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Inventory control of deteriorating items: A review

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C H R O N I C L E

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A B S T R A C T

This paper presents a literature review for inventory control of deteriorating items since 2018. A classification including 18 classes and 33 subclasses is offered to categorize inventory control models, constraints, and solution methods used in previous studies. Providing standard classes in this field, such as demand, deterioration, shortages, number of warehouses, and time value of money alongside new classes, for example, the type of model costs and supply chain, inventory constraints, number of supply chain levels, time horizon, lead time, considering multi-item models, preservation technology, financial conditions, non-instantaneous deteriorating items, environmental issues, and solution methods made this classification more comprehensive. A brief history and explanation are given to understand each class better, and related articles are grouped in these classes. The research gaps and a crucial aspect that paves the way for future research are presented in each category. A broad view of the future of this topic is provided, and exciting opportunities are highlighted for researchers to contribute to this field and inspire them to explore these potential areas of research. The potential for future research in this subject is vast and promising; this article offers numerous opportunities for researchers to make significant contributions. The results show that the best ways to extend this topic are using variable deterioration rates, costs, and demand functions, considering realistic assumptions, including allowable shortages with partial backlogging, two warehouses, inflation and discounts, preservation technology, uncertain lead time, and environmental issues. Developing cyclic (if possible), multi-item, and production models with financial conditions and various inventory constraints is an excellent way to develop existing models. Finally, solving the proposed models using exact methods to find the global answer is a great effort to contribute to this field.

1. Introduction

A large number of articles are published every year on inventory control of deteriorating items, which shows the interest of researchers in this field. Therefore, the literature review of this topic is vital in establishing a roadmap for researchers. Some expert researchers did this task periodically (Janssen et al., 2016; Khanlarzade et al., 2014; Li et al., 2010; Mirabelli & Solina, 2022). However, some of these studies are more significant and will be discussed. (Nahmias, 1982) was the first to provide a systematic classification in this field, bringing clarity and organization to the review. He reviewed the ordering policies for perishable inventories and classified the existing articles into two main classes, including fixed and random lifetimes and several sub-classes. About one decade later, Raafat (1991) presented a complete review of the mathematical modeling for deteriorating items inventory systems. He provided a better classification than previous work, but the articles he reviewed were about half that Nahmias did. Ten years later, one of the best review articles in this field was presented by Goyal and Giri (2001). They described some main phrases and helped other researchers better understand this subject. They classified the articles since the early 1990s mainly by the shelf-life characteristic of the inventoried items and some other conditions and constraints. It took another decade for a noteworthy review in this field to come out. Bakkar et al. (2012) used the classification

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of Goyal and Giri but changed the ordering and reviewed over 200 articles contributed to this subject. Classification of the journals and publications was the notable aspect of their work. Chaudhary et al. (2018) reviewed over 400 papers; however, about half of these works were newer than 2012. They provided more sub-classes than previous works, contributed to the classification, and brought new classes and aspects. Table 1 provides brief information about these articles.

Based on researchers' attention to inventory control of deteriorating items, the high importance of this field in real-world problems and modern financial markets, the passage of six years since the last landmark review article, and the publication of about 300 articles, the necessity of presenting a comprehensive and complete review study is clear.

In this article, we studied previous classifications, rearranged them, added new aspects and conditions, and provided a new and comprehensive classification to review more than 300 articles published in inventory control of deteriorating items since 2018.

Table 1
Brief details on deteriorating items inventory control review articles

Reference	classes	sub-classes	number of reviewed papers	Publish year	investigated publication years
(Nahmias, 1982)	2	9	130	1982	Since 1967
(Raafat, 1991)	8	15	70	1991	Since 1982
(Goyal & Giri, 2001)	8	7	130	2001	Since the early 1990s
(Bakker et al., 2012)	9	11	241	2012	Since 2001
(Chaudhari et al., 2018)	5	17	418	2018	Since 1990
This paper	18	32	302 (200 in table)	2024	Since 2018

2. Methodology

Our purpose in this study is to review the published articles on inventory control of deteriorating items, so we used the phrase "deteriorate" (to make sure we do not miss main words such as deteriorating, deterioration, and deteriorate) in the advanced Google Scholar search and selected "since 2018" in the year section (the basis of our work is the citation year). We investigated over 30 pages in search results and collected about 300 related articles. We ignored irrelevant works by scanning the title and abstract and reached the point where the number of associated papers was negligible. Some reviewed articles did not finish the publication process at the time, but the online version was available. The following sub-sections present the search results according to the publication year and journal.

2.1 The publication year

In this part, we sorted the articles by year; Table 2 and Fig 1 show the results.

Table 2
Publication years of the reviewed articles

year	2018	2019	2020	2021	2022	2023	2024
number of papers	51	59	48	29	19	7	34
Percentage(%)	20.65	23.89	19.43	11.74	7.69	2.83	13.77

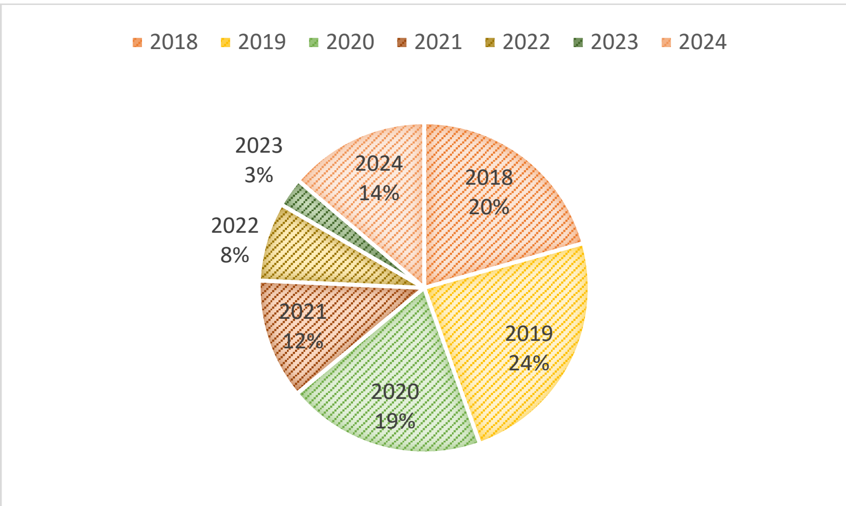

Fig. 1. Publication years of the reviewed articles

One reason for the decrease in studies between 2021 and 2023 is the outbreak of the COVID-19 pandemic and the researchers' attention to issues related to this disease. Also, related articles with different keywords may have been published in these years but were not reviewed in this article. The general trend shows that many articles are published on this topic every year, and the number of articles published in recent years has increased, which emphasizes the interest of researchers in this subject literature.

2.2 The publication journal

This section examines which journals have contributed the most to this topic in recent years. This helps researchers to find the proper journal for their consideration. Table 3 and Fig 2 show the results.

Table 3
Publication journals of the reviewed articles

Journal	Number of Articles	Percentage (%)	Journal	Number of Articles	Percentage (%)
RAIRO-Operations Research	14	5.67	Journal of Management Analytics	3	1.21
Opsearch	13	5.26	Kybernetes	3	1.21
Journal of Cleaner Production	11	4.45	Soft Computing	3	1.21
International Journal of Systems Science: Operations & Logistics	11	4.45	Computers & Operations Research	2	0.81
Annals of Operations Research	9	3.64	Environment, Development and Sustainability	2	0.81
Computers & industrial engineering	8	3.24	International Journal of Management Science and Engineering Management	2	0.81
International Journal of Mathematics in Operational Research	7	2.83	International Journal of Production Research	2	0.81
International journal of procurement management	7	2.83	International Journal of Supply and Operations Management	2	0.81
International Journal of Production Economics	7	2.83	Journal of Research Administration	2	0.81
International Journal of Applied and Computational Mathematics	6	2.43	Mathematical and Computer Modelling of Dynamical Systems	2	0.81
Journal of Industrial & Management Optimization	6	2.43	Neural Computing and Applications	2	0.81
Alexandria Engineering Journal	5	2.02	Omega	2	0.81
International Journal of Logistics Systems and Management	5	2.02	Operations and Supply Chain Management: An International Journal	2	0.81
Mathematics	5	2.02	Operations Research	2	0.81
Operational Research	5	2.02	Optimization and inventory management	2	0.81
Journal of Industrial Engineering International	4	1.62	Sādhanā	2	0.81
Journal of the Operational Research Society	4	1.62	Supply Chain Analytics	2	0.81
Applied Mathematical Modelling	3	1.21	Transportation Research Part E: Logistics and Transportation Review	2	0.81
International Journal of System Assurance Engineering and Management	3	1.21	Other (72 journals which published only one article)	72	29.15
Journal of Industrial and Production Engineering	3	1.21	Total	247	100

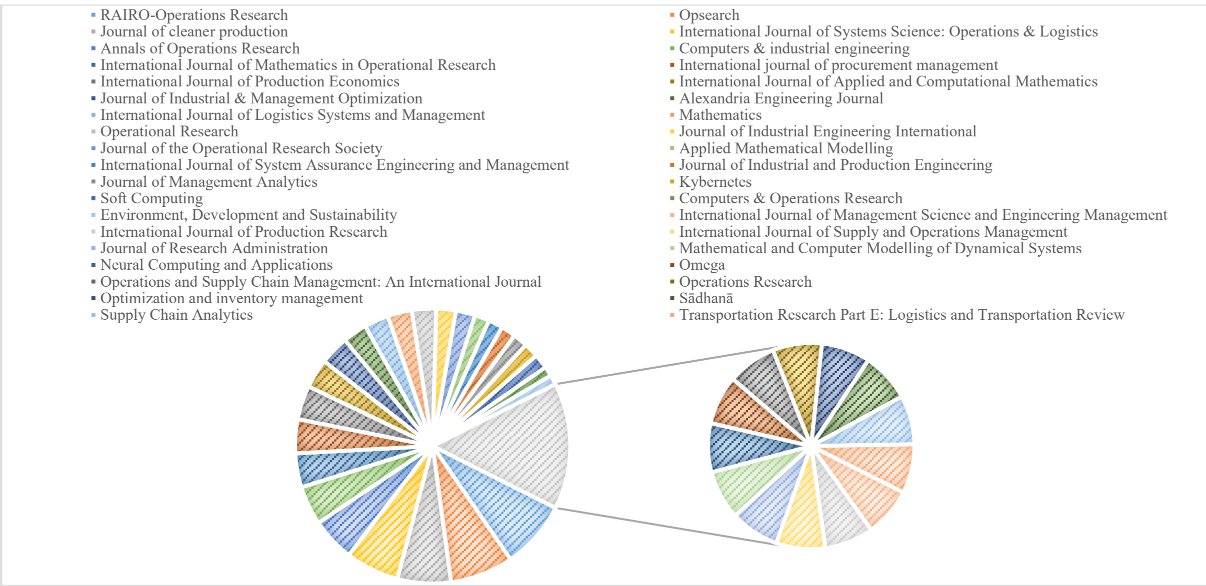

Fig. 2. Publication journals of the reviewed articles

2.3 Classification

We present a systematic classification to classify different conditions of the articles in this field. This comprehensive classification is provided by summarizing and rearranging the main aspects of the previous review studies and adding this article's contributions. The researchers should present the position of their work in these classes in the assumptions section of their articles so that the readers have a broad view of their study. 18 classes and 33 sub-classes are presented below. The percentage of the articles in each sub-class is provided in the parentheses before it to show the research gap in each category and is only related to the review table (Table 4) works (200 papers).

2.3.1 Deterioration

The most important indicator in this research topic is the type of deterioration. Previous works suggested three categories, including a) fixed lifetime, b) age-dependent, and c) time—or inventory-dependent, with the second one being probabilistic and the others being deterministic. These categories are good but not enough; here, we provided four subclasses covering almost all of the works in the literature.

I- Deterministic, Constant (50%): This category is the most popular and easy subclass and contains a constant fraction of the in-hand inventory deterioration rate (Acosta et al., 2018; Agi & Soni, 2020; Pooya & Pakdaman, 2019). This type of deterioration is generally formulated as $\theta I(t)$, where $I(t)$ represents the available inventory in hand at any given time and $0 < \theta \leq 1$ is the deterioration rate. In ordering models, based on the work of Ghare and Schrader (1963), inventory level decreases due to the deterioration and demand, following the equation $\frac{dI(t)}{dt} = -\theta I(t) - D$, where D is the demand value at time t (The demand function will be discussed in the next section). Solving the differential equation above leads us to the primary equation in this literature, the inventory in hand equation, as: $I(t) = e^{-\theta t} \int e^{\theta t} D dt$; this equation results in other essential equations (held inventory in any given time interval, ordering quantity, and primary costs). Generally, for production models, the researchers assume no deterioration during the production period, and the equations are the same. We must calculate the inventory in hand function for other cases.

II- Deterministic, Variable (43.5%): This subclass includes all articles with deterministic but not constant deterioration rates, contains variable deterioration rates (e.g., time-variable, three parameters Weibull), and deterioration rates that vary due to preservation technology but are measurable at any specific condition (Barman et al., 2021; Chaudhari et al., 2020; Mahapatra et al., 2022b; Mahato et al., 2024; Pervin et al., 2020; Yadav et al., 2024). Different functions were used in this subclass; Adak and Mahapatra (2022) assumed the deterioration depends on reliability and time and calculated it as $\theta(t) = r^{-\alpha} t$ where r is the reliability and α is a parameter. Chołodowicz and Orłowski (2021) considered the deterioration rate as a two-parameter Weibull function as $\theta(t) = \alpha\beta t^{\beta-1}$ where α is the scale parameter, and β is the shape parameter, and both have positive values; Barman et al. (2023) extended their work in many aspects but used the same assumption for the deterioration rate. Chandramohan et al. (2023) assumed the deterioration rate decreases due to the inspection. The deterioration rate in the work of Gupta et al. (2020) is time-dependent and follows the equation $\theta(t) = 1/(1 + k - t)$, where k is the expiration time of the product. Mahapatra et al. (2019b) used a three-parameter Weibull distribution to model the deterioration. The deterioration rate in their work at any given time t is $\theta(t) = \alpha\beta(t-\gamma)t^{\beta-1}e^{-\alpha(t-\gamma)^{t^{\beta}}}$ and $\alpha > 0$ is the scale parameter, $b > 0$ is the shape parameter, $t > 0$ is time of deterioration and γ is the location parameter and $t \geq \gamma$. Since Weibull distribution includes all types of deterioration, such as constant, increasing, and decreasing, it is popular in this subclass. It is generally defined as $\alpha\beta t^{\beta-1}, \alpha > 0,\ \beta > 0$. If $\beta > 1$, it shows increasing deterioration; for $\beta < 1$ it is decreasing, and for $\beta = 1$ it shows constant deterioration (Kurade & Latpate, 2021). Mashud et al. (2020b) considered the deterioration rate to be dependent on the preservation technology investments; this is a development of the work of Mishra et al. (2018), who considered the deterioration rate reduced by using $p(\gamma) = e^{-q\gamma}$ where γ denotes the investment in preservation technology, and q is the sensitive parameter of the investment.

III- Uncertain, Probabilistic (2.5%): Stochastic and interval-valued deterioration rates belong to this category (Rahman et al., 2020a; Rahman et al., 2020b; Tai et al., 2019). Chen et al. (2021) considered that the quality of the products decreases due to transportation, and a fraction of the products are of low quality at the destination; this fraction has a probabilistic value. Maihami et al. (2019) assumed three different probabilistic functions for the deterioration rates. In their work, for the retailer, the deterioration follows a uniform distribution and $\theta = \frac{\omega_1+\omega_2}{2}$ where $\omega_1, \omega_2 > 0$ and $\omega_1 < \omega_2$, the deterioration of the manufacturer's inventory follows a triangular distribution as $\theta = \frac{\alpha_1+\alpha_2+\alpha_3}{3}$ where α_1 is the lower limit, α_2 is the upper limit and α_3 is the mode, and we have $\alpha_1 \leq \alpha_3 \leq \alpha_2$; For the distributor, the deterioration follows a beta distribution in the interval (0,1) as $\theta = \frac{\gamma_1}{\gamma_1+\gamma_2}$ and $\gamma_1, \gamma_2 > 0$.

