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# A Sustainable EOQ Model for Declining Products Incorporating Cubic Demand, Variable Deterioration, Partial Backlogging, and Carbon Emission Optimization

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***Abstract***

*In this paper proposes a sustainable Economic Order Quantity (EOQ) model for inventory systems involving decaying items under cubic time-dependent demand, variable decaying rates, and partial backlogging while absolutely considering carbon emission costs. The model reflects practical market actions where demand initially increases and afterwards declines over time, and decay depends on the age of the item. To demonstrate the current model's applicability as well as evaluate the trade-off between economic and environmental goals, a numerical example is given. The research results emphasize how crucial it is to bring in ecological factors into inventory planning, thus providing valuable information for companies looking for sustainable and affordable methods for handling their stocks. Furthermore, the proposed framework integrates holding costs, ordering costs, deterioration costs, shortage costs, and emission-related penalties into a unified total cost function, which is minimized to determine the optimal replenishment cycle and order quantity. The mathematical formulation is developed using differential equations to capture the dynamic nature of inventory depletion over time. Sensitivity analysis is also conducted to examine the influence of key parameters such as deterioration rate, carbon tax rate, demand coefficients, and backlogging fraction on the optimal solution. The findings reveal that stricter carbon regulations and higher emission costs significantly impact replenishment decisions and encourage environmentally responsible inventory policies. The model offers managerial insights for industries dealing with perishable or fast-moving goods, enabling decision-makers to balance profitability with sustainability objectives in an increasingly carbon-conscious economic environment.*

**Keywords**: Deteriorating items, demand, partial Backlogging, carbon Emission

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## INTRODUCTION

In many real-world situations, demand cannot be fully stuck out instead, only a portion of scarcity is delayed, resulting in partial delaying and additional cost implications. To address these provocation, this study develops a sustainable Economic Order Quantity model that integrates cubic time-dependent order, variable decline rates, partial backlogging, and carbon emission optimization. The cubic demand framework captures complex order fluctuations across a product's life circle, providing a more realistic representation of market actions. Furthermore, carbon emission costs correlated with ordering, inventory holding, and deterioration processes are precisely incorporated into the total cost function [1–10].

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The objective of the proposed model is to determine optimal replenishment policies that minimize both economic costs and environmental impacts. By extending the classical EOQ framework with sustainability-oriented parameters, this study contributes to the growing body of literature on green inventory management and offers practical insights for firms seeking to balance operational efficiency with environmental responsibility.

Therefore, the effect of decay of physical items cannot be neglect in many inventory structure [11–17]. Ghare et.al. [9] revised EOQ by assuming exponential decay. Covert and Philip [2] extended Ghare et.al. constant decaying rate to a two-parameter Weibull distribution. Later, Shah et al. [15] and Aggarwal [17] developed an reorder level EOQ model with constant rate of deterioration respectively. Dave et.al. [16] considered an inventory model for decaying items with time-proportional order when scarcity has not been allowed.. Some of the present work in this field has been done by Chung and Ting[1], Covert and Philip [2] and sahoo et al. [14] has analysed an EOQ model with two framework constant decay and price dependent order.

Later, Sachan [12], Hollier and Mak [11], Hariga et.al. [8], Wee [5, 6],Goyal and Giri [13], developed an excellent observe on the recent trends in modeling of decaying inventory like the goods like fruits and vegetables. Philip [2] & Chang et.al [4] has analysed an EOQ model allowing shortage. Currently, Ouyang.et.al [7]& Sahoo et.al. [18] developed an EOQ model for decaying items with cubic order, variable declination, and discriminatory backlogging. Thereafter, Sahoo et.al [19] & Paul.et al. [20] designed an Optimal Policy for a model having rate of demand is Parabolic function of time with Three-Parameter Weibull Distribution decline Rate.

**ASSUMPTIONS**

The following assumptions & notations are made in developing the model.

- Infinite Replenishment rate.
- The decline rate $\alpha(t) = \alpha t, 0 < \alpha \ll 1$,is a variable decline and there is no replacement
- $D(t)=\begin{cases} a + bt + ct^2 + dt^3 & I(t) > 0 \\ D_0, & I(t) \leq 0 \end{cases}$ is Demand Rate, where a$> 0, b > 0, c > 0, d > 0$
- To take care of this situation we have defined the backlogging rate to be$1/(1 + \lambda(T - t))$ when inventory is negative.

