



Optimal Pricing for Deteriorating Items using Preservation Technology: A Carbon Emission and Comparative Demand Analysis

Jitendra Kumar

Department of Mathematics, Marwari College, L.N. Mithila University, Darbhanga, Bihar

***Corresponding Email:** jitte.dm@gmail.com

Abstract: This paper presents an Economic Production Quantity (EPQ) inventory model for deteriorating items by incorporating preservation technology and price-dependent demand in a continuous review system. Preservation technology is assumed to reduce the deterioration rate, while energy consumption associated with preservation generates carbon emission costs, reflecting environmental considerations. Demand is modeled using linear, exponential, and logarithmic price-dependent functions to represent different market behaviors. Inventory dynamics during production and depletion phases are described using differential equations, and a profit function is developed to determine the optimal selling price. A comparative demand analysis is conducted to examine the effect of different demand structures on profitability and inventory cycle length under carbon emission considerations. Numerical results and sensitivity analysis illustrate the impact of price sensitivity and carbon cost on system performance. The model provides useful managerial insights for balancing pricing decisions, inventory control, and environmental responsibility.

Keywords: Preservation technology; Carbon emission; Comparative demand behavior; Pricing strategy; EPQ inventory model.

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* Corresponding Author



1. Introduction

In recent years, inventory management for deteriorating products has gained considerable attention due to increasing market competition, rising operational costs, and growing environmental concerns. Many industries such as food processing, pharmaceuticals, chemicals, and cold-chain logistics regularly deal with items whose quality and usability decline over time. Traditional inventory models, which assume constant demand and no deterioration, often fail to capture these real-world complexities. As a result, businesses face challenges in balancing inventory holding costs, product loss due to deterioration, and pricing decisions that directly influence customer demand and profitability.

To reduce the negative effects of deterioration, firms increasingly rely on preservation technologies such as refrigeration, controlled storage, and energy-based preservation systems. While these technologies help extend product life, they also consume energy and contribute to carbon emissions, raising sustainability and cost-related concerns. With stricter environmental regulations and rising awareness of carbon footprints, it has become essential to incorporate carbon emission considerations into inventory decision-making. Integrating environmental costs with operational policies allows organizations to design inventory systems that are not only economically viable but also environmentally responsible.

Another critical factor influencing inventory performance is the behavior of customer demand in response to price changes. In practice, demand rarely remains constant and often varies depending on the selling price and market structure. Different price-dependent demand patterns, such as linear, exponential, and logarithmic forms, represent varying consumer sensitivities and purchasing behaviors. Understanding how these demand structures affect inventory decisions and profitability is crucial for effective pricing and production planning. Motivated by these factors, this study develops an EPQ-based inventory model for deteriorating items that incorporates preservation technology, carbon emission cost, and price-dependent demand, and provides a comparative demand analysis to support informed managerial decision-making.

2. Literature Review

The development of inventory models for deteriorating items has been central to operations research since the early work of Ghare and Schrader (1963), who first incorporated inventory decay into economic ordering models. Classical approaches, as summarized by Goyal and Giri (2001), primarily extended the deterministic Economic Order Quantity (EOQ) and Economic Production Quantity (EPQ) frameworks to account for deterioration, varying demand patterns, and shortages. Over time, these foundational studies evolved to capture more realistic operational complexities, increasingly emphasizing demand variability and cost optimization under deteriorating conditions.

As inventory systems became more complex, research began integrating additional factors affecting real-world operations. Several studies have examined deteriorating inventory models under different demand structures and market conditions. Wee (1995) studied lot-sizing for deteriorating products in declining markets, while Jaggi et al. (2015) focused on two-warehouse systems with imperfect quality items. Recent contributions by Pervin (2024) and San-José et al. (2024) further explored deterioration dynamics under environmental policies such as carbon emission taxes, developing sustainable inventory systems that consider carbon-related costs alongside traditional holding and shortage costs. These studies highlight that sustainability considerations can no longer be treated as external to inventory decisions, but rather as intrinsic policy variables that influence cost and replenishment outcomes.