IV- Uncertain, Fuzzy (4%): This subclass includes fuzzy, fuzzy-stochastic, intuitionistic fuzzy, and neutrosophic fuzzy deterioration rates. This part's most popular fuzziness method is triangular fuzzy sets, which are the easiest for defuzzification (Rani et al., 2019; Sharma et al., 2020; Tiwari et al., 2019). Indrajitsingha et al. (2018) presented both crisp and fuzzy models; in the fuzzy model, they assumed the deterioration rate is a triangular number and used the centroid method for defuzzification as $\theta = \frac{\theta_1+\theta_2+\theta_3}{3}$. Later, Indrajitsingha et al. (2019) developed their previous work assuming new assumptions, such as two warehouses and allowable shortages; however, they used similar fuzzy sets for the deterioration rate. In the work of Mohammadzadeh and Mirzazadeh (2018), the deterioration rate is an R-shaped fuzzy number. Supakar et al., 2024b assumed the deterioration rate is in the neutrosophic environment and provided complex, crisp values.

2.3.2 Demand

The demand function is one of the most essential factors to consider in the mathematical models used in inventory control for deteriorating items; almost all models are related to the demand function. Four subclasses including uniform, time-varying, stock-dependent, and price-dependent demand functions were presented in previous reviews. Still, we reorganized these categories into two subclasses and added two more categories to cover this class's needs in modeling real-world problems. The following list shows these classifications.

I- Deterministic, Constant (16.5%): This category includes constant demand rate, e.g., two per day, 100 for all over the time horizon (Tiwari et al., 2018b; Yadav et al., 2018). Daryanto and Wee (2018) presented a single vendor-buyer integrated model for the inventory control of deteriorating items; they developed their model for a single item, considering environmental issues and carbon emissions, and assumed the demand rate is constant and known. They developed their model and provided a three-echelon green supply chain inventory model for imperfect perishable items (Daryanto & Wee, 2020); they assumed new conditions in this work. However, they did not change their assumption about the constant demand rate. The main idea of the work of Ghandehari and Dezhtaherian (2019) is considering financial conditions in the inventory control of items with deterioration. They made many realistic assumptions, including allowable shortages with partial backlogging and payment delays in an inflationary environment. However, the demand rate in their work is constant and deterministic. Pal et al. (2018) developed the work of Dye (2013) by considering that the deterioration starts randomly at a specific time after the item enters the inventory system. In their work, shortages are allowed, preservation technology reduces the deterioration rate, and the market demand is considered constant and known.

II- Deterministic, Variable (68%): All other deterministic demand shapes belong here. Demand rates related to stock, time, price, inventory, showcase inventory, advertisement, and a combination of these cases are variable demands (Kaushik & Sharma, 2020; Taparia et al., 2020; Mahata et al., 2020; Mashud et al., 2018). This category is more reasonable for modeling real-world markets (especially showcase inventory—and advertisement-dependent functions in today's competitive markets) and attracts more researchers (especially time—and stock-dependent functions). Paul et al. (2021) investigated the effect of the default risk and price-dependent demand on the optimal credit period for a deteriorating inventory model. They considered the market demand increased with the customer credit period(n) and decreased with the retailer's selling price(s), which is given by $\frac{\alpha n^x}{s^\beta}$, where α is the scaling parameter, $x > 0$ is a constant, and β is the price coefficient. Paul et al. (2022) extended their previous work with environmental consideration and assuming a price- and green-sensitive demand rate. In their new work, the demand is calculated by $D = D_0 + \alpha g - \beta S_r$, where α and $\beta (\alpha > \beta)$ are the coefficients of greenness(g) and selling price(S_r) and D_0 is the fixed demand rate. In a comprehensive study by Mohanty et al. (2018), an inventory model for deteriorating items is presented in which preservation technology reduces the deterioration rate, trade credit is allowed, and shortages are allowable. The main contribution of their work is the random planning horizon, which affects all other conditions of the model. In this work, the demand rate is time-dependent, follows a ramp-type function; the demand rate is αt for a given time($t \leq \mu$), and will be constant($\alpha\mu$) after. This category is widely used, and many different functions were used to describe the variable demand rates; however, one of the most common functions in this section is $D = D_0 \pm \alpha f$ where D_0 is the fixed demand rate, α is a coefficient, and f is a function (time, stock, price, and other factors)(Tiwari et al. ,2018a; Manna et al. ,2021; Tiwari et al., 2018c; Rahman et al., 2020b).

III- Uncertain, Probabilistic (8%): Stochastic demands with known and unknown distribution functions and random or interval-valued demands are classified in this subclass (Bandaly & Hassan, 2020; Jose & Reshmi, 2021; Kurade & Latpate, 2021). Ahmadi et al. (2020) provided a good study in this category. They presented an (s,S) inventory control policy to provide the forecasted demand of the hospitals from suppliers. The demand rate for their work is uncertain, and one of the main contributions of their work is considering lead time. They did not ignore inventory constraints in their work and developed a constrained model; however, due to their proposed model's difficulty, they could not obtain the global optimum and used a genetic algorithm to provide a good solution. Rahman et al. (2020a;2020b) studied two inventory models for deteriorating items. The demand rates in their works were dependent to time credit and selling price separately. The demand rates in their works depended on time credit and selling price separately. The demand rates follow the last function we presented in the previous subclass. However, they used interval values instead of deterministic parameters, making their work noticeable. They used quantum-behaved particle swarm optimization to solve the proposed models of both articles. Maihami and Karimi (2014) presented an optimal pricing and replenishment policy for non-instantaneous deteriorating items. They considered the demand to be stochastic and price dependent; the demand function of their work is $D(p) + \varepsilon$ where $D(p)$ is a decreasing and certain function of price(p), and ε is a non-negative and random variable with the deterministic expected value. Soni and Chauhan (2018) extended their work by considering preservation technology investments; however, they adopted other assumptions of the older article.

IV- Uncertain, Fuzzy (7.5%): This subclass includes all fuzzy shapes of demand rates (Mallick et al., 2023; Patro et al., 2018; Rabbani et al., 2018); however, the most popular fuzziness method in this section is the triangular fuzzy sets. Mahapatra et al.

(2019a) developed a fuzzy EOQ model for deteriorating items. They considered allowable shortages with complete backlogging and learning effects in a finite time horizon. The demand rate in their work follows the commonly mentioned function, as $D(\rho) = d_0 + d_1\rho$, where d_0 is the fixed part and d_1 is the scale parameter of sales effort. In this article d_0 is a triangular fuzzy number $\widetilde{d_0} = (d_0 - \Delta_l, d_0, d_0 + \Delta_r)$, where $0 < \Delta_l, \Delta_r < d_0$, and these paramateres are determined by the decision maker. Mahapatra et al. (2022a) extended their work by considering preservation technology strategies in the proposed model. They also changed the fuzziness concept and assumed that the fixed part of the demand is a trapezoidal fuzzy number $\widetilde{d_0} = (d_0 - \Delta_{l2}, d_0 - \Delta_{l1}, d_0 + \Delta_{r1}, d_0 + \Delta_{r2})$, where $0 < \Delta_{l1} < \Delta_{l2} < d_0$; $0 < \Delta_{r1} < \Delta_{r2} < d_0$; $\Delta_{r1} - \Delta_{l1} + \Delta_{r2} - \Delta_{l2} > 0$, and decision maker decides about these parameters. Indrajitsingha et al. (2018) presented a fuzzy inventory model in which the demand rate depends on the stock. The demand function follows $D(t) = aI^b, 0 \le t < t_1$ and $D(t) = D, t_1 \le t < T$, where $a > 0; 0 < b < 1$ are parameters and I is the inventory in hand. In this work, many parameters, including $D,\ a,\ b$, deterioration rate and cost, and holding cost, are triangular fuzzy numbers. They developed their model in the work of Indrajitsingha et al. (2019a). They introduced another demand function dependent on the selling price (the same as the common form we introduced). They assumed inventory costs, demand parameters, and backlog rate to be triangular fuzzy numbers. They presented their model in a two-warehouse environment.

2.3.3 Shortages

Shortages are essential in the markets, making mathematical models more flexible to handle real-world problems. Many researchers (46.5%) ignore this phenomenon (Huang et al., 2018a; Jani et al., 2020; Liao et al., 2020; Mahata et al., 2020); this assumption does not fit the real-world markets and is suitable for industries with infinite production rates, which is unreasonable. Even in production models, it is more realistic to consider shortages (for example, for raw materials). Researchers assume this strategy will make the mathematical models less complex, making their work less reliable and applicable. Three categories are provided below for the consideration of shortages.

I-Lost sales (1%): In this subclass, shortages are not allowed, but a penalty cost for lost sales is considered. Li et al. (2018) developed a model for drug inventory in the healthcare industry. They considered shortages available as lost sales. Considering stochastic lead time is the main contribution of their work. They assumed shortages occurred during the lead time. Presenting an inventory model for deteriorating items with triangular demand function and carbon emission effects is the main idea of the work of Singh and Mishra (2021). They stated that the shortages are not allowed, but considering lost sale costs is the reason for putting this article in this subclass.

II- Partial backlogging (43.5%): Partial backlogging is the best way to consider shortages. This type is the most general, and the other two subclasses can be obtained by changing the parameters of this state (Maihami et al., 2021; Mashud et al., 2021b; Mishra et al., 2021b; Mishra et al., 2020; Uthayakumar and Priyadharshini, 2024). This type of shortage is usually considered in such a way that the longer the waiting time for replenishment, the fewer customers will wait to meet their demand. Many functions, such as fixed value (Rahman et al., 2021) and time-variable backlogging rate (Chakrabarty et al., 2018b), are considered to describe partial backlogging. However, two standard functions used by many researchers in this field will be presented. Gupta et al. (2020) presented optimal ordering policies for a retailer for time-varying deteriorating items under realistic assumptions such as a two-warehouse system, permissible delay in payments, and allowable shortages with partial backlogging. In their work, the partial backlogging rate for the negative inventory is defined as $e^{-\delta(T-t)}$, where $\delta > 0$ is the backlogging parameter, and $T - t$ is the waiting time for the next replenishment. This function, for $\delta = 0$, shows the complete backlog; if $\delta = \infty$, we have lost sales. Many researchers used this function to show partial backlogging in their models (Chakrabarty et al., 2018a; Rana et al., 2021). Das and Roy (2018) developed a model for non-instantaneous deteriorating items in an uncertain environment. They assumed the model deals with a single item, the time horizon is finite, and demand is time-dependent. Later, they extended their work in the work of Das et al. (2021). They added preservation technology investments and multiple trade credits to their previous model; they solved their proposed model using particle swarm optimization. Chang and Dye (1999) presented an EOQ model for deteriorating items, considering the demand rate is time-dependent; Teng et al. (2003) revised their work and corrected some misunderstandings about opportunity costs. Later, Karimi et al. (2019) extended their work and added allowable rework of the deteriorated products. Karimi and Sadjadi (2022) developed their previous model, made it available for multi-items, added capacity constraints, and solved it with dynamic programming. Karimi and Sadjadi (2024) changed some aspects of the proposed model and presented it for non-instantaneous deteriorating items with ordering time constraints in an inflationary environment. At last, Karimi and Sadjadi (2025) extended their model and presented it with allowable discounts and budget constraints; they solved the proposed model using nine solution methods, including two exact solution procedures. The articles mentioned above used the same function to describe partial backlogging. In this state, the backlog rate is defined as $\frac{1}{1+\beta(T-t)}$, where $\beta > 0$ is the backlog parameter and $T - t$ is the waiting time for the next refill. In this function, $\beta = 0$ refers to complete backlog, and $\beta = \infty$, shows lost sales. The second common state of partial backlogging is the most popular form of this function, widely used by many researchers (Khan et al., 2022b; Jaggi et al., 2018b; Bhunia et al., 2018).

III- Complete backlog (9%): A complete (or full) backlog is considered when all customers wait for the next replenishment and will not go to other suppliers to fulfill their demands (Mahapatra et al., 2019a; Mashud et al., 2019; Rout et al., 2020). This type of shortage does not exist in the competitive market and can be used in exclusive markets such as aircraft and spacecraft parts. Tat et al. (2015) proposed an EOQ model for non-instantaneous deteriorating items in vendor-managed inventory systems. The presented model was created for a two-level supply chain consisting of a single supplier and a single retailer; Barman et al. (2022) developed their work and considered a price-sensitive demand instead of their constant demand rate. Barman claims that since they assumed a production rate in their model, the concept of an EOQ model is not correct in Tat's work, and in addition, their model will not result in a selling price and can not obtain sales revenue. Barman corrected these aspects; however, they did not change the assumption about shortages and full backlogging, which Tat established.

2.3.4 Warehouses

Researchers always consider the warehouse and storage space in mathematical modeling for inventory control problems. Deteriorating items are not excluded. Storage space has been used in all the mathematical models in this literature, and the difference is in the number of these warehouses. In most studies (86%), one warehouse with limited or unlimited storage capacity has been used (Choudhury et al., 2022a; Das et al., 2020; Hasan et al., 2020; Rahaman et al., 2020; Rahman et al., 2021; Supakar & Mahato, 2022). Multi-echelon models where each level has one warehouse are also included in this category. Mishra et al. (2013) presented an inventory model for deteriorating items with time-dependent demand. They considered a single warehouse with unlimited space, allowable shortages with partial backlogging, and finite horizon time. Assuming time-variable holding costs made their work valuable. Khan et al. (2022b) improved the mentioned work in several ways; they changed the assumption about backlogging rate and made it variable instead of constant, non-instantaneous items were considered, a mixed cash and prepayment agreement was adopted, and fundamental assumptions about storage facilities were assumed. They assumed the warehouse space was limited, and a without-ending situation was inserted. An algorithm was proposed to solve the proposed models, and graphical and analytical proofs were provided to show the existence and uniqueness of the solutions in several states. This study provided two categories for considering more than one warehouse as below.

I- Two warehouses (12.5%): A central warehouse and a rented one are usually considered in this case (Kaur et al., 2024; Khan et al., 2019; Manna et al., 2021; Mashud et al., 2020c). The main warehouse (owned warehouse, OW) has lower costs and limited space, while the secondary one (rented warehouse, RW) has a different deterioration rate and unlimited space. Liang et al. (2011) presented a mathematical model to optimize the replenishment policies in an inventory system for deteriorating items. They developed their model under a two-warehouse environment and considered the preservation facilities in the rented warehouse to be better than the owned one; as a result, holding costs are higher, and the deterioration rate is lower in RW. They assume we consume the inventory in RW first, and in the first period, this inventory vanishes due to demand and deterioration. However, during this time, the inventory in OW decreases due to deterioration. Fig 3 shows the graphical representation of a two-warehouse model.

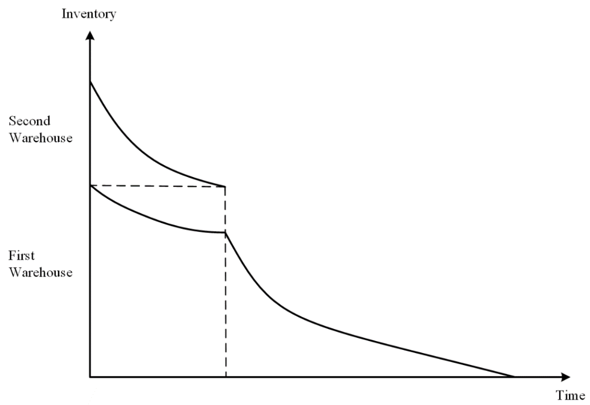

Fig. 3. Graphical representation of a two-warehouse model

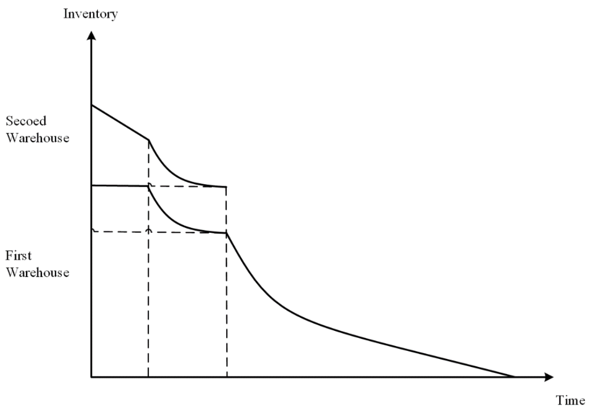

Fig. 4. Graphical representation of a two-warehouse inventory model for non-instantaneous deteriorating items

Udayakumar and Geetha (2018) developed the work of Liang et al. (2011) and presented it for a non-instantaneous deteriorating item. Shortages were not permitted in both works, and exact solutions were provided. Fig 4 shows the graphical representation of a two-warehouse inventory model for non-instantaneous deteriorating items.