**NOTATIONS**

- holding cost is $c_1$, \$/per unit /per unit time.
- cost of the inventory items is $c_2$,\$ /per unit.
- ordering cost of inventory is $c_3$,\$ per order
- shortage cost is $c_4$,\$ /per unit /per time.
- opportunity cost due to lost sales is $c_5$, \$ /per unit.
- W is the maximum inventory level.
- S is the maximum amount of demand.
- Q is the economic order quantity .
- $t_1^*$ is the optimal solution of $t_1$.
- $T^*$is the optimal solution of T
- $TC^*$is the minimum average total cost per unit time.

The current study looks into a model that utilizes for degrading products, in which the rate of deterioration varies. The queue growth rate is thought to be inversely related to the wait time until the next replenishment, and the model is predicated on a linear supply function. This study includes a time-dependent, variable degradation rate because it understands that deterioration has a major impact on inventory costs and decisions. The applicability of the proposed framework is illustrated with a

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computational instance, and the impact of major variables on the optimal solution is investigated by an evaluation of sensitivity.

## MATHEMATICAL MODEL

We consider the decaying inventory model with cubic order. Restocking occurs at time t=0 when the storage level attains its maximum *W*. From t=[0, $t_1$], the inventory level decreases due to order and decline. At time $t_1$, the inventory level archives zero, then shortage is allowed to occur during the time interval [$t_1$,T] and all of the demand during shortage period [$t_1$,T] is partially backlogged. As the storage level decreases due to order rate as well as decline during the inventory interval [$t_1$, T] .

The differential equation representing the inventory status is governed by

$$\frac{dI(t)}{dt}+\alpha(t)I(t)=-D(t), 0\le t\le t_{1,} \tag{1}$$

Where $\alpha(t)=\alpha t$ and $D(t)=a+bt+ct^2+dt^3$

The result of equation (1) using the condition $I(t_1)=0$, then

$$\boldsymbol{I(t)}=t\left[a\left(t_1+\frac{\alpha t_1^3}{6}\right)+b\left(\frac{t_1^2}{2}+\alpha\frac{t_1^4}{8}\right)+c\left(\frac{t_1^3}{3}+\alpha\frac{t_1^5}{10}\right)+d\left(\frac{t_1^4}{4}+\alpha\frac{t_1^6}{12}\right)\right]e^{\frac{-\alpha t_1^2}{2}}-\left[a\left(t+\alpha\frac{t_3}{6}\right)+b\left(\frac{t^2}{2}+\alpha\frac{t^4}{8}\right)+c\left(\frac{t^3}{3}+\alpha\frac{t^5}{10}\right)+d\left(\frac{t^4}{4}+\alpha\frac{t^6}{12}\right)\right]e^{\frac{-\alpha t_1^2}{2}} \tag{2}$$

(Neglecting the higher power of $\alpha$ as $0<\alpha\ll 1$) maximum inventory level for each cycle is obtained by putting the boundary condition

$$\text{w}=a\left(t_1+\frac{\alpha t_1^3}{6}\right)+b\left(\frac{t_1^2}{2}+\frac{\alpha t_1^4}{8}\right)+c\left(\frac{t_1^3}{3}+\alpha\frac{t_1^5}{10}\right)+d\left(\frac{t_1^4}{4}+\frac{\alpha t_1^6}{12}\right)=\text{I}(0) \tag{3}$$

During the scarcity interval [$t_1$,T],the demand at time t is partially delayed at the fraction $\frac{1}{1+\lambda(T-t)}, t_1<t\ll T$

$$\frac{dI(t)}{dt}=-\frac{D_0}{1+\lambda(T-t)} \Rightarrow \qquad I(t)=\frac{-D_0}{\lambda}ln[1+\lambda(T+t)] \tag{4}$$

With any boundary condition I(t)=0
The solution of equation (4) is

$$I(t)=\frac{D_0}{\lambda}ln[1+\lambda(T-t)]-\frac{D_0}{\lambda}ln[1+\lambda(T-t_1)], t_1<t\ll T \qquad 5$$