A growing stream of research has investigated the role of preservation technology as a strategic tool to mitigate deterioration. Early examples by Iqbal and Sarkar (2020) demonstrated that investment in preservation technology could significantly reduce deterioration-related losses without compromising overall system profitability. Subsequent studies by Rahman et al. (2021) and Nath and Sen (2021) integrated such preservation mechanisms with stock- and price-dependent demand, offering richer insights into how operational choices affect inventory lifecycles. Recent work by Kumar et al. (2025) proposed inventory models that balance investments in preservation technology with carbon emission reduction, reinforcing the

emerging consensus that energy-efficient preservation yields dual benefits in reduced waste and lower environmental impact.

Pricing decisions and demand responsiveness have also been central to modern inventory research. Whitin's (1955) seminal work linking pricing and inventory set the stage for later studies on price-dependent demand. Jung and Klein (2006) and Teksan and Geunes (2016) showed that pricing policies can significantly shape inventory performance and cost efficiency, particularly under non-constant demand conditions. Recent research extends this line by incorporating environmental factors with pricing decisions. For example, Taleizadeh et al. (2020) examined joint pricing and inventory optimization with carbon considerations, and Suvetha et al. (2025) explored sustainable production-inventory systems that integrate environmental taxes with power-pattern demand dynamics. These studies illustrate the importance of addressing economic and environmental drivers simultaneously in decision-making frameworks.

Despite these advancements, there remains a gap in the literature regarding comparative analysis across different price-dependent demand patterns when carbon emission costs and preservation technology investments are both considered. Some recent works have begun to address this gap using multiobjective or hybrid optimization techniques, but comprehensive comparative frameworks remain limited. For instance, the 2025 study by Limi and Rangarajan proposed a two-warehouse model integrating preservation technology and carbon emissions with hybrid payment schemes, demonstrating practical implications for cost-sensitive contexts. However, such models rarely investigate how different demand structures—such as linear, exponential, or logarithmic price dependencies—affect profit and sustainability outcomes. This gap motivates the current research, which aims to integrate environmental and operational considerations within an EPQ framework and perform a comparative demand analysis to better inform inventory policy under diverse market behaviors.

3. Assumptions and Notations

3.1 Assumptions

The assumptions of the model have been provided as:

1. The study considers a single deteriorating product whose quality decreases over time once it is stored in inventory.
2. Preservation technology is used to slow down deterioration, and its operation requires energy consumption.
3. Energy consumption during preservation results in carbon emissions, and a fixed carbon emission cost is associated with this energy usage.
4. Product demand depends on the selling price and follows linear, exponential, or logarithmic patterns to represent different market behaviors.
5. Shortages are allowed, and all unmet demand during stock-out periods is completely backlogged.

3.2 Notation

The following notations are used in this research

Notations	Explanations
Q	Order quantity
R	Reorder point
L	Lead time
h	Holding cost per unit per unit time
C_o	Ordering cost per order
C_s	Shortage or backorder cost per unit

C_p	Production cost per unit
C_c	Purchasing cost per unit
C_e	Energy cost per unit
θ	Natural deterioration rate without preservation
$\theta' = \theta f(E_e)$	Deterioration rate with preservation technology
E_e	Energy efficiency factor of the preservation technology
$D(p)$	Demand rate as a function of price
	Linear Demand $D(p) = a - bp$
	Exponential Demand $D(p) = Ae^{-Bp}$
	Logarithmic Demand $D(p) = c - d * \ln(p)$
P	Production or replenishment rate
S	Selling price per unit
α	Cost per unit of energy efficiency per unit of inventory
C_f	Fixed cost associated with the implementation of preservation technology
γ	Carbon emission cost per unit of energy consumed
Π	Profit function

4. Mathematical Model

In this section, an EPQ-based inventory model is formulated for deteriorating items by incorporating the effects of preservation technology and price-dependent demand. The model captures the evolution of inventory levels over time while explicitly considering deterioration, energy consumption, and carbon emission costs. Since the use of preservation technology helps slow down product deterioration, the deterioration rate is assumed to depend on the energy efficiency of the preservation system. Let θ denote the natural deterioration rate in the absence of preservation. When preservation technology is applied, this rate is reduced, and the effective deterioration rate θ' is expressed as a function of the energy efficiency of the technology as follows:

$$\theta' = \theta f(E_e) = \theta e^{-\beta E_e}$$

The differential equations are

$$\frac{dI(t)}{dt} = P - D(p) - \theta' I(t) \quad 0 \leq t \leq t_1, \quad I(0) = 0 \quad (1)$$

$$\frac{dI(t)}{dt} = -D(p) - \theta' I(t), \quad t_1 \leq t \leq t_2 \quad I(t_2) = 0 \quad (2)$$

$$\frac{dI(t)}{dt} = -D(p) \quad t_2 \leq t \leq T, \quad I(t_2) = 0 \quad (3)$$

Solutions of the above equations are as follows

$$I(t) = \frac{P-D(p)}{\theta'} (1 - e^{-\theta' t}), \quad 0 \leq t \leq t_1 \quad (4)$$

$$I(t) = \frac{-D(p)}{\theta'} (1 - e^{-\theta' t}) = D(p) \frac{(e^{\theta'(-t+t_2)} - 1)}{\theta'}, \quad t_1 \leq t \leq t_2 \quad (5)$$

$$I(t) = -D(p)(t - t_2), \quad t_2 \leq t \leq T, \quad (6)$$

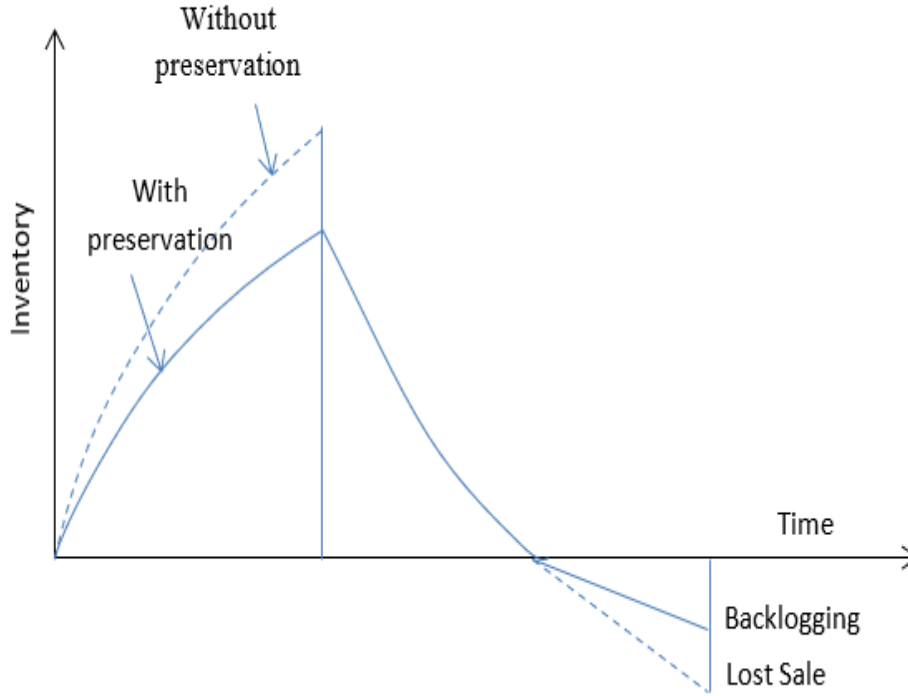


Figure 1: Inventory level depiction with respect to time.

Cost Structure

The total cost per cycle includes production cost, holding cost, ordering cost, preservation-related energy cost, and carbon emission cost. Energy consumption required for preservation contributes to carbon emissions, and the carbon emission cost is assumed to be proportional to the energy used. All costs are calculated as follows:

Setup cost: A fixed setup cost is incurred for each production cycle whenever a new production run is initiated and can be taken as

$$ST = C_o$$

Production cost: The production cost is proportional to the number of units produced during a cycle. Thus the production cost can be calculated as

$$MC = C_p D(p)(t_2)$$

Purchasing cost: The purchasing cost represents the expenditure incurred to procure the materials to meet the demand during stockout; the cost of purchasing the backordered items is taken as

$$PC = C_c D(p)(T - t_2)$$

Energy cost: Energy cost is incurred due to the operation of preservation technology used to control the deterioration of products, the cost of energy is calculated as below

$$EC = C_e \left(\int_0^{t_1} I(t) dt + \int_{t_1}^{t_2} I(t) dt \right) = C_e \left(\frac{(-D(p)+P) \left(t_1 + \frac{-1+e^{-t_1 \theta'}}{\theta'} \right)}{\theta'} + \frac{D(p) \left(-1+e^{\theta'(-t_1+t_2)} + \theta' t_1 - \theta' t_2 \right)}{\theta'^2} \right)$$