II- Multiple warehouses (1.5%): In some studies, it has been assumed that there are several warehouses to store products. Chakrabarty et al. (2020) presented a multi-warehouse, multi-item inventory model for non-instantaneous deteriorating items. Their demand function was stock-dependent, and they considered shortages to be allowable with partial backlogging. Developing the proposed model in an uncertain environment made their work remarkable. Fig 5 shows a multi-warehouse model. Maiti (2020) presented a multi-item, multi-outlet fuzzy inventory model for deteriorating items. He considered several stores to distribute the products, and each store has its parameters. So, the model was considered a multi-warehouse model. However, the proposed model is the sum of several single-warehouse models. Investigating multi-stores with different objectives under single management made his problem a multi-objective optimization problem. He used a multi-objective genetic algorithm and a fuzzy-simulation-based multi-objective genetic algorithm to solve the proposed crisp and fuzzy models. Considering multiple retail centers that share inventory levels made the work of Onggo et al. (2019) a multi-warehouse problem. They developed their model to investigate how stochastic demand affects the supply chain management of perishable agri-foods. They used simulation-based heuristic methods (sim heuristics) to solve their proposed uncertain problem.

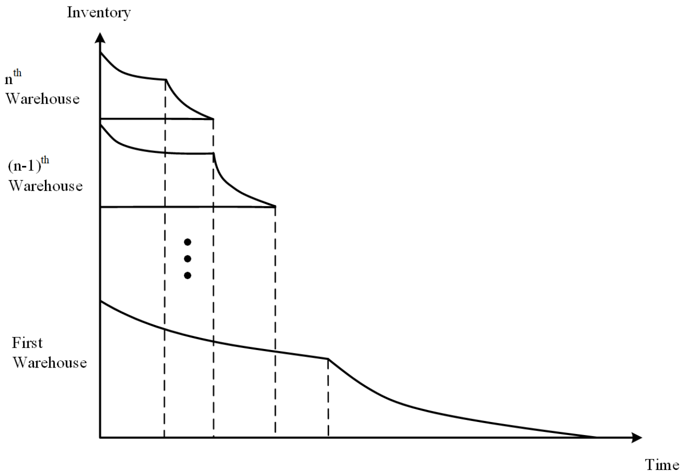

Fig. 5. Graphical representation of a multi-warehouse inventory model

2.3.5 Time value of money (inflation and discount)

The time value of money is an essential phenomenon in today's competitive markets (Barman et al., 2023; Yu et al., 2020). Still, it is usually ignored (78%) due to the complexity of the models and the difficulty of solution methods. The most important factor for calculating the time value of money is inflation; however, according to the nature of this class, the discount is also included. Discounts related to high-level financial payments are not categorized in this class. Finally, three different categories are provided to assume the time value of money.

I- Inflation (5%): Inflation is generally the rate of increase in prices of the fundamental products for living in a country over time. The presence of inflation and the decrease in the value of money over time is an assumption consistent with the real world (Yadav et al., 2019; Sethi et al., 2024). This assumption does not affect the calculation of inventory equation; however, it changes the equations related to the inventory costs and makes linear models nonlinear (and makes nonlinear models more complex) in general. For a given inflation rate, $0 < r$, (inflation rate can be greater than 1), in a given time, t, we should multiply $(1 + r)^t$ by all costs to consider the effect of inflation. Shah et al. (2012) investigated optimal ordering policy and pricing for an inventory model with quadratic demand with available trade credit. They assumed the trade credit is linked to the order quantity, the demand rate is time- and price-dependent, and shortages are not allowed. Saha and Sen (2019) extended their works. They considered deterioration of products, allowable shortages with partial backlogging with time-varying backlog rates, and the effect of inflation on the proposed model, which were ignored in the previous work. They could not find the global solution due to the complexity of the model and provided an algorithm to find a local answer. Sharma et al. (2018a) developed a mathematical model for inventory control of deteriorating items. They considered the deterioration rate to be variable and the demand function to be ramp-type. Considering allowable shortages with partial backlogging, investigating the learning effect on different costs, and assuming the inflation made their work valuable. They found solutions for their proposed models; however, providing graphical proofs for convexity (instead of analytical) made their solutions local answers.

II- Discount (11.5%): This category includes various types of discounts (e.g., all units quantity, step quantity, or seasonal discounts) (Rahman et al., 2022). Discounts motivate customers to purchase more and are a tool for higher-level supply chain members to sell their products to the lower-level ones; for example, manufacturer to the supplier, supplier to retailer, retailer to distributor, and distributor to the customer. The discount is usually expressed as a percentage ($d\%$), and for the all-units discount, it is multiplied by the term $(100 - d)\%$ in the purchase price (for other discounts, models must be developed according to the assumptions). Cheng et al. (2020) considered two-phase advance sales with discounts. They used the same equation as we mentioned above to investigate the effect of discount at each phase. One of the main contributions of their work is developing the mathematical model of a cyclic supply chain. They assumed a return guarantee for the products and considered a fraction of items could be sold after return with a discount. Shaikh et al. (2019c) developed a mathematical model for inventory control of deteriorating items in a two-warehouse environment. They considered advance payments in their work. However, they could not find the global solution to the proposed problem and used particle swarm optimization to find a local answer. They showed the convexity of their model graphically. Khan et al. (2022a) removed the limitation of the work of Shaikh et al. (2019c) by considering variable type per unit selling price instead of a constant value; their proposed model is suitable for inventory models with selling price-dependent demand functions. They considered all-unit discounts in their work, assuming a descending step function for purchase costs. They solved their model mathematically and found the global solution.

III- Both inflation and discount (5.5%): This category is related to studies dealing with inflation and discount (Chakrabarty et al., 2020; Rana et al., 2021; Saxena et al., 2024). Liao and Huang (2010) presented an inventory model for deteriorating items with trade credit consideration and capacity constraint. However, they did not consider shortages and the time value of money. Chakrabarty et al. (2018a) extended their work by adding allowable shortages with partial backlogging and time value of money to their proposed model. In their two-warehouse model, a constant inflation rate was used, and a discount rate represented the time value of money. The net constant discount rate of inflation in their work was the difference between the discount rate and the inflation rate. Due to the complexity of the developed model, they found a local optimum solution and ignored the exact solution. In the same year, Chakrabarty et al. (2018b) developed their previous model and added a non-instantaneous deterioration assumption. They proved the convexity of their model numerically and graphically. However, their optimum solution is considered a local answer due to the lack of mathematical proof of the convexity.

2.3.6 Model

The type of mathematical model is essential in this subject literature. Many aspects of modeling and solution methods depend on the model type. The type of model refers to the type of real problem that the model is made to simulate. However, maximization and minimization are not crucial in this class and are easily interchangeable. We offer two subclasses here, including ordering and production. Generally, when an article studies suppliers and retailers, the mathematical model is ordering, and when it talks about manufacturers and plants, the model is production planning.

I- Ordering model (73%): Different ordering and replenishment policies (e.g., continuous and periodic review policies and economic order quantity) belong to this subclass (Kurade & Latpate, 2021; Mahapatra et al., 2022a; Pilati et al., 2024; Shaikh & Cárdenas-Barrón, 2020; Shaikh et al., 2019e; Sharma et al., 2020). One of the most widely used models in the literature is the economic order quantity (EOQ) model, which can model real-world problems. In EOQ models (ignoring shortages), we have: $Q = I(0) = \int e^{\theta t} D dt$, which is the in-hand inventory at time $t = 0$, solving this equation leads us to the economic ordering quantity of the general model. Teng et al. (2016) studied lot-size policies for deteriorating items; they considered advance payments and expiration dates for their products. Mashud et al. (2019) extended their work by adding realistic assumptions such as linear holding costs and discount incentives for multiple prepayments. They developed an ordering strategy inventory model for deteriorating items; their provided solution is a global answer since they proved the convexity of the model analytically. The work of Wu et al. (2016) is an extension of several works. Under two-level trade credit financing, they developed an optimal lot size for deteriorating items. They used the same assumption for deterioration rate as that in the works of Sarkar (2012) and Wang et al. (2014), while they applied the positive exponential demand function of the works of Chern et al. (2013) and Teng and Lou (2012). Paul et al. (2021) investigated the effect of default risk on optimal credit period and cycle time in an ordering inventory model for deteriorating items. They extended the work of Wu et al. (2016) by assuming selling price and credit-period dependent demand, down-stream trade-credit period, and allowable shortages with partial backlogging.

II- Production planning (27%): This category includes models related to planning for manufacturing plants (Dey et al., 2024b; Hati & Maity, 2024; Sivashankari & Valarmathi, 2024). The most popular model in this category is EPQ (economic production quantity). In this study, articles with both models (for example, in multi-echelon models) are considered production models. Duan et al. (2018) developed optimal pricing, production, and inventory for deteriorating items. They assumed uncertainty in their model. Their work is a developed model of the work of Herbon and Kogan (2014); they used control theory to deal with uncertain demand in a dynamic pricing and production problem. However, Herbon and Kogan (2014) did not consider the deterioration in their work, which Duan et al. (2018) did. Also, their work is related to the work of Li et al. (2015) who addressed the joint pricing and inventory control policy for a stochastic inventory model for deteriorating items. Duan et al. (2018) extended their work by considering stochastic demand instead of a constant value.

2.3.7. Multi echelons

The number of supply chain levels significantly impacts the modeling and solution methods. Therefore, we should pay attention to this aspect, which has been neglected in previous review studies. This category includes all problems related to game theory, cooperation, competition, and Stackelberg solutions. A supply chain has different levels (echelons), such as manufacturer, supplier, retailer, and customer. In a model, one of these levels (except the customer) or a combination of these levels may be used. Note that the level is essential in this part; for example, several retailers or suppliers placed on the same level are not considered multi-levels (some articles (Ahmadi et al., 2020) considered it a multi-echelon model, but it is incorrect). Two subclasses are provided for developing multi-echelon models. However, many researchers study single-echelon supply chains (75.5%). A supply chain is single-echelon when the model examines only one level of the supply chain. Studies that present several levels of the supply chain in an integrated model are also considered a single-echelon supply chain (Chen et al., 2021; Indrajitsingha et al., 2018; Transchel & Hansen, 2019; Verma, 2024; Yang et al., 2020; Yu et al., 2020). Taleizadeh and Nematollahi (2014) introduced an inventory control problem considering deterioration of products, allowable shortages with the complete backlog, and financial conditions. They used a truncated Taylor series to approximate the effect of inflation and solved the problem analytically. Ghandehari and Dezhtaherian (2019) extended their model by considering partial backlogging and changing some financial considerations. Both of these works studied one level of the supply chain. Aliyu and Sani (2018) extended the work of Aliyu and Sani (2016) by assuming constant holding cost and variable deterioration rate, which were variable and constant, respectively, in their previous work. In both studies, they developed an inventory model for deteriorating items with an exponentially decreasing demand function. They claimed the proposed model is highly nonlinear and can not be solved analytically. However, they used a direct search method to provide solutions. The basis of the consideration in this paper is the mathematical model; some researchers discuss multiple levels in their articles but do not assume it in their models; we did not consider their model as multi-echelon works.

I- Two-echelon supply chain (18.5%): This subclass contains two levels of supply chain. Manufacture-supplier, supplier-retailer, retailer-customer, and other combinations of these levels are in this category (He et al., 2020; Mahato & Mahata, 2021; Pourmohammad-Zia et al., 2021). Stranieri and Stella (2022) presented a two-echelon supply chain consisting of a factory, its warehouse, and three distribution centers. A two-echelon supply chain is shown in Fig 6.

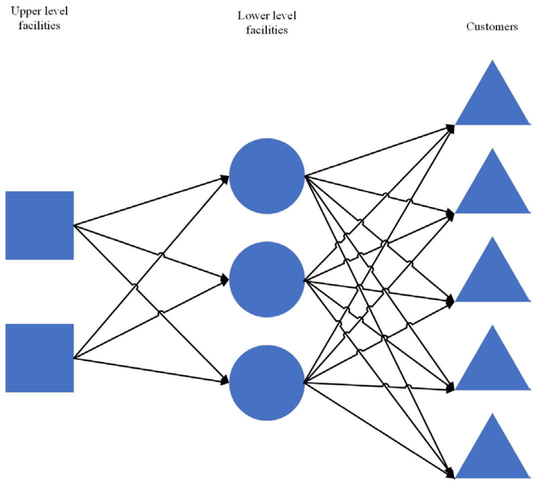

Fig. 6. Graphical representation of a two-echelon supply chain

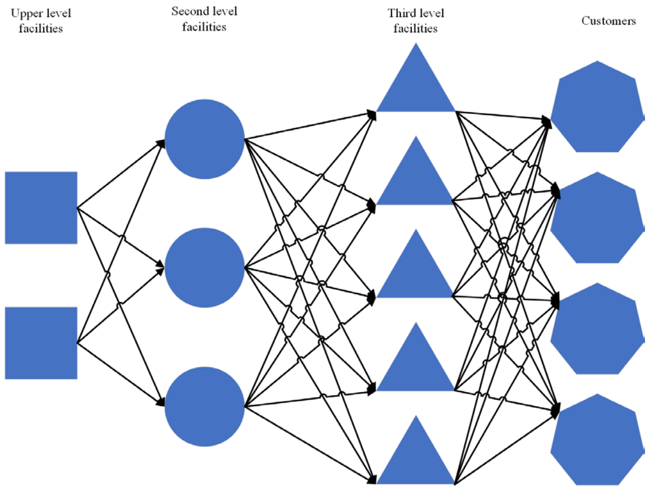

Fig. 7. Graphical representation of a three-echelon supply chain

Tat et al. (2015) developed an integrated inventory model for a supplier and a buyer; their model was a single-echelon model. Barman et al. (2022) extended their work and developed a two-layer supply chain model. Their manufacturer-retailer supply chain was dealing with producing non-instantaneous deteriorating items. They studied their model with and without shortages. They developed their model in the work of Barman et al. (2023). They presented a bi-objective model in a two-echelon supply chain consisting of a manufacturer and a retailer and solved the problem using a metaheuristic method. Selecting seed nodes and competitive pricing in a two-echelon supply chain consisting of a manufacturer and a retailer is the main idea of the work of Morshedin et al. (2024).

II- Three-echelon supply chain (6%): Mathematical models with three levels (e.g., manufacturer-supplier-retailer) are in this subclass (Daryanto & Wee, 2020; Daryanto et al., 2019; Sebatjane, 2022; Tiwari et al., 2018a). Senses et al. (2021) presented a three-echelon supply chain consisting of three plants, its suppliers and warehouses, and distribution centers. Fig 7 shows a three-echelon supply chain.

Sebatjane (2022) presented an inventory model for growing and deteriorating items in a three-echelon food supply chain consisting of farming-processing-retail echelons. He studied the impact of preservation technology on lot-sizing and ordering decisions. He proved his model is convex and provided an algorithm to obtain the exact solution. Wang et al. (2011) presented a three-level supply chain for one producer, one distributor, and one retailer. They investigated how different deterioration rates in each echelon affect individual and integrated inventory policies. Daryanto et al. (2019) extended their model by adding transportation and emission costs. Their three-echelon supply chain is considered a supplier, a third-party logistics service, and a buyer. Since they proved the convexity of their model empirically, the solution they obtained is a local answer.

