure 8. Analysis of the overall utility metric in (a) Scenario A (b) Scenario B, (c) Scenario C, for different deterioration rates

4.4.1. Insights from Utility Metric Analysis

In this subsection, we evaluate the insights obtained from the overall utility metric, analyzing how investment in cold plasma technology affects utility across different scenarios and deterioration rates. The utility metric achieves its highest value at a deterioration rate of 0.3, where conditions such as cost reduction and quality improvement show the most significant effects (Fig 8). Conversely, as the deterioration rate rises to 0.5 and 0.8, utility declines, emphasizing the diminishing benefits of advanced technologies under high deterioration rates. These results highlight the critical need for additional measures beyond cold plasma, such as improved packaging or optimized logistics, to maintain product quality and enhance supply chain efficiency. Figure 9 illustrates the effect of increasing investment in cold plasma technology on the utility metric across the three considered scenarios. In all scenarios, higher investment levels lead to an improvement in utility, indicating that the economic and environmental benefits of cold plasma technology outweigh its associated costs as adoption intensifies. Among the scenarios, Scenario A—where the primary effect of the technology is carbon emission reduction—achieves the highest utility values. This outcome reflects the stronger influence of emission reduction on both cost savings and demand enhancement, which are directly captured in the utility metric. In contrast, scenarios that mainly emphasize waste reduction, such as Scenario C, exhibit a more moderate growth in utility. Although waste reduction contributes positively to sustainability, its indirect economic impact on demand and revenue is less pronounced than that of carbon emission mitigation within the proposed model. Consequently, the utility metric increases at a slower rate in these scenarios, highlighting the relatively stronger role of emission reduction in improving overall supply chain performance.

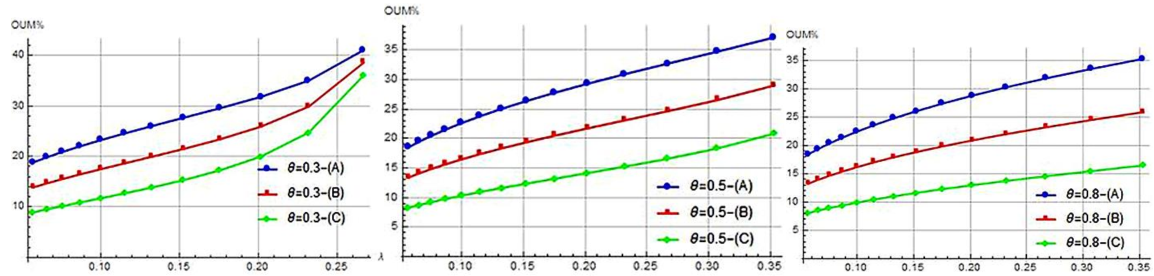

Figure 9. Impact of weightings on the variations in the utility metric for deterioration rates (a) 0.3, (b) 0.5, (c) 0.8.

4.4.2. Strategic Recommendations for Supply Chain Optimization

This subsection presents strategic recommendations for supply chain optimization based on the utility metric analysis, highlighting approaches that balance economic and environmental objectives.

1. Prioritizing Carbon Reduction: Companies should focus on reducing carbon emissions, particularly when targeting environmentally-conscious markets. Investments in cold plasma and similar technologies offer dual benefits: improving profitability and bolstering sustainability credentials.

2. Balancing Goals: While waste reduction is important, its standalone impact on utility is less pronounced. An integrated approach that aligns waste reduction with carbon mitigation strategies is essential for long-term supply chain optimization.

3. Strategic Recommendations: For products sensitive to shelf life, prioritizing high-efficiency, sustainable technologies like cold plasma ensures both environmental and economic gains. Policymakers can further incentivize adoption by supporting advanced preservation methods.

These findings underline the necessity of incorporating dual objectives (waste and carbon reduction) into strategic supply chain decisions to maximize overall utility and competitiveness.

5. Conclusion and Recommendations

This study highlights the transformative impact of cold plasma technology on supply chains for deteriorating goods, particularly in the dairy sector. The results reveal that cold plasma can significantly enhance profitability by reducing carbon emissions, extending product shelf life, and minimizing waste. Key findings demonstrate that while initial technology costs may increase expenditures, they lead to long-term benefits, including reduced indirect supply chain costs and enhanced environmental sustainability. By reducing costs associated with product deterioration, particularly for items with high spoilage rates, the technology considerably improved supply chain productivity. In the realm of market and pricing strategies, observations indicated that operating in larger markets with lower product deterioration rates resulted in improved profitability and waste reduction. However, in price-sensitive markets, implementing dynamic pricing strategies was found to be essential for balancing demand and costs effectively. A standout achievement of this technology is its positive environmental impact. The adoption of cold plasma significantly reduced carbon emissions, which not only aligns with sustainability goals but also enhances a company's brand image. From a strategic perspective, the study emphasizes optimizing the use of the technology, highlighting the importance of tailoring cold plasma implementation to specific supply chain conditions. While products with high deterioration rates benefit the most, as those rates decline, complementary strategies such as improved packaging and logistics become crucial. Furthermore, the analysis of balancing costs and benefits reveals that investing in cold plasma technology delivers substantial long-term profitability. Combined with its environmental advantages, this makes it a viable solution for sustainable supply chain management. Finally, regarding policy and market alignment, government incentives can encourage adoption by helping to offset the initial investment costs. Simultaneously, companies targeting environmentally conscious consumers can leverage cold plasma technology to strengthen their market position. Despite the valuable insights provided by this study, several limitations should be acknowledged. First, the proposed model is developed for a single-period, two-level supply chain consisting of one manufacturer and one retailer, which may limit its applicability to more complex multi-echelon or competitive supply chain structures. Second, demand is assumed to be deterministic and price-sensitive, whereas in real-world settings, demand is often subject to uncertainty, seasonality, and stochastic fluctuations. Third, the model assumes full and immediate access to cold plasma technology, without considering capacity constraints, adoption barriers, or technological learning effects. In addition, government policies such as subsidies or incentives for green technologies are not explicitly modeled as uncertain or dynamic parameters. These limitations open several avenues for future research. Future studies may extend the proposed framework to multi-period and multi-player supply chains, incorporate uncertainty in demand and product deterioration, and examine the effects of stochastic subsidies or dynamic carbon regulation policies. Moreover, integrating cold plasma technology with other advanced preservation solutions, such as nanotechnology and active packaging, could help identify more effective and hybrid sustainability strategies. In addition, the adoption of data-driven and AI-based demand forecasting models, along with advanced simulation techniques, may provide deeper insights into supply chain performance under varying market and operational conditions. Further investigation into policy incentives and economic mechanisms can also support the broader adoption of green technologies, thereby contributing to long-term sustainability and resource conservation.

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