Carbon emission tax: Carbon emission cost is incurred due to environmental charges associated with energy consumption during preservation and a carbon cap to reduce the carbon is induced which is Z. therefore the carbon emission tax can be calculated as follows

$$CT = \varphi(CE(1 - \tau(1 - \text{Exp}[-\eta G_m])) - Z)$$

Where

$$CE = C_c \left(\int_0^{t_1} I(t) dt + \int_{t_1}^{t_2} I(t) dt \right) = C_c \left(\frac{(-D(p)+P) \left(t_1 + \frac{-1+e^{-t_1 \theta'}}{\theta'} \right)}{\theta'} + \frac{D(p) \left(-1+e^{\theta'(-t_1+t_2)} + \theta' t_1 - \theta' t_2 \right)}{\theta'^2} \right)$$

Thus, the total cost per unit time of the underlying unified inventory system during the cycle, is given by

$$CT = \varphi \left(C_c \left(\frac{(-D(p)+P) \left(t_1 + \frac{-1+e^{-t_1\theta'}}{\theta'} \right)}{\theta'} + \frac{D(p) \left(-1+e^{\theta'(-t_1+t_2)} + \theta' t_1 - \theta' t_2 \right)}{\theta'^2} \right) (1 - \tau(1 - \text{Exp}[-\eta G_m])) - Z \right)$$

Deterioration cost: Deterioration cost arises from the loss of product value caused by spoilage or decay over time. The cost of deterioration can be calculated as

$$\begin{aligned} DC &= C_d \left(\int_0^{t_1} \theta' I(t) dt + \int_{t_1}^{t_2} \theta' I(t) dt \right) \\ &= C_d \theta' \left(\frac{(-D(p)+P) \left(t_1 + \frac{-1+e^{-t_1\theta'}}{\theta'} \right)}{\theta'} + \frac{D(p) \left(-1+e^{\theta'(-t_1+t_2)} + \theta' t_1 - \theta' t_2 \right)}{\theta'^2} \right) \end{aligned}$$

Holding Cost: Holding cost represents the expense associated with storing inventory, including warehousing, handling, and insurance.

$$\begin{aligned} HC &= h \left(\int_0^{t_1} I(t) dt + \int_{t_1}^{t_2} I(t) dt \right) \\ HC &= h \left(\frac{(-D(p)+P) \left(t_1 + \frac{-1+e^{-t_1\theta'}}{\theta'} \right)}{\theta'} + \frac{D(p) \left(-1+e^{\theta'(-t_1+t_2)} + \theta' t_1 - \theta' t_2 \right)}{\theta'^2} \right) \end{aligned}$$

Preservation technology cost: Preservation technology cost includes the investment and operational expenses required to reduce the rate of deterioration, the cost of preservation technology is calculated as

$$PT = \alpha E_e D(p) T + C_f$$

Revenue: Revenue is generated from selling the product at a fixed selling price, proportional to the demand rate. Hence during the whole cycle, revenue generated is

$$R = p D(p) T$$

5. Solution procedure

Total profit per unit time is obtained by maximizing the net economic return, calculated as total sales revenue minus the combined effects of production, inventory holding, deterioration, preservation, energy consumption, and carbon emission costs. Hence the total profit can be calculated as

$$\begin{aligned} \Pi(p) = & \frac{1}{T} \left\{ pD(p)T - \left\{ C_o + C_p D(p)(t_2) + C_c D(p)(T - t_2) + (C_e + h + \right. \right. \\ & C_d \theta') \left(\frac{(-D(p)+P) \left(t_1 + \frac{-1+e^{-t_1 \theta'}}{\theta'} \right)}{\theta'} + \frac{D(p) (-1+e^{\theta'(-t_1+t_2)} + \theta' t_1 - \theta' t_2)}{\theta'^2} \right) + \\ & \varphi \left(C_c \left(\frac{(-D(p)+P) \left(t_1 + \frac{-1+e^{-t_1 \theta'}}{\theta'} \right)}{\theta'} + \frac{D(p) (-1+e^{\theta'(-t_1+t_2)} + \theta' t_1 - \theta' t_2)}{\theta'^2} \right) (1 - \tau(1 - \text{Exp}[-\eta G_m])) - \right. \\ & \left. \left. Z \right) + \alpha E_e D(p)T + C_f \right\} \end{aligned} \quad (7)$$