2.3.8. Costs and prices

When examining economic problems, one of the main aspects of the mathematical model is costs and prices, which are usually considered fixed values in this literature. Since not constant costs or prices complicate mathematical models in this field, many studies have used this assumption as innovation. Four subclasses are provided in this class. In this article, in reviewed papers, the classification is done by considering all of the costs and prices, which means even if one was variable, the article was classified as variable costs and prices.

I- Deterministic, Constant (52%): This category is used for models with constant and deterministic values for all costs and prices (Jaggi et al., 2019; Kalantari & Taleizadeh, 2020; Perez & Torres, 2019). Zanoni and Jaber (2015) presented an integrated vendor-buyer supply chain to optimize its inventory policy. Their demand function was a stock-dependent function that Ghiami and Beullens (2020) employed. They extended the previous model by adding deterioration to it. They developed a two-warehouse inventory model for perishable items in a two-echelon supply chain; they considered constant values for costs in their article.

II- Deterministic, Variable (41.5%): Models with variable costs and prices belong to this subclass (Padiyar et al., 2021; Sharma et al., 2019; Singh et al., 2019). Optimal pricing studies and studies with time-variable holding costs are the most common cases in this category. Rezagholifam et al. (2022) studied optimal pricing and ordering policies for deteriorating items. They assumed that the deterioration starts after a while, there are capacity constraints, and the demand is stock-dependent. They considered multiple pricing over time and presented an exact solution for their work. Providing analytical sensitivity analysis made their work notable. Kim et al. (2018) investigated a new way to calculate imperfect items in a production planning model. Their improved method can obtain imperfect products without approximation. They also considered a long-run imperfect production. Sepehri et al. (2021a) used the concept of reducing defective items by spending money. They considered the selling price, the total investments in preservation technology, and the green supply chain to be decision variables. Khanra et al. (2011) presented an EOQ model for deteriorating items assuming a time-dependent quadratic demand function and allowable delay in payments. Sen and Saha (2018) developed their model in three different ways: a) considering allowable shortages, b) changing the demand function, and c) assuming three different cases for payments instead of two. They considered a time-dependent linear holding cost as $h = \alpha + \beta t$ in their work.

III- Uncertain, Fuzzy (4.5%): This subclass includes all fuzzy shapes of costs and prices; however, the most popular fuzziness method in this section is the triangular fuzzy sets (Maiti, 2020; Indrajitsingha et al., 2018; Indrajitsingha et al., 2019a). There are several methods for defuzzification of a triangular fuzzy number; let $\tilde{F} = (a, b, c)$ be a triangular fuzzy number, then $\alpha - cut$ of $\tilde{F}$ $(0 \le \alpha \le 1)$ is denoted by $F(\alpha)$, and is defined as $F(\alpha) = [F_L(\alpha), F_R(\alpha)]$, where $F_L(\alpha) = a + (b - a)\alpha$, and $F_R(\alpha) = c - (c - b)\alpha$, are the left and right endpoints of $F(\alpha)$. The digned distance of $\tilde{F}$ is defined as $d(\tilde{F}, \tilde{0}) = \int_0^1 d([F_L(\alpha), F_R(\alpha)], \tilde{0}) = \frac{1}{4}(a + 2b + c)$. The centroid method on the mentioned fuzzy number is $C(\tilde{F}) = \frac{a+b+c}{3}$. The graded integration of $\tilde{F}$ is $P(\tilde{F}) = \frac{\int_0^{w_a} h(\frac{L^{-1}(h)+R^{-1}(h)}{2})dh}{\int_0^{w_a} hdh}$, with conditions $0 < h \le w_a$ and $0 < w_a \le 1$, $P(\tilde{F}) = \frac{1}{6}(a + 4b + c)$. Since it is easier to analyze fuzzy numbers compared to stochastic values, this type of uncertainty is more popular than the probabilistic cases (Supakar & Mahato, 2022; Supakar et al., 2024b). Shaikh et al. (2018) introduced a crisp model for inventory control of perishable items, then used the concept of nearest interval approximation of fuzzy numbers introduced by Grzegorzewski (2002) to deal with uncertainty in their work. In this method, a fuzzy number ($\tilde{A}$), with an interval of confidence at the level α; $[A_L(\alpha), A_R(\alpha)]$, can be approximated with a crisp interval ($[\int_0^1 A_L(\alpha)d\alpha, \int_0^1 A_R(\alpha)d\alpha]$). All costs and profits of the inventory in their uncertain model, including profit per unit, ordering, purchasing, holding, shortage, opportunity, and advertisement costs considered to be fuzzy numbers.

IV- Uncertain, Probabilistic (2%): Mathematical models with different types of stochastic costs and prices are classified in this subclass (Shaikh et al., 2019a). Rahman et al. (2020b) claimed that considering uncertain inventory parameters as fuzzy numbers is valuable; however, calculating fuzzy set elements is not simple and does not differ from crisp values. They suggest using stochastic values, such as interval-valued numbers, to fill this gap. Rahman et al. (2020a) developed a stochastic inventory model for deteriorating items. They assumed allowable shortages with partial backlogging in an infinite planning horizon. Selling price and inventory costs, including ordering, opportunity, and shortage, are considered to be interval-valued as $[min, max]$ for each parameter in their work. The work of Mondal et al. (2019) studies the deterioration and amelioration of the products in an inventory system. They developed crisp and stochastic models; inventory costs were assumed interval-valued numbers in their stochastic model. Interestingly, all of the articles we found in this category (4 cases in the current review) used partial swarm optimization to find a local answer for their problem, which shows the strength of this method in dealing with uncertainty.

2.3.9. Solution method

One of the most critical issues considered less in previous review studies is problem-solving methods. Developing a mathematical model without a solution has less value. Due to the nonlinear nature of the mathematical models in this literature, the solution methods have always been limited. Since the solution methods are limited and the models are complex, real conditions, including discrete variables, various assumptions, such as inflation and allowable shortages, advance payments, and many other aspects, have been ignored in many studies. On the other hand, some researchers used local solutions (such as meta-heuristic and heuristic methods) to develop more comprehensive models. However, researchers have achieved both goals (accurate models and global optimal solutions) in recent years using dynamic programming (Karimi & Sadjadi, 2022; Karimi & Sadjadi, 2024; Mahata et al., 2019). So, it is incorrect to say that finding a global solution is impossible, and it is better to say it is difficult. This article pays much attention to this class. However, we did not check whether the models of reviewed studies are pseudo-convex. Two subclasses are provided for the solution method.

I- Global optimum solution (61.5%): Finding the global optimum solution has always been valuable. However, due to the complex nature of the models available in the literature on inventory control for deteriorating items, this task becomes more valuable and complex. Derivation and mathematical algorithm methods are the most popular methods used for a long time in this field to find the optimal solution. The main drawback of these methods is that it must be proved mathematically that the entire model space (including the objective function and constraints) is convex (concave); on the other hand, they can not solve models with discrete variables (especially the derivation method). For this reason, some researchers have given up on the global optimum solution or realistic models with more accurate assumptions. However, some researchers have taken this trouble and made these proofs to increase the value of their work. Another method used in recent years to find the global optimum solution is dynamic programming, which does not have the weaknesses of the mentioned methods (there is no need to prove convexity or concavity, and it can deal with discrete and continuous variables). Software that provides the global optimum answer (such as GAMS with zero gap conditions) and the greedy search method are also included in this category (Dey et al., 2024a; Khakzad & Gholamian, 2020; Lin et al., 2018; Mashud et al., 2020b; Mashud et al., 2019; Rout et al., 2021a; Sebatjane, 2022). The greedy search cannot be widely used due to the immense time required to find a solution. However, we can use it to solve minor problems. Kaya & Ghahroodi (2018) used an average cost dynamic programming introduced by Bertsekas (2005) to optimize their stochastic inventory model for perishable items. The demand rate in their proposed model was age- and price-dependent. Assuming a salvage value made their work significant. Liao et al. (2020) borrowed the idea of non-defective items presented by Salameh and Jaber (2000) to develop a mathematical model for non-instantaneous deteriorating items inventory control considering a delay in payments. They found the global optimum solution analytically, and their proposed method is exact. Karimi and Sadjadi (2025) used greedy search to validate their proposed backward dynamic programming developed to solve a wide range of periodic and multi-item problems in this research field by changing them into standard knapsack problems. One of the main exact methods used in this literature review to find the global optimum of a problem ($minimizing\ TC(x)$) considering x as the decision variable is the algorithm shown in Fig 8.

Algorithm 1
Step 1: Let $TC^* = \infty$; find all available decision variable values that satisfy $\frac{\partial TC}{\partial x} = 0$.
Step 2: If $\frac{\partial^2 TC}{\partial x^2} \geq 0$ and $TC(x) < TC^*$, then $TC^* = TC(x)$.
Step 3: Do Step 2 for all available values in Step 1.
Step 4: The global optimum is x^*, which results in TC^*.

Fig. 8. A popular algorithm to find the optimum answer to the problem

Note that if there is more than one variable, we should calculate the Hessian Matrix in Step 2 to find the behavior of the objective function. If we cannot find all available values satisfying the equation in step 1, we need analytical proof of the problem's convexity (concavity) to consider the final solution a global one. We considered papers that used this method and did not claim to have found all possible values for satisfying the equation as local optimum solutions (except articles that provided mathematical proof of convexity).

II- Local optimum solution (38.5%): As mentioned, many researchers have used local solution methods to find the optimal answer (Khan et al., 2022b; Pando et al., 2018; Singh & Mishra, 2021). Heuristic and meta-heuristic methods (e.g., simulated annealing, genetic algorithm, particle swarm optimization), simulations, derivation method, and mathematical algorithms, for example, the proposed algorithm shown in Fig 8, without analytical proof of convexity (concavity) are included in this category (Daryanto & Wee, 2020). Some researchers have used graphical methods to show the model's convexity or concavity. This study respects their work. However, the graphical proofs are not general, and the answers obtained from these methods are considered local. In a recent work, Saxena et al. (2024) presented an optimal inventory problem for deteriorating items considering greenhouse gas emissions from the item itself. They borrowed the function of the emissions from the work of Sommer et al. (2000), the relationship between emissions and temperature from Guo et al. (2020), and the leakage of the gas from the article presented by Tingey et al. (2000). They proposed an analytical method to find the optimum solution; however, the lack of mathematical proof of convexity made their obtained solution a local one. We know that the solutions provided by metaheuristic and heuristic methods are the local answers; however, many researchers used these methods (especially particle swarm optimization [PSO] in stochastic problems) to find a good (not global) answer for their problem more easily (Shaikh et al., 2019c; Supakar et al., 2024a; Das et al., 2021; Mondal et al., 2019; Rahman et al., 2020b).

2.3.10. Multi-item modeling

Multi-item modeling is one of the main aspects affecting mathematical model development. Developing a model for several items is more complicated. However, without inventory constraints, a model for multiple products is just the sum of several single-item models. It cannot be called a multi-item model. Nowadays, it is rare to find a market that sells only one product, so considering multiple items makes the model more realistic. This article investigates whether the proposed models of the reviewed papers are multi-item (6.5%). Single-item models are more common (93.5%) and consider only one product type in the inventory system (Braglia et al., 2019; Çalışkan, 2021a; He et al., 2020; Sharma et al., 2020). The inventory system contains more than one product in the multi-item models (Gupta & Mishra, 2024; Taghizadeh-Yazdi et al., 2020). For example, $Minimizing\ TC(x)$ is a single-item mathematical model. Its multi-item shape is a knapsack problem as $Minimizing\ TC(\{x_1, x_2, \dots, x_i\}),\ subject\ to\ \sum_i x_i v_i < Cap$, where TC is the total cost of the inventory system, x_i is the ordering quantity of the product i, v_i is the volume of the product i, and Cap is the maximum available capacity of the vehicle or warehouse. Fig 9 shows a multi-item inventory model for deteriorating items with allowable shortages.

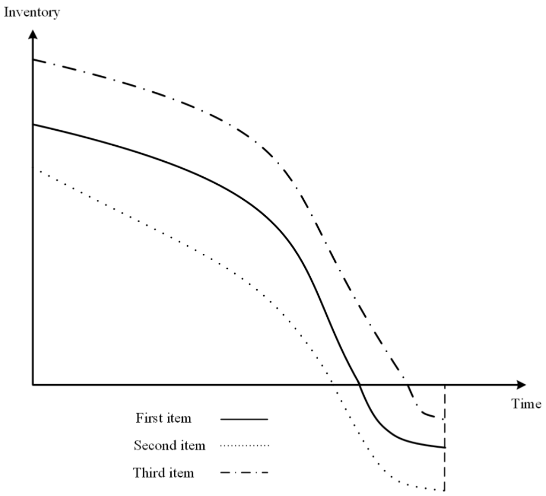

Fig. 9. A multi-item inventory model with allowable shortages

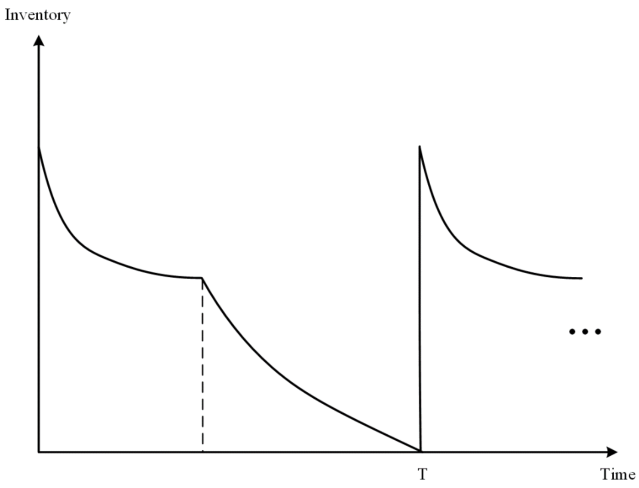

Fig. 10. The graphical representation of a finite inventory system

Mahmoodi (2019) developed a multi-item inventory model in a competitive environment. His article developed the works of Adida and Perakis (2010) and Chen and Xiao (2017) who investigated pricing policies in a competitive market. His main contribution was developing the mentioned papers for deteriorating items. He presented his work in two cases, considering and ignoring allowable shortages. The global answers of their models were obtained analytically; however, the analytical solutions of the nonlinear models in this literature review are complex, and we can use numerical optimization procedures to find optimum solutions for the proposed models. Dynamic programming, which can solve knapsack problems numerically and provides global optimum, is one of the best solution methods for these models (Karimi & Sadjadi, 2025).

2.3.11. Time horizon

The time horizon concept is one aspect that has been misunderstood in many studies. The concept of time horizon refers to the period in which planning takes place, and in exceptional cases, it can be considered infinite. However, many researchers have considered the time horizon infinite, not to make their models constrained (which is only accurate in exceptional cases). Usually, we plan for a finite time horizon while considering no time constraints. Two categories are considered for this class, which are explained in detail below.

I- Finite (65.5%): In the literature, we usually plan for a specific period, which can be a parameter or variable (Khan et al., 2022b; Mallick et al., 2023; Padiyar et al., 2024; Riazi et al., 2024; Wang et al., 2024). If this value is a parameter, the model may have constraints, and it is more difficult to solve, while this is usually not the case if this value is variable. In both instances, the planning horizon is finite. In this study, studies that did not directly declare the time horizon and planned for a limited time are considered finite. Limited long-term planning and the stochastic time horizon (Mohanty et al., 2018) are considered finite, too. Hasan et al. (2020) modified the price-dependent demand function of Yao et al. (2008) to present an inventory model for agricultural products with deterioration. The replenishment time in their work is a decision variable; however, the planning horizon is not infinite. Fig 10 shows an inventory system that repeats in a finite cycle.

Abad and Jaggi (2003) investigated the impact of price factors on the returns policies in a supply chain. Jaggi et al. (2019) developed their model for an inventory system consisting of perishable items. They used Abad and Jaggi's assumptions about trade credits. They provided a Stackelberg and Nash equilibrium solution for their two-echelon supply chain.