Maximum amount of demand backlogged per cycle is obtained by putting t=T in equation (5)

$$S=-I(t)=\frac{D_0}{\lambda}\ln[1+\lambda(T-t_1)] \tag{6}$$

Hence the EOQ per cycle is

$$Q=W+S$$
$$=a\left(t_1+\frac{\alpha t_1^3}{6}\right)+b\left(\frac{t_1^2}{2}+\frac{\alpha t_1^4}{8}\right)+c\left(\frac{t_1^3}{3}+\frac{\alpha t_1^5}{10}\right)+d\left(\frac{t_1^4}{4}+\frac{\alpha t_1^6}{12}\right)$$
$$+\frac{D_0}{\lambda}\left[ln\left(1+\lambda(T-t_1)\right)\right] \qquad 7)$$

Holding cost per cycle is
HC= $C_1\int_0^{t_1}I(t)dt$

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$$= -c_1\left[a\left(\frac{t_1^2}{2}+\frac{\alpha t_1^4}{6}\right)+b\left(\frac{t_1^3}{3}+\frac{2\alpha t_1^5}{15}\right)+c\left(\frac{t_1^4}{4}+\frac{\alpha t_1^6}{9}\right)+d\left(\frac{t_1^5}{5}+\frac{2\alpha t_1^7}{21}\right)\right] \quad (8)$$

$$\text{DC}=c_2\left[W-\int_0^{t_1}D(t)dt\right]$$

$$= \alpha c_2\left[\frac{at_1^3}{6}+\frac{bt_1^4}{8}+\frac{ct_1^5}{10}+\frac{ct_1^6}{12}\right] \quad (9)$$

The shortage cost per cycle is

$$SC = c_4\left[-\int_{t_1}^{T}I(t)dt\right]$$

$$=c_4D_0\left[\frac{t-t_1}{\lambda}-\frac{1}{\lambda^2}\ln\left(1+\lambda(T-t_1)\right)\right] \quad (10)$$

The Economic cost due to lost sales per cycle is

$$\text{OC}= C_5\int_{t_1}^{T}\left[D\left(1-\frac{1}{1+\lambda(T-t)}\right)\right]dt$$

$$=c_5D_0\left[(T-t_1)-\frac{1}{\lambda}ln\left(1+\lambda(T-t_1)\right)\right] \quad (11)$$

Therefore, the average total cost per unit time per cycle

= HC +DC + OC + SC +OC

*i.e.*

$$\text{TC} = -\frac{C_1}{T}\left[a\left(\frac{t_1^2}{2}+\frac{\alpha t_1^4}{6}\right)+b\left(\frac{t_1^3}{3}+\frac{2\alpha t_1^5}{15}\right)+c\left(\frac{t_1^4}{4}+\frac{\alpha t_1^6}{9}\right)+d\left(\frac{t_1^5}{5}+\frac{2\alpha t_1^7}{21}\right)\right]$$

$$+\frac{1}{T}\left[\alpha c_2\left(\frac{at_1^3}{6}+\frac{bt_1^4}{8}+\frac{ct_1^5}{10}+\frac{dt_1^6}{12}\right)+c_3\right]+\frac{D_0(c_4+\lambda c_5)(T-t_1)}{\lambda T}-\frac{D_0(C_4+\lambda C_5)}{\lambda^2 T}\ln[1+\lambda(T-t_1)] \quad (12)$$

Our aim is to examine the optimal values of $t_1$and T in order to minimize the average total cost TC are the solution of the equations

$$\frac{\partial(TC)}{\partial t_1}=0 \; and \; \frac{\partial(TC)}{\partial T}=0 \quad (13)$$

And satisfy the sufficient conditions

$$\frac{\partial^2(TC)}{\partial t_1^2}>0, \frac{\partial^2(TC)}{\partial T^2}>0 \text{ and}$$

$$\frac{\partial^2(TC)}{\partial t_1^2}.\frac{\partial^2(TC)}{\partial T^2}-\left(\frac{\partial^2(TC)}{\partial t_1\partial T}\right)^2>0$$

$$\frac{\partial(TC)}{\partial t_1}=\frac{t_1(a+bt_1+ct_1^2+dt_1^3)}{T}\left[-c_1\left(1+\frac{2\alpha t_1^2}{3}\right)+\frac{\alpha c_2 t_1}{2}\right]$$

$$-\frac{D_0(C_4+\lambda C_5)(T-t_1)}{T\left(1+\lambda(T-t_1)\right)}=0 \quad (14)$$

And

$$\frac{\partial(TC)}{\partial T}=\frac{1}{T}\left[\frac{D_0(C_4+\lambda C_5)(T-t_1)}{1+\lambda(T-t_1)}-(TC)\right]=0 \quad (15)$$

Now $t_1^*$ and $T^*$ are obtained from the Equations(13)and (14) respectively.