Here

$$\theta' = \theta f(E_e) = \theta e^{-\beta E_e}$$

And demand $D(p)$ is assumed to depend on the selling price and is represented using three alternative functional forms to capture different market behaviors:

1. Linearly price dependent Demand $D(p) = a - bp$, where a is the potential demand and $b > 0$. In this case Demand decreases linearly as price increases. This kind of demand is Suitable for competitive and mass-market products.

2. Exponential Demand $D(p) = Ae^{-Bp}$, where $A, B > 0$. Here demand decreases rapidly with price. It represents highly price-sensitive markets (e.g., luxury or digital goods).
3. Logarithmic Demand $D(p) = c - d\ln(p)$, where $c, d > 0$. In this case Demand decreases slowly with increasing price. It Reflects low price sensitivity and is Suitable for essential goods or premium branded products.

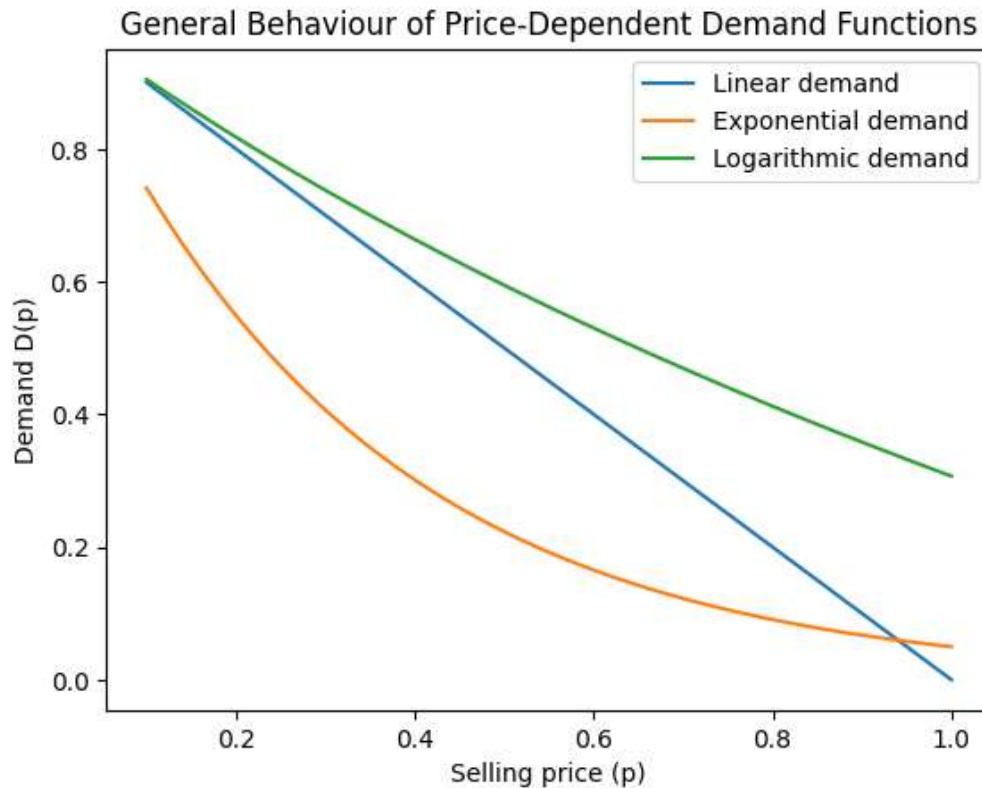


Figure 2: General Behaviour of Price-Dependent Demand Functions.

These demand functions allow a comparative analysis of how different pricing responses affect inventory performance and profitability.