II- Infinite (34.5%): If planning is done for an infinite time, the time horizon is infinite (Mashud et al., 2021c; Mokhtari et al., 2020; Verma, 2024). This situation happens when the objective function is for one unit of time; in this case, considering inflation into account makes the model more realistic. Although limited studies have used this case correctly, in this article, this assumption has not been changed for the studies that have been declared to have an infinite time horizon to respect the authors. Shah et al. (2018) provided an optimal ordering policy for deteriorating items considering several trade credits with a quadratic demand function. They stated that the time horizon is infinite; since they calculated the total costs for one unit of time, their planning time is a correct form of infinite time horizon. Unfortunately, many researchers did not assume this phenomenon in its correct form, and it is hard to find a work that uses the correct infinite time horizon. Providing more details in this class is out of the scope of this review and needs further investigation.

2.3.12. Supply chain type

One of the most commonly used assumptions in the inventory control of perishable items is the unusability of deteriorated products. For example, the following assumptions are widely used:

a) There is no repair or replacement for deteriorated items.

b) There is no change in deteriorated products.

c) The deteriorated items are discarded instantly.

d) The deteriorated items have no value.

These assumptions are consistent with the nature of deteriorating items; for example, rotten meat, spoiled food, expired milk, or evaporated alcohol cannot be used in the same original form (they may be used in another way in another industry, which is not discussed in this article). However, there are situations of deterioration (such as obsolescence) where it may be possible to use all or part of the deteriorated goods in the same industry in their original form. For example, parts of high-tech goods, such as speakers, which do not become obsolete as quickly as parts such as processing unita and graphics cards, can be used in subsequent products (Karimi et al., 2019). In this case, the deteriorated products return to the supply chain cycle, and the supply chain changes from an “open” to a “cyclic” state. These two modes are considered as subclasses of this class.

I- Open supply chain (90.5%): The supply chain is considered open if the deteriorated products leave the supply chain immediately and do not return to it. This category is widely used and is a common assumption in the literature (Panda et al., 2019; Shaikh & Cárdenas-Barrón, 2020; Uthayakumar & Priyadharshini, 2024; Yang et al., 2020; Yu et al., 2020). In many studies, deteriorated products are sold at a discounted price during the same period of deterioration; in this case, since these products have left the system, the supply chain is open. Barman et al. (2023) developed a two-layer supply chain to discuss pricing and inventory policies for products with Weibull distribution deterioration. They assumed product replacement or repair is not allowed during the inventory cycle. Banu and Mondal (2020) analyzed an inventory model with two-level trade credit. They used q-fuzzy numbers to investigate the effect of customers’ credit on the demand rate. Mallick et al. (2023) used their idea to model the nature of stock level. They extended the work of Banu and Mondal (2020) for deteriorating items, considered inflation a constant value, and assumed there were no repairs or replacements for deteriorated items. Fig 11 shows the graphical shape of an open supply chain. In this type of supply chain, a fraction of products provided by ordering and production are discarded due to deterioration, and the remaining inventory satisfies the demand.

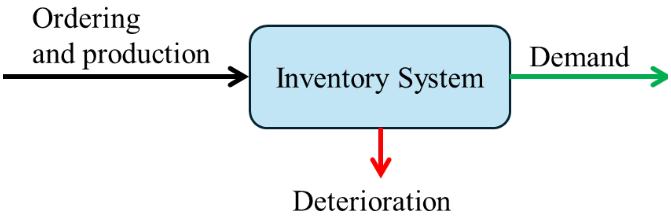

Fig. 11. The graphical shape of an open supply chain

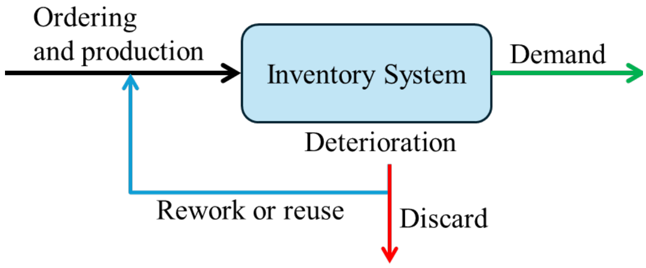

Fig. 12. The graphical representation of a cyclic supply chain

II- Cyclic supply chain (9.5%): A supply chain is considered cyclic if the deteriorated products are returned to the inventory system and reused in any form (Padiyar et al., 2024; Pervin et al., 2023; Verma & Mishra, 2024). Also, the supply chain is cyclic if there is a product replacement warranty (Cheng et al., 2020; Loedy et al., 2018). However, the main shape of the cyclic supply chain was used in the work of Karimi et al. (2019), which was a development of the work of Teng et al. (2003). They developed a model for inventory control for deteriorating items, considering a fraction of deteriorated products (their main focus was high-tech products) can be used after rework. The reworking makes a supply chain cyclic and more realistic, but the complexity of the model makes the researchers ignore this aspect in many studies. The representation of the cyclic supply chain is shown in Fig 12. This chart shows that a fraction of deteriorated items will leave the system immediately, and the other fraction can be used after rework (or any other sort of use). Another notable work in this subclass is the work of Mishra et al. (2019). They developed their inventory model mainly for re-manufactured products. The salvage value has a dual behavior in this subclass. The model is cyclical if the deteriorated products at the end of the planning horizon return to the cycle and are sold at a different price to meet part of the demand. The supply chain is considered open if these products are sold at the end of the time horizon without returning to the inventory system.

2.3.13. Lead time

Delivery delay time is the gap between ordering (production) and receiving the products. Fig 13 shows the inventory in hand and inventory positioning. Inventory position is the number of products ordered before but have not arrived in the inventory system yet. The gap between inventory in hand and inventory positioning is the delivery time, known as lead time. In Fig 13, t_1 is the ordering time, t_2 is the receiving time, and the difference between these two $t_2 - t_2$ is the lead time. In this example, the lead times for two periods have different values.

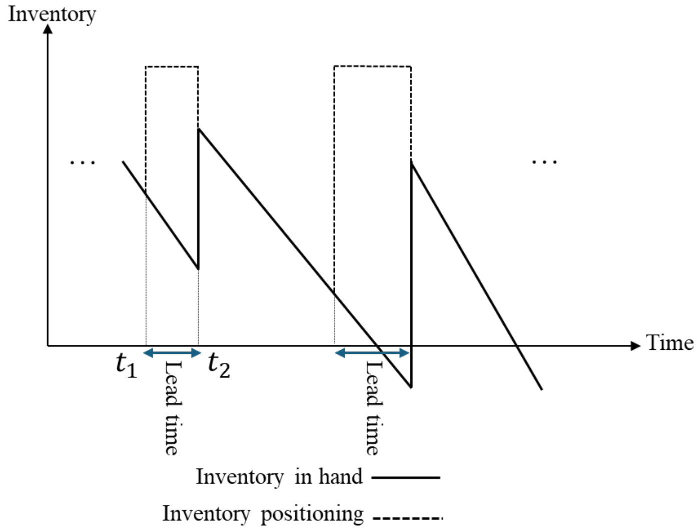

Fig. 13. The position of the lead time in an inventory system

Lead time is one of the most neglected topics in the literature. In many studies, the lead time is assumed to be zero or negligible. If there is a lead time, the safety stock is needed, which complicates the mathematical model. It should be noted that some delivery delays cannot be called lead time and are related to advance payments. Lead time can be zero or have a positive value; however, the best way to describe the real world is an uncertain lead time (especially stochastic). In this section, three subclasses are assumed.

I- Zero (91.5%): An oft-used assumption is that replenishment is instantaneous and at an infinite rate. In this case, the lead time is zero. The authors use this assumption to simplify their models (Manna et al., 2021; Mashud, 2020; Taghizadeh-Yazdi et al., 2020). Tripathi (2017) studied economic ordering policies for the inventory system of deteriorating items, considering a stock-dependent demand function. His study investigated financial conditions using a discounted cash flow approach. Later, Mishra et al. (2019) used his concept of credit period to develop their inventory control model for re-manufactured deteriorated items. They considered shortages to be not permitted and lead time to be negligible or zero. They provided an analytical approach to obtain a global solution for their model.

II- Constant (7.5%): If the lead time value is positive and definite in a mathematical model, the model is included in this subclass. However, this assumption does not change the model. It is enough to place the order earlier (as much as the lead time) so that the model does not change compared to the zero lead time. In this study, a separate subclass has been considered for this condition to respect the originality of the reviewed works (Ali et al., 2024; He et al., 2020; Khan et al., 2020b; Mallick et al., 2023; Mashud et al., 2021b). In some studies, zero lead time is assumed to be constant, which is incorrect. He and Huang (2013) optimized inventory and pricing policies for deteriorating products with seasonal demand. They investigated the effect of preservation technology on their model, which was used by Mashud et al. (2021b) later to develop their model. They considered advance payments and controllable carbon emissions to build their sustainable inventory model for deteriorating items. They considered that when advance payments are not permitted, the lead time is near zero; when there are advance payments, the lead time has a positive and constant value.

III-Uncertain (1%): The most realistic assumption related to this situation is when the lead time is positive and uncertain. The model becomes more complicated compared to the absence of lead time, and safety stock is usually necessary in this case (Transchel & Hansen, 2019). Li et al. (2018) developed an inventory model for deteriorating drugs. They considered constant demand and allowable shortages; they assumed a stochastic lead time and calculated each inventory cost's expected value to investigate the effect of probabilistic lead time. They calculated the global solution mathematically, considering a confidence level for the stochastic distribution function of the lead time.

2.3.14. Inventory constraints

One of the most neglected conditions in the literature review is the inventory constraints in the models. Constraints make the mathematical model more realistic and adapt it to the real world, however, the main issue is the difficulty and limitation of the solution methods. Many researchers ignored inventory constraints (78%) to make their solution methods less complex (Jose & Reshmi, 2021; Kalantari & Taleizadeh, 2020; Priyamvada et al., 2021; Shaikh et al., 2019d; Verma, 2024; Yang, 2023); these models are developed with objective functions. However, in recent studies, real constraints have been added to the model using more efficient solution methods such as dynamic programming (Karimi & Sadjadi, 2022; Karimi & Sadjadi, 2024; Karimi & Sadjadi, 2025). Inventory constraints relate to ordering, storage, shortage, and production. State constraints such as non-negative time, price, or inventory level or constraints related to variable type are unrelated to this category. Some models are developed with mentioned constraints (22%) such as budget, holding space, ordering time or capacity, upper and lower bounds for variables, and other inventory constraints (Acevedo-Ojeda et al., 2020; Rezagholifam et al., 2022; Taghizadeh-Yazdi et al., 2020; Tashakkor et al., 2018; Tiwari et al., 2018c; Xu et al., 2020). There are models with maximum shortages allowed and holding capacity constraints in which the upper or lower bound are variables; in this case, the mathematical model is not constrained. In two warehouse models, if both spaces are limited, the model is constrained; for any other situation, the models have no inventory constraints. Adulyasak et al. (2015) reviewed the production routing problems and compared their models and solution methods. The work of Qiu et al. (2019) is valuable when discussing inventory constraints in mathematical models for deteriorating items. This work is an extension of the work of Adulyasak et al. (2015). Qiu et al. (2019) developed production routing problems (PRPs) with perishable inventory (PRPPI). They presented an integrated production, replenishment, delivery, routing, and inventory system for deteriorating items with more than 20 constraints. They used a branch-and-cut algorithm to find the solution to their problem. They considered shortages not allowed; adding allowable shortages to their model is an excellent scope for developing their remarkable work.

2.3.15. Preservation technology

In the past, the deterioration rate was thought to be an uncontrollable phenomenon, but today, with the advancement of technology, this is possible. Preservation technology reduces the deterioration rate and increases the useful life of perishable products. One such technology is refrigerators, which lower the temperature of deteriorating products or perform inspections that reduce the rate of deterioration (Chandramohan et al., 2023). Establishing a trade-off between the amount spent on preservation technology and the savings resulting from reduced deterioration rates has recently attracted the attention of many researchers (Adak & Mahapatra, 2022; Bandaly & Hassan, 2020; Liao et al., 2024; Mishra et al., 2021b; Priyamvada et al., 2021; Sepehri et al., 2021a; Soni & Chauhan, 2018; Supakar et al., 2024b). Considering preservation technology makes the model and solution method more complicated, but on the other hand, it makes the model more adaptable to today's competitive market. This article separates studies with preservation technology (21%) from those without this phenomenon (79%). Dye (2013) investigated the effect of preservation technology on an inventory model for non-instantaneous deteriorating items. He considered a constant demand rate and assumed that investing in preservation technology reduces the deterioration rate. He ignored the disposal costs of the deteriorated products. Li et al. (2019) extended this work by considering a price-dependent demand rate and taking disposal costs for deteriorated products into account. They also considered that preservation technology affects the length of the non-deteriorating period for the products. They solved their problem analytically and provided the global optimum for their model. There are many different reducing functions for modeling the effect of preservation technology and providing a standard form for it is outside the scope of this article.

2.3.16. Financial conditions

One assumption that makes the model conform to the real world is that it includes financial conditions. Models with financial conditions (36.5%) include advance and delay in payments, discounts, full or partial time credits, trade credits, or short-term interest-free loans, credit policies consisting of a single-level, two-level, partial, and credit risk (Das et al., 2024; Jaggi et al., 2018a; Mondal et al., 2024; Roy et al., 2020; Sandhya & Chitra, 2024; Singh & Jain, 2024; Supakar et al., 2024a; Tiwari et al., 2022; Tripathi et al., 2019). Since financial conditions usually require the model to be checked in several cases, and its solution requires more time and precision, many researchers ignore it (63.5%). This article categorizes the studies according to whether or not they have financial conditions. Liao et al. (2020;2024) developed an inventory model for non-instantaneous deteriorating items. In the first article, they considered a permitted delay in payments, while the main idea of the second article is to consider advanced payments and the effects of preservation technology. Two leading researchers in this area who investigated different financial considerations are Mashud (2019; 2020a; 2020c; 2021a; 2021b; 2021c) and Shaikh (2018; 2019b; 2019c; 2019e; 2020). Yang (2023) extended his previous works (2019;2021), considering the fluctuating demand function in the inventory model for deteriorating items. In all of these works, he considered that the storage capacity is limited and the downstream trade credit is partial.

2.3.17. Non-instantaneous deteriorations

When and how the deterioration starts can completely change the mathematical model. The instantaneous (80%) onset of deterioration is the assumption used in most literature studies (Mokhtari et al., 2020; Priyamvada et al., 2022; Sepehri et al., 2021a). However, for some special items, such as high-tech or medical and food products, deterioration may be negligible initially and may start after some time. In this case, the deterioration is non-instantaneous (20%). In non-instantaneous models, the inventory system is initially traditional, and after the start of deterioration, it becomes a standard nonlinear inventory model for perishable items (Das et al., 2020; Jana & Das, 2021; Khan et al., 2022b; Liao et al., 2024; Rabiu & Ali, 2024; Shah et al., 2024; Viswanath & Thilagavathi, 2024). Fig 14 shows the inventory system for a non-instantaneous deteriorating item. In the first interval of time (zero to t_1), the inventory in hand is linear, and inventory reduction occurs only due to demand. After the deterioration (t_1 to t_2), the system's nonlinear behavior is started, and the reduction in inventory is the result of the deterioration and the demand. Since, by letting the non-deterioration period be zero, we can change non-instantaneous models into instantaneous models, these models are more general. Rathore (2019) investigated the effect of the preservation technology and trade credit on the replenishment policies in an inventory model for deteriorating items. He assumed that the demand is dependent on the advertisement. Rapolu and Kandpal (2020) extended his work in many aspects. They presented an inventory control model for deteriorating items under trade credit in which the demand is advertisement-dependent, and a preservation technology affects the deterioration rate. They considered the advertisement frequency a positive integer, which was continuous in the other work. They presented an iterative algorithm to find the optimal frequency of advertisement. In Rathore's work, price is a parameter; however, it is a decision variable in the work of Rapolu and Kandpal. They considered allowable shortages, which were ignored in his model. They changed his constant deterioration cost to a three-parameter Weibull distribution deterioration, and at last, they developed the instantaneous model presented by Rathore for non-instantaneous items.