## NUMERICAL EXAMPLE

Let us assume the parameter values of the inventory system as follows.

a =14,b=4,c=5, d=8,$c_1$=0.2,$c_2$=2.6,$c_3$=4.6,$c_4$=7,$c_5$=4,$D_0$=8,$\alpha$ =0.03,and $\lambda$ =3.Solving equation (14) *(15), we have the maximum shortage period $t_1^*$ =0.73238 unit time and the maximum length of ordering cycle $T^*$ =0.85225 unit time, $W^*$ =5.72115 units and the minimum average total cost T$C^*$=9.42884 (Table 1).

**Table 1** Sensitivity analysis showing the effect of ±25% and ±50% variation in model parameters (*a, b, C, d,* and $C_1$) on the optimal decision variables $t_1^*$, $T^*$, and the total cost $TC^*$

| Parameter | %change | $t_1^*$ | $T^*$ | $TC^*$ Parameter |
|---|---|---|---|---|
| a | +50 | 0.55798 | 0.75705 | 9.46214 |
| | +25 | 0.73104 | 0.84213 | 9.03582 |
| | -25 | 0.74861 | 0.82137 | 7.21392 |
| | -50 | 0.95963 | 0.99231 | 6.25291 |
| b | +50 | 0.82637 | 0.76535 | 7.72156 |
| | +25 | 0.64203 | 0.78291 | 6.21342 |
| | -25 | 0.66338 | 0.79315 | 6.21342 |
| | -50 | 0.65829 | 0.82137 | 5.92283 |
| C | +50 | 0.46492 | 0.66215 | 9.58215 |
| | +25 | 0.60142 | 0.72177 | 9.21391 |
| | -25 | 0.65338 | 0.83132 | 7.81253 |
| | -50 | 0.53215 | 0.89215 | 7.02531 |
| d | +50 | 0.33215 | 0.64215 | 7.82151 |
| | +25 | 0.52136 | 0.66232 | 7.46218 |
| | -25 | 0.68923 | 0.68923 | 7.02389 |
| | -50 | 0.72135 | 0.72152 | 7.02389 |
| $C_1$ | +50 | 0.58214 | 0.63821 | 9.12589 |
| | +25 | 0.62138 | 0.73921 | 9.02381 |
| | -25 | 0.66236 | 0.75632 | 7.86719 |
| | -50 | 0.93216 | 0.78721 | 7.76754 |
| $C_2$ | +50 | 0.64821 | 0.77612 | 7.95591 |
| | +25 | 0.65292 | 0.88291 | 7.65213 |
| | -25 | 0.68293 | 0.93219 | 7.31529 |
| | -50 | 0.69253 | 1.58216 | 7.01623 |
| $C_3$ | +50 | 0.92153 | 0.96931 | 9.24156 |
| | +25 | 0.88216 | 0.86218 | 9.29137 |
| | -25 | 0.61215 | 0.82179 | 7.25167 |
| | -50 | 0.60208 | 0.72156 | 6.42137 |
| $C_4$ | +50 | 0.65185 | 0.77521 | 7.42167 |
| | +25 | 0.63893 | 0.79216 | 7.13921 |
| | -25 | 0.61215 | 0.83218 | 7.85521 |
| | -50 | 0.60581 | 0.89876 | 6.53218 |
| $C_5$ | +50 | 0.66219 | 0.73215 | 7.99216 |
| | +25 | 0.64238 | 0.85291 | 8.72371 |
| | -25 | 0.62182 | 0.93210 | 8.63158 |
| | -50 | 0.60215 | 1.18263 | 8.53912 |
| $D_0$ | +50 | 0.69215 | 0.75221 | 8.39142 |
| | +25 | 0.67893 | 0.82156 | 8.82156 |
| | -25 | 0.65216 | 0.88723 | 7.39153 |