Based on that the optimal profit function can be calculated for all three cases

Case 1: $\Pi_1(p)$; where $\frac{d\Pi_1(p)}{dp} = 0$ and $\frac{d^2\Pi_1(p)}{dp^2} < 0$

Case 2: $\Pi_2(p)$; where $\frac{d\Pi_2(p)}{dp} = 0$ and $\frac{d^2\Pi_2(p)}{dp^2} < 0$

Case 3: $\Pi_3(p)$; where $\frac{d\Pi_3(p)}{dp} = 0$ and $\frac{d^2\Pi_3(p)}{dp^2} < 0$

6. Numerical Analysis

Following parametric values have been considered to illustrate the problem :

$$C_f = 100, C_o = 80, T = 1.2, \alpha = 0.6, E_e = 5, C_c = 0.3, C_p = 6, t_2 = 0.7, \varphi = 0.4, Z = 300, \tau = 0.15, \eta = 0.12, h = 1.2, C_e = 0.6, C_d = 1.8, \theta = 0.01, \beta = 3$$

Example 1 (Case 1): for case 1 Initial Demand Coefficient a is taken as 100 and Price Sensitivity b is taken as 5. Using the above parametric values in the mathematical expressions we got the Optimal Total Profit: 800 \$ at Optimal selling price: 22. Convexity of the profit function has been shown in figure 3.

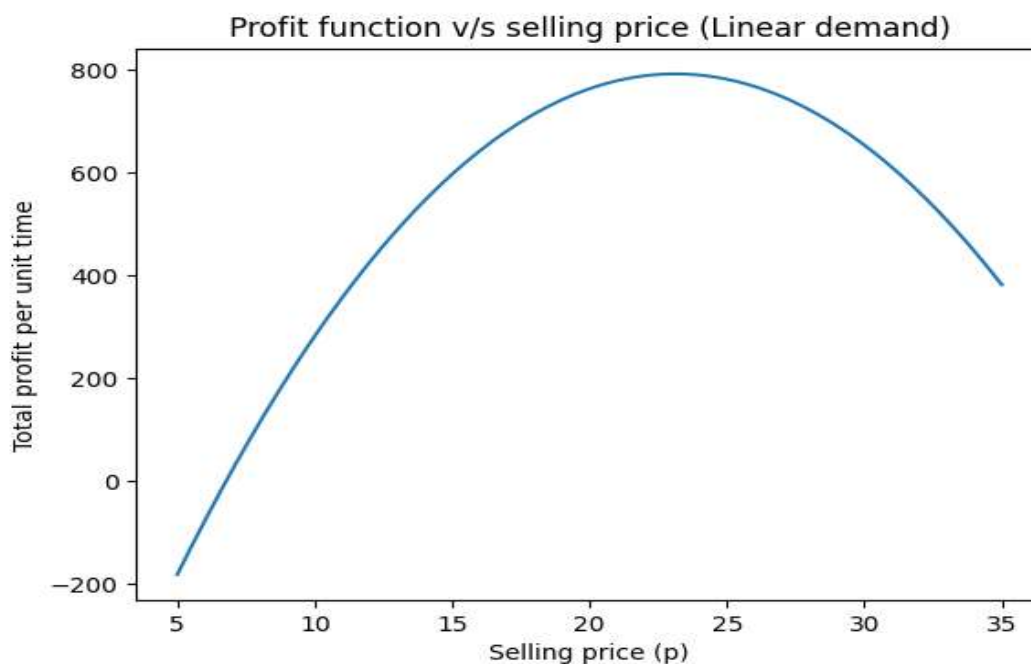


Figure 3: Convexity of the profit function for case 1.

Example 2 (Case 2: Exponential Demand Model): for case 2 Initial Demand Coefficient A is taken as 100 and Price Sensitivity B is taken as 0.1. Using the above parametric values in the mathematical expressions we got the Optimal Total Profit: 276.31 \$ at Optimal selling price 19.26. Convexity of the profit function has been shown in figure.