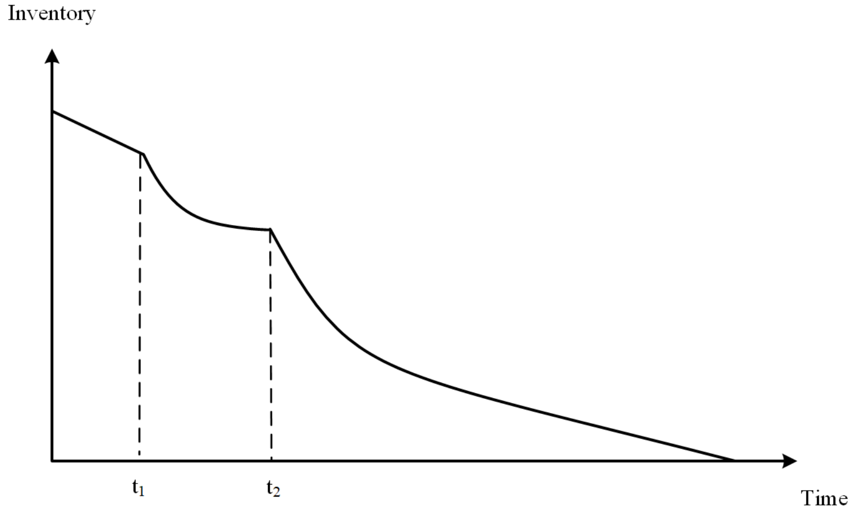

Fig. 14. The inventory system for a non-instantaneous deteriorating item

2.3.18. Environmental issues (carbon emission and green supply chain)

Recently, with the increasing attention of international organizations to environmental issues, studies related to the green supply chain and the emission of carbon and greenhouse gases have attracted the attention of many researchers (Choudhury et al., 2023; Murmu et al., 2023; Pervin, 2024; Pervin et al., 2023; Rout et al., 2021b; San-José et al., 2024). Considering the role of perishable items in environmental issues (such as radioactive materials, food wastes, and industrial pollutants), this literature has not been excluded from this issue. Previous studies in this article have been categorized in terms of their attention to environmental problems. Many studies (85%) ignored this issue (Khakzad & Gholamian, 2020; Kumar et al., 2024; Mahato & Mahata, 2021; Sebatjane, 2022; Verma, 2024) while other works studied environmental obligations, such as controlling the emission of carbon, radioactive, and greenhouse gases or decreasing waste and pollution (15%). Mishra et al. (2020) developed a model for inventory control for deteriorating items. They considered the deterioration non-instantaneous and optimized the investments and selling price. Their results showed that investing in a sustainable supply chain is beneficial to control deterioration rate and emissions. Mishra et al. (2021b) extended the model of their previous study, considering allowable shortages with back-ordering under the carbon tax and cap regulations assumptions. Mashud et al. (2020b) extended these two works by combining investments in green technology and preservation technology for deteriorating items. Another notable work in this subclass is the work of Saxena et al. (2024). They studied different costs and aspects of green supply chain and gas emissions in their proposed model for deteriorating items inventory control.

The organization of classes and subclasses was fully explained in the current section. More detailed issues, such as the type of variable demand or how to pay attention to environmental problems, are beyond the scope of this study. Researchers can search the original studies reviewed in this article for more details. Note that in the studies that used several subclasses in one class, the one that is more important (or rare in some classes) is announced. For example, the study is classified as uncertain if both certain and uncertain models are presented. Also, in a study with several subclasses, in which one of them can transform into others by making changes (for example, a shortage with partial backlogging can change into lost sales or complete backlogging by changing the parameters), the most general gorm is declared. The more common category is assumed in some classes where the subclass is not explicitly stated (such as the planning horizon).

2.4. Comprehensive review

This section will review some remarkable articles in detail to find the critical factors in providing a good study on this topic. We suggest researchers highlight their contributions based on the proposed classification (like what we did in this section) to show how their work helps to fill research gaps. Khakzad and Gholamian (2020) studied the effect of inspection on the deterioration rate in an inventory model for deteriorating items. They assumed that the number of inspection times during replenishment affects the average deterioration rate. Key factors of their works are a) considering variable deterioration rate depending on multiple inspections, b) prepayments were imposed to the retailer by the supplier, c) the convexity of the model is provided, and the solution method is exact, and d) they validated their model and solution procedure by analyzing a case study in the real world. They reached some noticeable insights. For example, they found that the managers can investigate the effect of inspection by simulating the model without any concern about actual costs. Khan et al.'s (2020b) main idea is to investigate the effect of non-instantaneous deterioration. They developed a two-warehouse model and considered the decay in owned warehouses to begin earlier due to better inventory management in the rented one. Their main strengths are a) they assumed the demand is price-dependent, b) investigating non-instantaneous deterioration in their work, which is rare, c) considering advance payments, d) developing a two-warehouse model to adapt the mathematical model to the real world, e) considering allowable shortages with partial backlogging, f) presenting three different models based on the starting times of deterioration and g) providing three exact algorithms to find the global optimum of each model. They suggested the managers use all tools, such as the latest methods, technology, and other facilities, to arrest the deterioration rate, which is the primary outcome of their study.

The main subject of the work studied by Mishra et al. (2021b) is considering environmental issues in a green supply chain and reducing carbon emissions. They investigated the effect of preservation technology in a greenhouse farm to control the deterioration and carbon emissions. Their study developed a carbon cap and tax-regulated sustainable inventory management for a buyer. Their work includes a) variable demand in two forms, one linear and one nonlinear, both dependent on the price; b) considering carbon emissions, c) investigating how the preservation technology affects the model, d) considering partial backlogging, and e) solving the problem with exact methods and obtaining the global solution. Their more meaningful results are as follows: 1) total profit is concave, and the optimum answer is the global solution; 2) carbon tax improves the total profit, and 3) preservation and green technology investments reduce the deterioration and carbon emissions.

Sepehri et al.'s (2021b) work considered many realistic assumptions. They studied an inventory model and pricing for deteriorating items with a maximum lifetime; they assumed carbon emissions are controllable and a payment delay is available. Their model includes price-dependent demand and carbon cap-and-trade regulation. Remarkable aspects of their work are: a) variable demand function, b) variable deterioration function depending on the maximum lifetime, c) considering carbon emissions. and d) proving the model is pseudo-convex and the obtained solution is global (but not necessarily unique). The results of their work show that carbon tax increases the total profit, and a trade-off must be considered in investigating carbon reduction technologies to increase the profit obtained along with eliminating emissions.

One of the prominent works in recent years is Duary et al. (2022). They developed a model with some good aspects, including multi-financial conditions, price discounts, shortages with partial backlog, and capacity constraints. Their work was created consisting of a) discounts in prices, b) two warehouses with different parameters, c) advance and delay in payments, d) partial backlogging with a waiting time-dependent rate, e) variable demand dependent on the selling price, time and frequency of advertisement, f) infinite time horizon with unit time objective function and, g) considering capacity constraint for vehicles. The main weakness of their work is the lack of an exact solution method due to the complexity of the nonlinear model. The sensitivity analysis results show that their model's primary outcome values depend on the location parameter of the demand function.

When finding a solution method (especially exact ones) is challenging for many researchers, Karimi and Sadjadi (2025) compared the performance of nine different solution methods for solving an inventory model for deteriorating items. They assumed a) shortages with partial backlogging are allowed, and the backlogging rate depends on the waiting time for the next replenishment, b) demand is a function of time, c) holding costs are variable and time-dependent, d) the model is developed for multi-items, e) there is a two-level quantity discount, f) capacity and budget are limited, g) the unspent money can be invested in an outside business, h) two exact method including dynamic programming and greedy search alongside seven metaheuristic methods were implemented to solve the problem, i) a comparison between solution methods are provided, j) the analytical and practical efficiency of each method is presented and k) it is assumed that variables are discrete and continuous. They solved the proposed model as a traditional knapsack problem using backward dynamic programming and validated the results by comparing them with a greedy search. The results show that the proposed method can solve the constrained problem well and is more capable than others in solving small and mid-sized problems (which represent real-world problems very well).

Based on what was mentioned, considering ignored assumptions and providing an exact optimal solution generally strengthens the article. This article will present research gaps and ways to fill them based on the review.

The review is completed int this section, reviewing more than 300 articles in 18 classes and 33 subclasses (some classes include only one state, we did not consider it as a subclass), is challenging; we have tried our best to do it without errors. Table 4 and Fig 15 summarize the classification of the reviewed papers.

Table 4
A summary of the classification of the reviewed articles

Reference	Deterioration	Demand	shortages	Warehouses	Time value of money	Model	Echelons	Costs and prices	Solution	Multi- items	Time Horizon	Supply chain	lead time	Inventory Constraints	Preservation technology	Financial conditions	Non-instantaneous	Environmental issues
(Acevedo-Ojeda et al., 2020)	V	C	N	1	N	PR	2	C	G	N	FI	OP	0	Y	N	N	N	N
(Acosta et al., 2018)	C	C	N	1	N	PR	3	C	G	N	FI	OP	0	Y	N	N	N	N
(Adak & Mahapatra, 2022)	V	V	PB	1	N	OR	1	V	G	Y	FI	OP	0	N	Y	N	N	N
(Affandi, 2018)	V	V	N	1	N	PR	1	C	G	Y	FI	OP	0	N	N	N	N	N
(Agi & Soni, 2020)	C	V	N	1	N	OR	1	C	G	N	IN	CY	0	Y	N	N	N	N
(Ahmadi et al., 2020)	V	P	CB	1	N	OR	2	V	L	N	FI	OP	C	Y	N	N	N	N
(Aliabadi et al., 2019)	C	V	PB	1	N	OR	3	C	L	N	IN	OP	0	N	N	Y	Y	Y
(Aliyu & Sani, 2018)	V	V	N	1	N	OR	1	C	G	N	IN	OP	0	N	N	N	N	N
(Bai et al., 2019)	C	V	N	1	N	PR	2	C	G	N	FI	OP	0	N	N	N	N	Y
(Bandaly & Hassan, 2020)	V	P	N	1	N	PR	1	V	L	Y	FI	OP	0	Y	Y	N	N	N
(Bardhan et al., 2019)	V	V	N	1	N	OR	1	V	G	N	FI	OP	0	N	Y	N	Y	N
(Barman et al., 2022)	C	V	CB	1	N	PR	2	V	G	N	FI	OP	0	N	N	Y	Y	N
(Barman et al., 2023)	V	V	N	1	N	OR	2	V	L	N	FI	OP	0	N	N	N	N	N
(Bhaula et al., 2019)	C	V	N	1	D	OR	2	C	L	N	FI	OP	0	N	N	Y	Y	N
(Bhunia et al., 2018)	C	V	PB	1	N	OR	1	C	L	N	IN	CY	0	Y	N	N	N	N
(Braglia et al., 2019)	C	P	PB	1	N	OR	1	C	G	N	FI	OP	C	N	N	N	N	N
(Çalışkan, 2021a)	C	C	PB	1	N	OR	1	C	L	N	FI	OP	0	N	N	N	N	N
(Çalışkan, 2021b)	C	C	PB	1	N	OR	1	C	L	N	FI	OP	0	N	N	N	N	N
(Chakrabarty et al., 2018a)	C	V	PB	2	B	OR	1	C	L	N	FI	OP	0	Y	N	Y	N	N
(Chakrabarty et al., 2018b)	V	V	PB	2	B	OR	1	C	L	N	FI	OP	0	Y	N	Y	Y	N
(Chakrabarty et al., 2020)	C	V	PB	M	B	OR	1	C	L	Y	FI	OP	0	Y	N	N	Y	N
(Chandramohan et al., 2023)	V	V	PB	1	N	OR	3	V	G	N	FI	OP	0	N	Y	Y	Y	Y
(Chen et al., 2021)	P	P	N	1	N	OR	1	V	G	N	FI	OP	0	N	N	N	N	N
(Chen et al., 2019)	C	V	N	1	N	OR	1	V	G	N	FI	OP	0	N	N	N	N	N
(Cheng et al., 2020)	C	V	N	1	D	OR	1	C	G	N	FI	CY	0	N	N	Y	N	N
(Choudhury & Mahata, 2022)	V	V	N	1	N	PR	2	V	G	N	FI	OP	0	N	Y	Y	N	N
(Choudhury et al., 2022a)	V	F	N	1	N	PR	2	C	G	N	FI	OP	0	N	N	Y	N	Y
(Choudhury et al., 2022b)	V	V	N	1	N	PR	2	C	G	N	FI	OP	0	N	N	N	N	Y
(Chung et al., 2019)	C	C	N	1	D	OR	1	C	G	N	IN	OP	0	N	N	Y	N	N
(Dari & Sani, 2020)	C	V	N	1	N	PR	1	V	G	N	FI	OP	0	N	N	N	N	N
(Daryanto & Wee, 2020)	V	C	N	1	N	PR	3	V	L	N	FI	OP	0	N	Y	N	N	Y
(Daryanto & Wee, 2018)	C	C	N	1	N	PR	2	C	L	N	FI	OP	0	N	N	N	N	Y
(Daryanto et al., 2019)	C	C	N	1	N	PR	3	C	L	N	FI	OP	0	N	N	N	N	Y
(Das & Roy, 2018)	V	V	PB	1	N	OR	1	V	G	N	IN	CY	0	N	N	N	Y	N
(Das et al., 2021)	V	V	PB	1	N	OR	1	V	L	N	FI	OP	0	Y	Y	Y	Y	N
(Das et al., 2020)	V	V	PB	1	N	OR	1	V	L	N	IN	OP	C	N	Y	N	Y	N
(Dolgui et al., 2018)	C	C	N	1	N	PR	3	C	L	N	FI	OP	C	Y	N	N	N	N
(Duan et al., 2018)	C	P	PB	1	N	PR	1	V	G	N	FI	OP	0	N	N	N	N	N
(Duary et al., 2022)	C	V	PB	2	D	OR	2	V	L	N	IN	OP	0	Y	N	Y	N	N
(Ghandehari & Dezhtaherian, 2019)	C	C	PB	1	B	OR	1	C	G	N	FI	OP	0	N	N	Y	N	N
(Ghiami & Beullens, 2020)	C	V	PB	2	D	OR	2	C	G	N	FI	OP	0	Y	N	N	N	N
(Gupta et al., 2020)	V	C	PB	2	D	OR	1	C	G	N	FI	OP	0	N	N	Y	N	N
(Halim et al., 2021)	C	V	N	1	N	PR	1	V	G	N	IN	OP	0	N	N	Y	N	N
(Hasan et al., 2020)	V	V	N	1	D	OR	1	V	G	N	FI	OP	0	N	Y	N	Y	N
(He et al., 2020)	C	V	N	1	N	OR	2	V	G	N	IN	OP	C	N	N	N	N	N
(Huang et al., 2018a)	C	V	N	1	N	PR	2	V	G	N	FI	OP	0	N	N	N	N	N
(Huang et al., 2018b)	V	V	N	1	N	PR	3	V	L	N	FI	OP	0	N	Y	N	N	Y
(Indrajitsingha et al., 2018)	F	F	N	1	N	PR	1	F	L	N	FI	OP	0	N	N	N	N	N
(Indrajitsingha et al., 2019a)	F	F	PB	2	N	OR	1	F	L	N	FI	OP	0	N	N	N	N	N
(Jaggi et al., 2018b)	C	V	PB	1	N	OR	1	C	L	N	FI	CY	0	N	N	Y	N	N
(Jaggi et al., 2019)	C	V	N	2	N	OR	2	C	L	N	FI	OP	0	Y	N	Y	N	N
(Jani et al., 2020)	C	V	N	1	I	OR	2	C	L	N	FI	OP	0	N	N	Y	N	N
(Jose & Reshmi, 2021)	C	P	PB	1	N	PR	1	C	G	N	FI	OP	0	N	N	N	N	N
(Kalantari & Taleizadeh, 2020)	V	C	N	1	N	PR	1	C	G	N	FI	OP	0	N	N	N	N	N
(Karimi & Sadjadi, 2022)	C	V	PB	1	N	OR	1	C	G	Y	FI	OP	0	Y	N	N	N	N
(Karimi & Sadjadi, 2024)	C	V	PB	1	I	OR	1	C	G	N	FI	OP	0	Y	N	N	Y	N
(Karimi & Sadjadi, 2025)	C	V	PB	1	D	OR	1	V	G	Y	FI	OP	0	Y	N	N	N	N
(Karimi et al., 2019)	C	V	PB	1	N	OR	1	C	G	N	FI	CY	0	N	N	N	N	N
(Kaur et al., 2024)	V	V	PB	2	I	OR	1	F	L	N	FI	OP	0	N	N	N	N	N
(Kaya & Ghahroodi, 2018)	C	P	N	1	N	OR	1	C	G	N	FI	CY	0	N	N	N	N	N
(Khakzad & Gholamian, 2020)	V	C	N	1	N	OR	1	V	G	N	FI	OP	0	N	Y	Y	N	N
(Khan et al., 2022a)	C	V	N	1	D	OR	1	V	G	N	FI	OP	0	N	N	N	N	N