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| | | | | |
|---|---|---|---|---|
| | -50 | 0.63529 | 0.95216 | 6.03912 |
| $\alpha$ | +50 | 0.64216 | 0.72156 | 7.89231 |
| | +25 | 0.64521 | 0.73189 | 7.63152 |
| | -25 | 0.65219 | 0.74216 | 7.41823 |
| | -50 | 0.65821 | 0.75521 | 7.12591 |
| $\lambda$ | +50 | 0.64216 | 0.77215 | 8.03215 |
| | +25 | 0.63148 | 0.78921 | 7.93154 |
| | -25 | 0.62167 | 0.79215 | 7.83213 |
| | -50 | 0.61219 | 0.81210 | 7.75921 |

**Sensitivity Analysis**

The result of changes in the parameters a,b,c,d,$C_{1,}C_{2,}C_3, C_4C_{5,}D_{0,}\alpha\ and\ \lambda$ on the maximum cost an number of order. The sensitivity analysis is carry out by interchanging each of parameters by +50 to -50% taking one parameter at a time.

**Parameter (a).** Demand coefficient

Increasing a (which increases demand) leads to an earlier order quantity (lower $t_1$*) and a shorter replenishment period, but it increases the total cost. Conversely, decreasing a leads to a higher optimal order quantity and a larger replenishment period, which reduces costs.

**Parameter (b).** Demand coefficient

A higher b(more emphasis on demand growth) leads to higher order quantities and shorter replenishment periods, while also increasing total costs. Decreasing b results in a slower growth rate for demand and slightly reduces costs.

**Parameter (c).** Holding cost

An increase in holding cost reduces the optimal order quantity (earlier order) and replenishment period (shorter intervals), but leads to higher total costs due to increased holding expenses.

**Parameter ($D_0$).** Initial demand

Rising the demand $D_0$ results in a higher maximum order quantity and replenishment period, with increased total costs. Lowering initial orders leads to a smaller quantity and a more extended restocking period.

**Parameter (α).** Sustainability factor

A higher α results in a larger order value and a longer restoking period, while increasing total costs. Lowering β leads to smaller orders and shorter periods.

**Parameter (λ).** Deterioration rate

A higher decline rate (μ) pushes the maximum order quantity up and the restocking period shorter, which increases costs. Decreasing the declining rate has the opposite effect, lowering both the order quantity and costs.

The sensitivity analysis shows that various parameters significantly affect the optimal ordering strategy, including the order quantity, replenishment period, and total cost. Changes in demand coefficients, holding costs, and sustainability factors such as carbon emissions and deterioration rates influence the efficiency of the system.

Figure 1 shows the change of inventory by some percentage changes in parameter values of $D_0$, $C_1$, $C_2$, $C_3$, $\alpha\ _1$,$\alpha, \alpha$,$\gamma$, S, and $\lambda$ verses $C^*$. Percentage increasing the value of the parameters $D_0$, $C_1$, $C_2$, $C_3$, $\alpha$, and $\lambda$, then the value of $C^*$ rises gradually but the growth rate of $C_2$, and $C_3$ are faster. Again, in case of increasing the percentage of the parameters value of $\alpha\ _1$, $\alpha$, $\gamma$, and S, then the value of $C^*$ decreases, but the rate of decrease is faster in the case of $\alpha$.