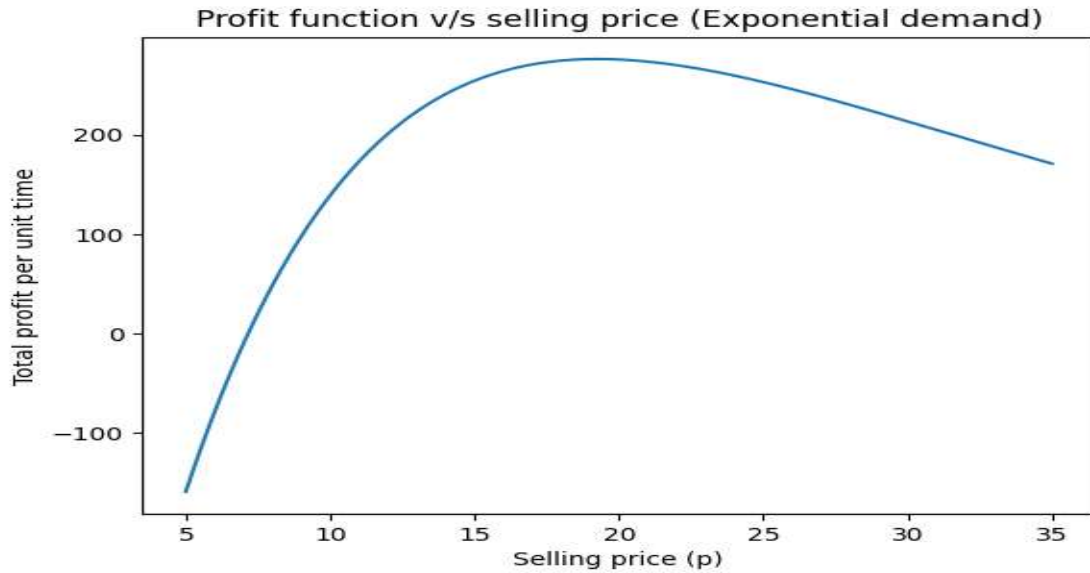


Figure 4: Convexity of the profit function for case 2

Example 3 (Case 3: Logarithmic Demand Model): for case 2 Initial Demand Coefficient c is taken as 120 and Price Sensitivity $d = 10$. Using the above parametric values in the mathematical expressions we got the Optimal Total Profit 5558.13 \$ at Optimal selling price 80. Convexity of the profit function has been shown in figure 5.

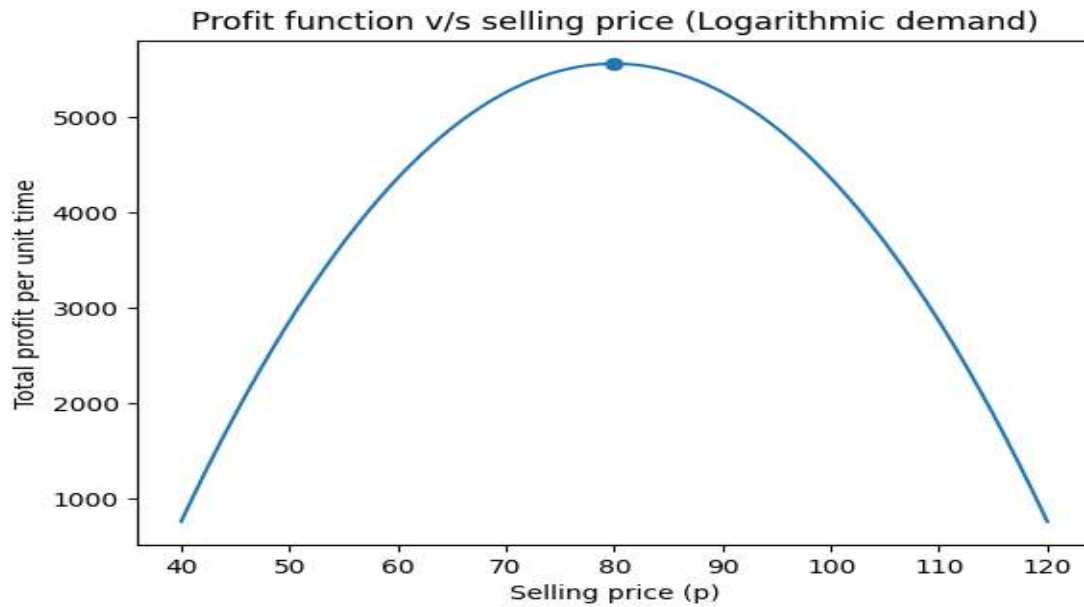


Figure 5: Convexity of the profit function for case.