Table 4

A summary of the classification of the reviewed articles (continued)

Reference	Deterioration	Demand	shortages	Warehouses	Time value of money	Model	Echelons	Costs and prices	Solution	Multi- items	Time Horizon	Supply chain	lead time	Inventory Constraints	Preservation technology	Financial conditions	Non-instantaneous	Environmental issues
(Khan et al., 2022b)	V	V	PB	1	N	OR	1	V	L	N	FI	CY	0	Y	N	Y	Y	Y
(Khan et al., 2020a)	V	V	PB	1	N	OR	1	V	G	N	FI	OP	C	N	N	Y	N	N
(Khan et al., 2019)	C	V	PB	2	N	OR	1	C	G	N	IN	OP	C	N	N	Y	N	N
(Khan et al., 2020b)	C	V	PB	2	N	OR	1	C	G	N	FI	OP	C	N	N	Y	Y	N
(Khanna et al., 2020)	V	V	N	1	N	OR	1	V	L	N	IN	OP	0	N	Y	N	N	N
(Khurana et al., 2018)	V	V	PB	1	N	PR	1	C	L	N	FI	OP	0	N	N	N	N	N
(Kumar & Chanda, 2018)	C	V	N	2	N	OR	1	C	L	N	FI	OP	0	N	N	N	N	N
(Kumar et al., 2024)	C	V	N	2	N	PR	1	V	L	N	FI	OP	0	N	N	N	N	N
(Kung et al., 2019)	C	C	PB	1	N	PR	1	C	G	N	FI	CY	0	N	N	N	N	N
(Kurade & Latpate, 2021)	V	P	PB	1	N	OR	1	C	L	N	FI	OP	0	N	N	N	N	N
(Lashgari et al., 2018)	C	C	PB	1	N	OR	1	C	G	N	IN	OP	C	N	N	Y	Y	N
(Li et al., 2019)	V	V	PB	1	N	OR	1	V	G	N	FI	OP	0	N	Y	N	Y	N
(Li et al., 2018)	C	C	LP	1	N	OR	1	C	G	N	FI	OP	P	Y	N	N	N	N
(Liao et al., 2020)	C	C	N	1	N	OR	1	C	G	N	IN	OP	0	N	N	Y	Y	N
(Lin et al., 2019)	C	P	N	2	N	OR	1	C	G	N	FI	OP	0	Y	N	N	N	N
(Lin et al., 2018)	C	C	N	1	N	PR	2	C	G	N	IN	OP	0	Y	N	Y	N	N
(Loedy et al., 2018)	C	V	CB	1	D	OR	1	C	L	N	IN	CY	0	N	N	N	N	N
(Mahapatra et al., 2022a)	V	F	CB	1	N	OR	1	V	G	N	FI	OP	0	N	Y	N	N	N
(Mahapatra et al., 2019a)	C	F	CB	1	N	OR	1	C	G	N	FI	OP	0	N	N	N	N	N
(Mahapatra et al., 2019b)	V	V	CB	1	I	OR	1	F	L	N	FI	OP	0	N	N	Y	N	N
(Mahata et al., 2020)	V	V	N	1	N	OR	2	C	G	N	IN	OP	0	N	N	Y	N	N
(Mahata et al., 2019)	C	V	N	1	B	OR	1	C	G	N	FI	OP	0	N	N	Y	N	N
(Mahata & Debnath, 2022)	V	V	N	1	N	OR	2	V	G	N	FI	OP	0	Y	Y	N	N	N
(Mahato & Mahata, 2021)	V	V	N	1	N	OR	2	C	G	N	FI	OP	0	N	N	Y	N	N
(Mahmoodi, 2019)	C	V	CB	1	N	OR	2	V	G	Y	FI	OP	0	N	N	N	N	N
(Maihami et al., 2021)	C	V	PB	1	N	OR	1	V	G	N	FI	OP	0	N	N	N	Y	Y
(Maihami et al., 2019)	P	P	N	1	N	PR	3	V	L	N	FI	OP	0	N	N	N	N	N
(Maiti, 2020)	C	V	N	M	N	OR	1	F	L	Y	IN	OP	0	N	N	N	N	N
(Mallick et al., 2023)	C	F	N	1	I	OR	1	C	G	N	FI	OP	C	N	N	N	N	N
(Manna et al., 2021)	C	V	PB	2	D	OR	1	C	G	N	IN	OP	0	N	N	N	N	N
(Mashud, 2020)	C	V	CB	1	N	OR	1	C	G	N	IN	OP	0	Y	N	N	N	N
(Mashud et al., 2020a)	V	V	PB	1	N	OR	1	V	G	N	FI	CY	0	Y	Y	Y	Y	N
(Mashud et al., 2020b)	V	V	N	1	D	OR	1	V	G	N	FI	CY	0	N	Y	N	N	Y
(Mashud et al., 2021a)	V	V	N	1	D	OR	1	V	G	N	FI	OP	0	N	N	Y	N	N
(Mashud et al., 2021b)	V	V	PB	1	N	OR	1	C	G	N	FI	OP	C	N	Y	Y	Y	Y
(Mashud et al., 2019)	C	V	CB	1	N	OR	2	V	G	N	IN	OP	0	Y	N	Y	N	N
(Mashud et al., 2021c)	V	V	PB	1	N	OR	2	V	G	N	IN	OP	0	Y	Y	Y	Y	N
(Mashud et al., 2020c)	C	V	PB	2	D	OR	2	C	G	N	IN	OP	C	N	N	Y	Y	Y
(Mashud et al., 2018)	C	V	PB	1	N	OR	1	C	L	N	IN	OP	0	N	N	N	Y	N
(Md Mashud & Hasan, 2019)	C	V	PB	1	N	OR	1	C	G	N	IN	OP	0	Y	N	N	N	N
(Mishra et al., 2021a)	V	V	PB	1	N	OR	1	V	G	N	FI	OP	C	N	Y	Y	N	Y
(Mishra et al., 2018)	V	V	N	1	N	OR	1	V	G	N	IN	OP	0	N	Y	Y	N	N
(Mishra et al., 2021b)	V	V	PB	1	N	OR	1	V	G	N	IN	OP	0	N	Y	N	N	Y
(Mishra et al., 2019)	C	V	N	1	D	OR	1	C	G	N	FI	CY	0	N	N	Y	N	N
(Mishra et al., 2020)	V	V	N	1	N	OR	1	V	G	N	FI	OP	0	N	Y	Y	Y	Y
(Mohammadzadeh & (Mirzazadeh, 2018)	F	F	N	1	N	PR	2	V	G	N	FI	OP	0	N	N	N	N	N
(Mohanty et al., 2018)	V	V	PB	1	N	OR	1	V	L	N	FI	OP	0	N	Y	Y	N	N
(Mokhtari et al., 2020)	C	C	N	1	N	PR	1	C	L	N	IN	OP	0	N	N	N	N	N
(Mondal et al., 2019)	V	V	N	1	N	OR	1	P	L	N	IN	OP	0	N	N	N	N	N
(Mukherjee & Mahata, 2018)	V	V	N	1	N	OR	2	C	G	N	FI	OP	0	N	N	Y	N	N
(Onggo et al., 2019)	C	P	N	M	N	OR	1	C	L	N	FI	OP	0	Y	N	N	N	N
(Padiyar et al., 2024)	V	V	PB	1	I	PR	1	C	G	N	FI	CY	0	N	Y	N	N	N
(Pal et al., 2018)	V	C	PB	1	N	OR	1	V	G	N	FI	OP	0	N	Y	N	Y	N
(Palanivel et al., 2018)	C	V	PB	2	B	OR	1	C	G	N	FI	OP	0	N	N	N	Y	N
(Panda et al., 2019)	C	V	PB	2	N	OR	1	C	L	N	IN	OP	0	Y	N	Y	N	N
(Pando et al., 2018)	C	V	N	1	N	OR	1	V	L	N	IN	OP	0	N	N	N	N	N
(Patriarca et al., 2020)	V	V	PB	1	N	OR	1	V	L	N	FI	OP	0	N	N	N	N	N
(Patro et al., 2018)	C	F	N	1	D	OR	1	V	G	N	FI	OP	0	N	N	N	N	N
(Paul et al., 2022)	C	V	N	1	N	OR	1	V	G	N	FI	OP	0	N	N	N	N	Y
(Paul et al., 2021)	V	V	PB	1	N	OR	1	C	G	N	IN	OP	0	N	N	Y	N	N
(Perez & Torres, 2019)	C	C	N	1	D	PR	2	C	L	N	FI	OP	0	N	N	N	N	N
(Pervin et al., 2019)	C	V	PB	1	D	PR	2	C	G	Y	FI	OP	0	N	N	Y	N	N
(Pervin et al., 2023)	V	V	N	1	N	OR	1	V	G	N	FI	CY	0	N	N	N	Y	Y

Table 4
A summary of the classification of the reviewed articles (continued)

Reference	Deterioration	Demand	shortages	Warehouses	Time value of money	Model	Echelons	Costs and prices	Solution	Multi- items	Time Horizon	Supply chain	lead time	Inventory Constraints	Preservation technology	Financial conditions	Non-instantaneous	Environmental issues
(Pramanik & Maiti, 2019)	C	V	N	1	B	OR	1	C	L	N	FI	OP	0	N	N	Y	N	N
(Priyamvada et al., 2022)	V	V	N	1	N	OR	1	V	G	N	IN	OP	0	N	Y	N	N	N
(Priyamvada et al., 2021)	V	V	PB	1	N	PR	2	V	G	N	FI	OP	0	N	Y	N	N	N
(Qiu et al., 2019)	V	V	N	1	N	PR	1	C	G	N	FI	OP	0	Y	N	N	N	N
(Rabbani et al., 2018)	C	F	PB	1	N	OR	2	V	L	Y	FI	OP	0	Y	N	N	N	N
(Rahaman et al., 2020)	C	C	N	1	N	PR	1	C	L	N	IN	OP	0	N	N	N	N	N
(Rahman et al., 2020a)	P	P	PB	1	N	OR	1	P	L	N	IN	OP	0	N	N	N	N	N
(Rahman et al., 2021)	V	V	PB	1	D	OR	1	V	G	N	IN	OP	0	N	Y	Y	N	N
(Rahman et al., 2020b)	P	P	N	1	N	PR	1	P	L	N	IN	OP	0	N	Y	Y	N	N
(Rameswari & Uthayakumar, 2018)	C	V	N	1	N	OR	1	C	G	N	IN	OP	0	N	N	Y	N	N
(Rana et al., 2021)	C	V	PB	2	B	OR	1	C	L	N	IN	OP	0	N	N	N	N	N
(Rani et al., 2019)	F	F	N	1	N	PR	2	C	G	N	FI	CY	0	N	N	N	N	Y
(Rapolu & Kandpal , 2020)	V	V	PB	1	N	OR	1	V	G	N	FI	OP	0	Y	Y	Y	Y	N
(Rastogi & Singh, 2018)	C	V	PB	1	B	PR	1	C	L	N	FI	OP	0	N	N	N	N	N
(Rastogi & Singh, 2019)	V	V	PB	1	N	OR	1	V	L	N	FI	OP	0	N	N	N	N	N
(Rezagholifam et al., 2022)	C	V	N	1	N	OR	1	V	G	N	FI	OP	0	Y	N	N	Y	N
(Rout et al., 2020)	C	C	CB	1	N	PR	1	C	G	N	FI	OP	0	N	N	N	N	N
(Rout et al., 2021a)	C	V	PB	1	N	PR	1	C	G	N	IN	OP	0	N	N	N	N	N
(Rout et al., 2021b)	C	C	N	1	N	PR	2	C	L	N	FI	OP	0	Y	N	N	N	Y
(Saha & Sen, 2019)	V	V	PB	1	I	OR	1	C	L	N	IN	OP	0	N	N	N	N	N
(Sahoo et al., 2019)	V	V	PB	1	N	OR	1	C	G	N	FI	OP	0	N	N	N	N	N
(Saxena et al., 2024)	C	V	PB	1	B	OR	1	V	L	N	FI	OP	0	N	N	N	N	Y
(Sebatjane, 2022)	V	C	N	1	N	PR	3	V	G	N	IN	OP	0	N	Y	N	N	N
(Sen & Saha, 2018)	C	V	CB	1	N	OR	1	V	L	N	IN	OP	0	N	N	Y	N	N
(Sepehri et al., 2021a)	V	V	N	1	N	PR	2	V	G	N	FI	CY	0	N	Y	N	N	Y
(Sepehri et al., 2021b)	V	V	N	1	N	OR	1	V	G	N	FI	OP	0	N	N	Y	N	Y
(Shah et al., 2020)	C	V	N	1	N	PR	3	V	L	N	IN	OP	0	Y	N	Y	N	N
(Shah et al., 2018)	V	V	N	1	N	PR	1	V	L	N	IN	OP	0	N	Y	Y	N	N
(Shah et al., 2019)	C	V	N	1	N	OR	1	C	L	Y	IN	OP	0	N	N	N	N	N
(Shaikh & Cárdenas-Barrón, 2020)	C	V	N	1	N	OR	1	C	G	N	FI	OP	0	N	N	Y	Y	N
(Shaikh et al., 2018)	C	V	PB	1	N	OR	1	F	L	N	IN	OP	0	N	N	Y	N	N
(Shaikh et al., 2019a)	C	V	PB	2	I	OR	1	P	L	N	IN	OP	0	N	N	N	Y	N
(Shaikh et al., 2019b)	V	V	PB	1	N	OR	1	C	G	N	IN	OP	0	Y	N	Y	N	N
(Shaikh et al., 2019c)	C	V	PB	2	N	OR	1	F	L	N	IN	OP	0	N	N	Y	N	N
(Shaikh et al., 2019d)	C	V	PB	1	D	OR	1	V	G	N	IN	OP	0	N	N	N	N	N
(Shaikh et al., 2020)	V	V	PB	1	N	OR	1	V	G	N	FI	OP	0	N	Y	Y	N	N
(Shaikh et al., 2019e)	V	V	PB	1	N	OR	1	V	G	N	IN	OP	0	Y	Y	Y	N	N
(Sharifi et al., 2021)	C	C	CB	1	N	OR	1	C	G	N	FI	OP	0	N	N	N	N	N
(Sharma et al., 2020)	F	F	CB	1	N	OR	1	C	G	N	IN	OP	0	N	N	Y	Y	N
(Sharma et al., 2024)	V	V	PB	1	N	OR	1	V	L	N	IN	OP	C	N	N	Y	Y	N
(Sharma et al., 2018a)	C	V	PB	1	I	OR	1	V	L	N	FI	OP	0	N	N	Y	N	N
(Sharma et al., 2018b)	V	V	PB	1	N	OR	1	V	G	N	FI	OP	0	N	N	N	N	N
(Shen et al., 2019)	V	C	N	1	N	PR	2	V	L	N	IN	OP	0	N	Y	N	N	Y
(Shi et al., 2019)	C	V	N	1	N	OR	1	C	G	N	IN	OP	0	N	N	Y	N	N
(Singh, 2019)	V	V	PB	1	N	PR	1	V	G	N	FI	OP	0	N	Y	N	N	N
(Singh & Mishra, 2021)	F	F	LP	1	N	OR	1	C	L	Y	FI	OP	0	N	N	N	Y	Y
(Singh & Sharma, 2019)	V	V	PB	1	B	PR	2	C	G	N	IN	CY	0	N	N	N	N	N
(Singh et al., 2018)	V	V	CB	1	N	OR	1	C	G	N	IN	OP	0	N	N	N	N	N
(Soni & Chauhan, 2018)	V	P	PB	1	N	OR	1	V	G	N	FI	OP	0	N	Y	N	N	N
(Soni & Suthar, 2019)	V	P	PB	1	N	OR	1	V	G	N	IN	OP	0	Y	N	N	Y	N
(Supakar & Mahato, 2022)	V	F	N	1	D	PR	1	F	G	N	FI	OP	0	N	N	Y	N	N
(Supakar et al., 2024b)	F	F	N	1	N	PR	1	F	L	N	IN	OP	0	N	Y	N	N	N
(Taghizadeh-Yazdi et al., 2020)	C	V	PB	1	N	PR	3	V	G	Y	FI	OP	0	Y	N	N	N	N
(Tai et al., 2019)	P	C	N	1	N	OR	1	C	G	N	FI	CY	0	N	N	N	N	N
(Tashakkor et al., 2018)	V	V	N	1	N	OR	1	V	G	N	FI	OP	0	Y	N	N	Y	N
(Tayal et al., 2019)	C	V	PB	2	N	OR	1	C	L	N	IN	OP	0	Y	N	N	N	N
(Tiwari et al., 2019)	F	F	N	1	N	OR	1	C	L	N	IN	OP	0	N	N	Y	Y	Y
(Tiwari et al., 2018a)	V	V	PB	1	N	OR	3	C	G	N	FI	OP	0	N	N	Y	N	N
(Tiwari et al., 2018b)	C	C	N	1	N	PR	2	C	L	N	IN	OP	0	N	N	N	N	Y
(Tiwari et al., 2018c)	C	V	CB	2	N	OR	2	V	G	N	IN	OP	0	Y	N	N	N	N
(Transchel & Hansen, 2019)	V	P	N	1	N	OR	1	C	G	N	FI	OP	P	Y	N	N	N	N
(Udayakumar, & Geetha, 2018)	C	C	N	2	N	OR	1	C	G	N	IN	OP	0	N	N	Y	Y	N