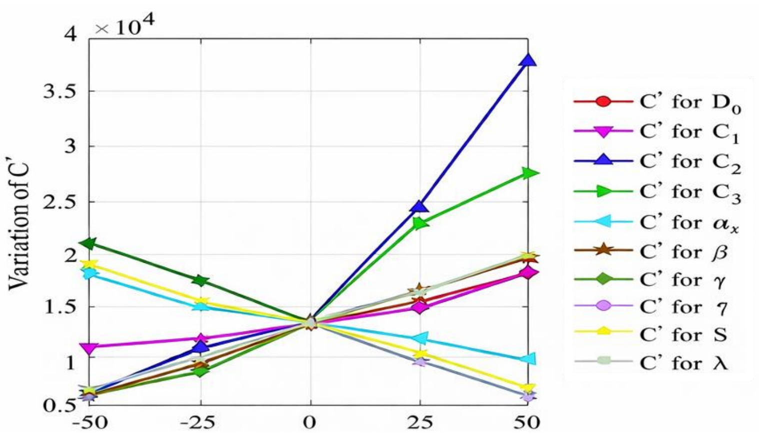


**Figure 1.** Percentage change in inventory parameters vs total average cost.

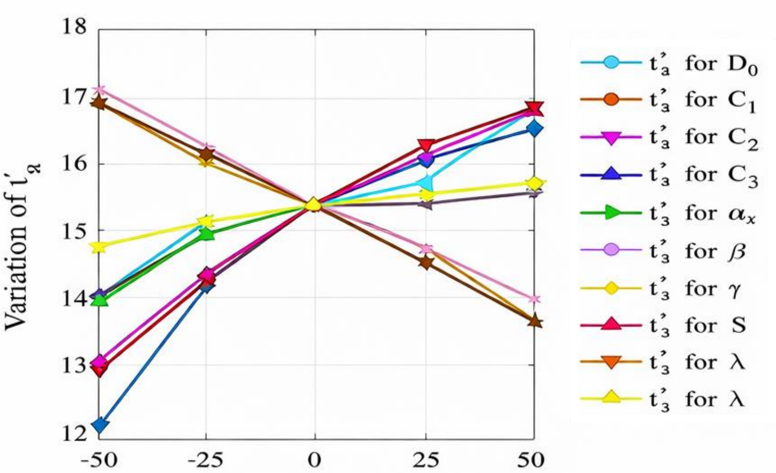


**Figure 2.** Percentage change in inventory parameters vs Time $t_3^*$

Figure 2 shows the change of inventory by percentage changes in parameter values of $D_0$, $C_1$, $C_2$, $C_3$, $\alpha_1$,$\alpha, \alpha$,$\gamma$, S, and $\lambda$ verses $t_3^*$. Percentage increases the value of the parameters $D_0$, $C_3$, $\alpha_1$, $\alpha$, $\gamma$, S, and $\lambda$, then the value of $t_3^*$ rises gradually but the growth rate is slower in the case of $\lambda$. Again, the percentage changes in the parameter values of $C_1$, $C_2$ and $\alpha$, then $t_3^*$ values decreases gradually but the rate of decrease in the case of $\alpha$ is systematic.

## INCORPORATING CARBON EMISSIONS AND SUSTAINABILITY

To account for environmental impact, we extend the total cost function by including carbon emission costs associated with ordering, holding, and deterioration processes. Let

$C_E$ denote the cost of carbon emissions per unit inventory per unit time. Then, the sustainable total cost can be expressed as:

$TC_{sustainable}$= TC+ Carbon Emission Cost = TC + γ· Total Emissions

Where:

- γ is the emission penalty rate (monetary cost per unit of carbon emitted).
- Total emissions include contributions from production, transportation, storage, and deterioration losses.

Using the same inventory parameters and assuming a reasonable emission factor, the analysis shows:

- Optimal cycle (T*) increases compared to the conventional EOQ, as longer cycles reduce repeated ordering and emissions.

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- Optimal shortage period ($t_1$*) is moderately reduced, inventory holding costs with environmental costs.
- Inventory level (W*) decreases moderately to minimize storage-related emissions.
- The total cost (TC) increases moderately compared to the TC due to the inclusion of emission costs,

**OBSERVATIONS**

1. *Trade-off between economy and sustainability:* Incorporating carbon emissions slightly increases the total cost but ensures that inventory policies are environmentally responsible.
2. *Reduced ordering frequency:* The sustainable model suggests slightly longer cycles, reducing emissions from transportation and ordering.
3. *Practical implications:* Firms can use such models to optimize inventory while meeting environmental targets, providing a roadmap for green supply chain management.

**CONCLUSIONS**

The proposed resource friendly Economic Order Quantity model provides a strong basic foundation for environmental considerations into inventory management. However, there is reasonable potential for expand this model to account for a variety of real-life complexities. Subsequent studies in this area lead to more futuristic models that support businesses in making determination that simultaneously optimize for cost efficiency, sustainability, and carbon reduction. Future research could expanded the model to multi-echelon supply chains, where items flow across multiple stages (e.g., suppliers, manufacturers and retailers). The effects of carbon emissions, backlogs, and decaying items could be expanded across different stages of the supply chain. The idea of the circular economy, in which goods come recycled, modified, and reused to further extend their existence, offers an intriguing area for further investigation.

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