7. Sensitivity analysis

Sensitivity analysis is performed to study the effect of key parameters on the optimal selling price and total profit, highlighting the robustness of the proposed model under cost and demand variations.

Table 1: Sensitivity analysis for case 1

	Parametric values	Optimal price	profit
Holding Cost	0.8	23.05	804.46
	1.2	23.12	790.94
	1.6	23.19	778.74
	2.0	33.10	1381.23

Price Sensitivity	3.0	23.12	790.94
Parameter b	4.0	18.15	500.77
Energy Cost C_e	0.4	23.09	799.55
	0.6	23.12	790.94
	0.8	23.17	782.88
Carbon Emission Cost Factor C_c	0.2	23.12	792.87
	0.3	23.12	790.94
	0.4	23.14	789.03

Table 2: Sensitivity analysis for case 2

	Parametric values	Optimal price	profit
Holding Cost	0.8	19.05	285.98
	1.2	19.26	276.31
	1.6	19.44	267.65
Price Sensitivity	0.05	26.58	585.25
Parameter b	0.08	19.26	276.31
	0.12	15.38	119.23
Energy Cost C_e	0.4	19.13	282.47
	0.6	19.26	276.31
	0.8	19.38	270.59
Carbon Emission Cost Factor C_c	0.2	19.23	277.69
	0.3	19.26	276.31
	0.4	19.28	274.96

Table 3: Sensitivity analysis for case 3

	Parametric values	Optimal price	profit
Holding Cost	0.8	80	5574.71
	1.2	80	5558.13
	1.6	80	5543.16
Price Sensitivity Parameter b	6	80	6855.79
	10	80	5558.13
	14	80	4262.56
Energy Cost C_e	0.4	80	5568.69
	0.6	80	5558.13
	0.8	80	5548.24
Carbon Emission Cost Factor C_c	0.2	80	5560.50
	0.3	80	5558.13
	0.4	80	5555.79

8. Observations

The following observations are found from above table-

- Price sensitivity has the strongest impact on both optimal selling price and maximum profit in all cases.
- The exponential demand case is the most sensitive to parameter changes and shows the sharpest decline in profit with increasing price sensitivity.
- In the linear demand case, profit and optimal price decrease moderately as price sensitivity increases.
- The logarithmic demand case shows high pricing stability, with minimal change in optimal price across parameter variations.
- Increasing holding cost reduces maximum profit in all cases, but its effect on optimal selling price is marginal.

- Higher energy cost due to preservation technology leads to a gradual decline in profit, with a slight upward shift in optimal price.
- Carbon emission cost negatively affects profit levels but has little influence on optimal pricing decisions.
- Among all cases, the logarithmic demand structure yields the highest and most stable profit, making it more robust under cost and environmental uncertainty.
- Overall, demand structure plays a more critical role than cost parameters in determining pricing robustness.

9. Conclusions

This study developed an EPQ-based inventory model for deteriorating items by integrating preservation technology, carbon emission cost, and price-dependent demand. Three demand structures—linear, exponential, and logarithmic—were analyzed to capture different market behaviors and their impact on pricing and profitability. The profit function was derived for each case and optimized with respect to the selling price, and concavity was analytically and numerically verified, ensuring the existence of a unique optimal solution. Numerical analysis and sensitivity results reveal that price sensitivity plays a dominant role in determining both optimal price and profit, while operational costs such as holding, energy, and carbon emission costs mainly affect profit levels rather than pricing decisions. Among the three demand structures, logarithmic demand provides the highest and most stable profit, demonstrating greater robustness to cost and environmental variations, whereas exponential demand exhibits the highest vulnerability to parameter changes.

The findings offer valuable managerial insights for designing effective pricing and inventory policies in environments characterized by deterioration and sustainability concerns. The proposed framework can be extended in future research by incorporating stochastic demand, government incentives for green technologies, or multi-echelon supply chain structures.

Declaration of Competing Interest: The authors declare that they have no known competing financial interests

or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability: No additional data has been used in the proposed research.

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