Table 4
A summary of the classification of the reviewed articles (continued)

Reference	Deterioration	Demand	shortages	Warehouses	Time value of money	Model	Echelons	Costs and prices	Solution	Multi- items	Time Horizon	Supply chain	lead time	Inventory Constraints	Preservation technology	Financial conditions	Non-instantaneous	Environmental issues
(Uthayakumar & Karuppasamy, 2019)	C	V	N	1	N	OR	1	C	L	N	IN	OP	0	N	N	N	N	N
(Uthayakumar & Priyadharshini, 2024)	C	V	PB	1	N	OR	1	V	L	N	IN	OP	0	N	N	Y	Y	N
(Verma, 2024)	V	C	N	1	I	PR	1	C	L	N	IN	OP	0	N	N	Y	N	N
(Viji & Karthikeyan, 2018)	V	C	CB	1	N	PR	1	C	L	N	FI	OP	0	N	N	N	N	N
(Wei et al., 2020)	V	V	N	1	N	OR	1	V	L	N	FI	OP	C	N	N	N	N	N
(Wu et al., 2018a)	V	C	PB	1	N	OR	1	C	G	N	FI	OP	0	N	N	Y	N	N
(Wu et al., 2018b)	V	V	PB	1	D	OR	1	C	G	N	FI	OP	0	N	N	Y	N	N
(Xu et al., 2020)	V	V	PB	1	N	OR	1	C	G	N	FI	OP	0	Y	N	N	N	Y
(Yadav & Swami, 2018)	V	V	PB	1	N	PR	1	V	L	N	IN	OP	0	N	N	N	N	N
(Yadav & Swami, 2019)	C	V	CB	2	N	OR	1	V	L	N	FI	OP	0	N	N	N	Y	N
(Yang, 2023)	C	V	N	2	D	OR	1	C	G	N	FI	OP	0	N	N	Y	N	N
(Yang et al., 2020)	V	V	N	1	N	OR	1	C	G	N	FI	OP	0	N	Y	N	N	N
(Yu et al., 2020)	V	V	CB	1	N	OR	1	C	G	N	FI	OP	0	N	Y	N	N	Y

C: Constant; V: Variable; F: Fuzzy; P: Probabilistic; PB: Partial backlogging; CB: Complete backlog; LS: Lost sales; I:Inflation; D: Discounts; B: Both; N: No; Y: Yes; PR: Production; OR: Ordering; G: Global; L: Local; FI: Finite; IN: Infinite; OP: Open supply chain; CY: Cyclic supply chain;

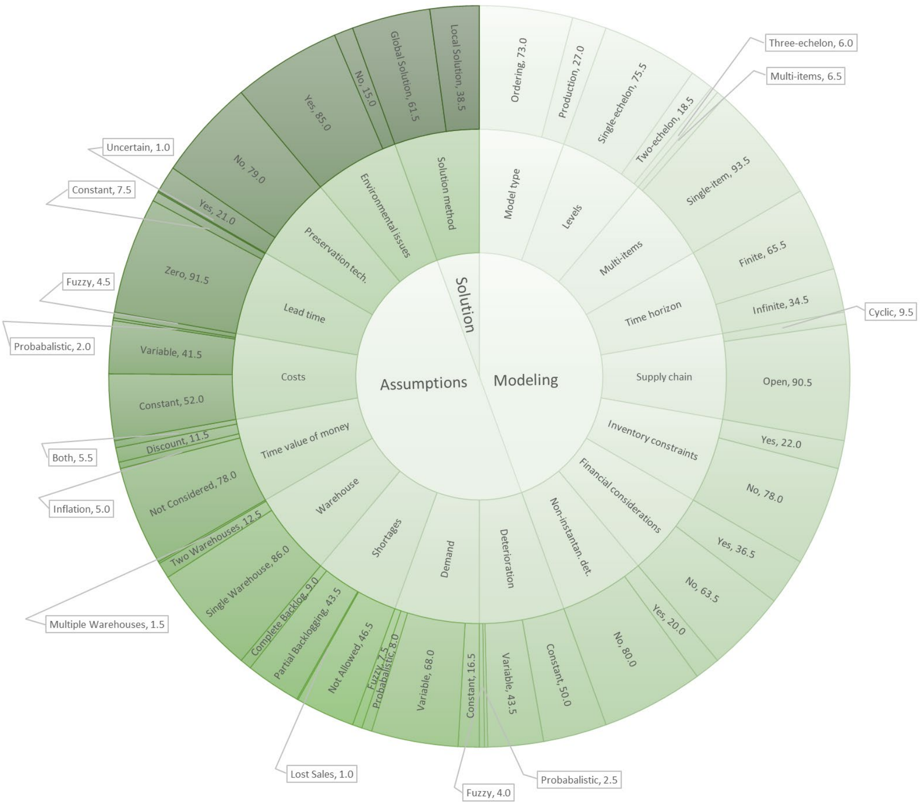

Fig. 15. Frequency of each subclass (percentage)

3. Results and discussion

After classifying the existing studies, it is necessary to investigate which categories have received less attention and which direction future studies should follow. This section presents research gaps and insights for researchers interested in this topic.

3.1 Research gaps and future scopes

In this section, we discuss research gaps and study points that have received the least attention among the 18 existing categories in previous studies. Fig 16 provides a summary of the research gaps and a roadmap for contributing to these findings. This figure does not show the priority of the classes, and the order is based on the classification section.

1. Deterioration: Probabilistic and fuzzy deterioration rates have attracted the least attention in this class. However, since sufficient historical data makes it possible to estimate the rate of deterioration with a good approximation, this is not the research gap for this category. In this section, considering the time-varying deterioration rate is the best way to develop existing models because these functions show the nature of decay in the best way.
2. Demand: In this category, it is better to use the uncertain demand and comprehensive variable demand function that depends on multiple parameters such as time, price, advertising, showcase inventory, and a complete combination of these items to improve the studies.
3. Shortages: The most apparent discussion of the research gap is about shortages. Undoubtedly, the allowable shortages make the model more realistic. Since partial backlogging includes all other subclasses and can be changed to all kinds of shortage states by changing the parameters, it is the best and most complete type of shortage to consider.
4. Warehouses: Considering two or more warehouses can make the model match the real world. Commonly, the business has a warehouse with a smaller space but close to the store and a larger warehouse further away with different parameters. However, it should be noted that this assumption can be valuable when combined with accurate assumptions, such as limited holding capacity.
5. Time value of money: Since there is no market in the real world that is not affected by inflation, this phenomenon must be considered. Also, in many cases, companies are willing to offer discounts to their customers and sell their products earlier to escape the destructive effects of inflation. So, assuming inflation and discounts simultaneously is the best way to develop mathematical models in this field.
6. Model: Production models are usually more general than ordering models; however, the model type is related to the supply level we study, and no subclass takes precedence over another. Researchers studied ordering models more than production planning models, and these models should be given more attention in this section. These models must be combined with fundamental assumptions, such as the limited and variable production rate, which is ignored in almost all the presented models in the subject literature.
7. Number of echelons: Different levels of the supply chain do not have priority over each other, and according to the study's needs, it is better to determine the number of levels. In this part, there is no research gap like in other classes.
8. Costs and prices: This class is the same as previous ones. Even though less attention has been given to uncertain values, the research gap in this category can be seen as attention to variable costs and prices.
9. Solution method: One of the most essential characteristics of a good study, which should be given special attention, is the solution method. Many existing research gaps in models and assumptions are due to the need for suitable solution methods. If suitable solution methods are provided, better and more realistic models can be presented. Here, it is better to use techniques that can find the global optimum answer and have more flexibility to solve different problems (such as dynamic programming).
10. Multi-items: Multi-item models are more general, and single-item models can be obtained by changing their parameters (setting the number of products). So, in this part, it is more significant to present multi-item models considering the inventory constraints. Note that a multi-item model without constraints is the sum of several single-item models and is not more valuable than these models.
11. Time horizon: Less attention to an infinite time horizon cannot be considered a research gap. This should also be determined according to the study's needs. In this context, it should be noted that finite time horizons should not be mistakenly considered infinite.
12. Supply chain type: Developing a cyclical model depends on the product type. For many products, it is impossible to reuse or rework the deteriorated products in the same inventory system. However, presenting cyclic models can fill the research gap in this class if possible.
13. lead time: One of the most common assumptions in this literature is that lead time is neglectable. Considering a positive value for lead time fills this research gap; however, it is better to assume probabilistic lead time to adapt the model to real-world conditions.
14. Inventory constraints: Researchers present unconstrained models to simplify the mathematical procedure and the solution method. For example, the usual assumption of infinite replenishment rate is not practical or logical, but it is widely used to simplify the model. In the literature, there is no unconstrained real-world market. So, presenting constrained models alongside efficient solution methods can make the study valuable.
15. Preservation technology: Due to the ever-increasing growth of technology, ignoring various technological aspects reduces the accuracy and performance of mathematical models in the real world. So, it is better to include preservation technology in the studies related to the mentioned issue.
16. Financial conditions: Paying attention to financial issues is necessary for survival in today's competitive market, and it is better to include this issue in different ways in the studies on inventory control for deteriorating items.
17. Non-instantaneous deteriorations: There is no research gap in this part. The nature of the studied product determines whether the deterioration is immediate or non-instantaneous, and it is necessary to use both modes for different products.

18. Environmental issues: Recently, with increasing attention to environmental problems, models including these issues can be more compatible with the real world and make the study more valuable.

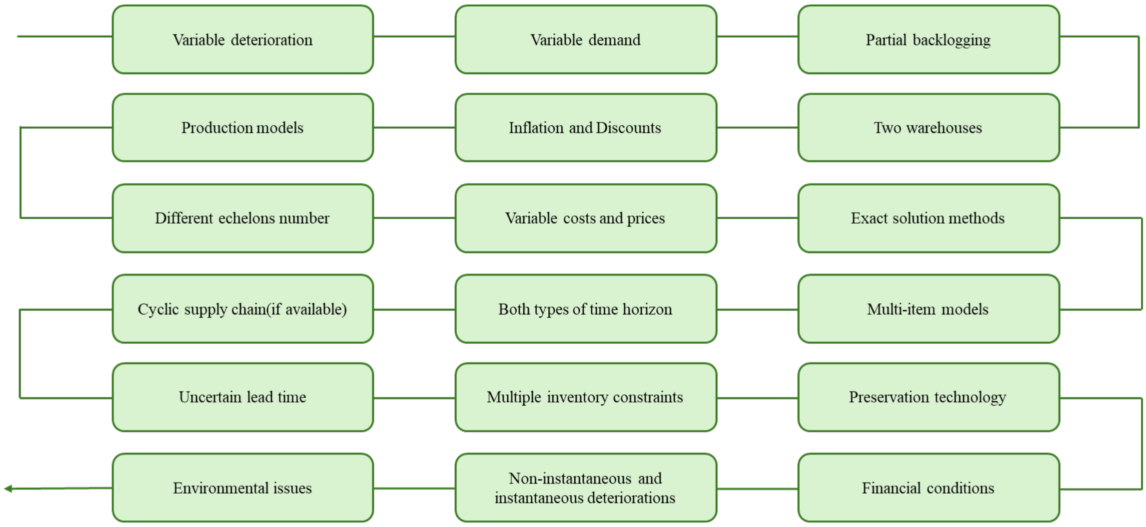

Fig. 16. Contribution roadmap

3.2 Research insights

In addition to what was mentioned in the previous section, researchers can enrich their work by considering new issues and combining different subclasses.

Some new contributions are as follows.

1. Developing multi-objective models with different objective functions, such as the amount of emissions, is an excellent way to extend current models in this literature.
2. Combining other problems, such as routing and location problems, with the exciting models is fascinating.
3. Adding multi-criteria decision-making problems (for example, vehicle or supplier selection) could be interesting.

Some of the combinations of the subclasses are listed below.

1. It is interesting to consider carbon emissions and preservation technology simultaneously. Preservation technology increases the company's profitability, but it also increases carbon emissions in general. It is interesting to strike a balance between these two aspects.
2. Considering inventory constraints with other subclasses can make the model more realistic.
3. Considering allowable shortages and variable holding costs and making a trade-off between the amount of holding inventories and shortages is a good way to develop current models.
4. Considering a stochastic lead time (even a positive value) and allowable shortages is challenging for researchers and managers in real-life companies.
5. Allowable shortages in production models were not considered so much in the past.

Research insights are presented in this section to give researchers some ideas for developing their works.

4. Conclusion

Due to the change in the definition of goods and the fact that almost no products can be found that have constant properties over time (some items like metals have low, but not zero, deterioration rates), attention to inventory control of perishable items is continuously increasing. So, many articles are published on this topic every year, and no major review was done after 2018. Therefore, it has been necessary to present a comprehensive and complete review since then. To fulfill this need, this article extensively reviewed 302 published articles in 18 classes and 33 subclasses. A comprehensive review is provided to show how researchers should address their contributions in each subclass. Research gaps in each class were determined, and the way to fill these gaps was presented. We suggest that every researcher interested in this topic place their works in each class carefully and mention them in the assumption section to make their works more accessible to understand and clarify their contributions better. In the last section, research insights were presented, and a roadmap for developing studies in this field was provided for researchers interested in this topic. The guidelines for presenting a review of the mentioned issue are given below.

We investigated deteriorating items, and researchers can study other synonyms of this word, such as perishable items. Future reviews can also consider different types of deterioration, such as obsolescence and decay. Also, researchers can do a more detailed review of the classes we discussed more generally (especially the last five). For example, a comprehensive review of environmental conditions can be done by investigating different aspects and models in this class. A complete review of solution methods can be provided, which discusses different solution methods used in the previous articles; that study investigates which local methods (such as metaheuristics) researchers used more or what exact methods they provided.

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