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Review of Logistics Models for Perishable Goods: Comparative Analysis of Location Planning and Inventory Management under Supply Chain Disruptions

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ABSTRACT

This study reviews and compares two logistics models tailored to perishable goods, focusing on the spatial and temporal dimensions of supply chain optimization. The first model proposes a population-density-based location planning framework that applies network centrality measures to determine optimal order fulfillment center locations. The second model introduces a two-warehouse inventory policy designed to handle disruption scenarios, such as lockdowns, by balancing demand variation and spoilage rates. Both models were evaluated for their methodological approaches, performance under disruption, and adaptability. The integrated review underscores the necessity of combining spatial efficiency with dynamic stock resilience to improve supply chain effectiveness for perishable goods. Findings suggest that hybrid models leveraging both geographic and temporal decision layers can significantly strengthen logistics adaptability.

Keyword: Logistics; Perishable Goods; Supply Chain; COVID-19; Inventory; Disruption Mitigation

1. INTRODUCTION

The supply chain management of perishable goods such as fresh food, pharmaceuticals, and biologically sensitive items has evolved into a critical operational domain due to the heightened risks associated with spoilage, expiration, and service level failure. Unlike durable goods, perishable items are constrained by shelf life and temperature sensitivity, making delays, misallocations, or forecasting errors exponentially more impactful in terms of waste and economic loss. According to the Food and Agriculture Organization (FAO), approximately one-third of all food produced globally nearly 1.3 billion tons is lost or wasted each year. A significant portion of this loss occurs due to inefficiencies in transportation, distribution planning, and inadequate inventory management strategies. From a quantitative standpoint, these inefficiencies translate into over USD 400 billion in annual losses, as well as massive carbon emissions associated with the production and disposal of unused perishable goods. Moreover, pandemics like COVID-19 have exposed structural vulnerabilities in global and regional supply chains, revealing the importance of resilience and adaptability in both spatial planning and temporal stock control.

Recent advances in operational research and supply chain analytics have led to a surge in scholarly interest in perishable goods logistics. A systematic review of literature indexed in ScienceDirect between 2022 and 2024 identified over 3,500 articles addressing supply chain design, logistics optimization, and inventory control related to perishable items. After screening using PRISMA methodology for relevance, publication recency, and access criteria, the pool was narrowed down to 50, and eventually to two high-impact studies which serve as the core of this review. This narrowing illustrates both the growing attention and the highly specific nature of advanced logistic solutions for perishable supply chains. Among the 3,500 articles initially considered, several themes consistently emerged: optimization modelling, spatial decision-making, inventory simulation, AI integration, risk mitigation, and sustainability in transportation. The convergence of these themes suggests a multidimensional approach is necessary for solving the contemporary logistical challenges associated with perishables.

Within this context, two notable models have been proposed and validated in recent years. The first, developed by Ekanayake et al. (2023), introduces a population-density-driven location planning strategy for the placement of order fulfilment centres (OFCs) within urban networks. This model utilizes centrality metrics closeness, betweenness, and eigenvector centrality drawn from graph theory to rank nodes in a spatial network, and applies Borda Count aggregation to determine the optimal distribution points. The objective is to minimize transportation costs, reduce delivery times, and improve access to consumers in high-demand areas, all of which are vital in the context of perishable goods whose value deteriorates with time. This location-centric model is especially suited to pre-disruption planning phases, urbanization management, and market expansion strategies. The second model, formulated by Das et al. (2022), addresses the volatility and risk associated with supply chain disruptions, with a particular emphasis on pandemic-induced lockdowns and emergency response logistics. This two-warehouse inventory model differentiates between owned warehouses (OWs) and rented warehouses (RWs), where goods are dynamically allocated based on spoilage rates (modelled using a two-parameter Weibull distribution), storage cost per unit, and demand fluctuation over time. The model adjusts for both supply shocks and demand reductions during disruptions, offering tactical guidance on stock retention and overflow handling. Its strength lies in its temporal adaptability and in modelling deterioration rates key to managing high-risk products such as fresh produce or vaccines under storage-limited conditions.

While both models provide valuable insights into different dimensions of the perishable goods supply chain, they are inherently limited when applied in isolation. The location planning model lacks flexibility in responding to real-time demand variability or emergency conditions, as it prioritizes static spatial optimization. Conversely, the inventory model provides robust disruption response mechanisms but assumes fixed warehouse locations, overlooking spatial distribution efficiencies that can reduce lead times and environmental impact. This disjointed application creates a critical research gap in the literature a lack of integrated frameworks that jointly address spatial optimization and temporal risk management in perishable goods logistics. This review article is motivated by the need to bridge that gap. By conducting a side-by-side evaluation of the two models, this study offers a critical assessment of their theoretical underpinnings, operational applications, and methodological strengths and limitations. Furthermore, the study explores potential integration pathways that combine the spatial intelligence of centrality-based location planning with the flexibility of two-warehouse inventory modelling. Such integration is hypothesized to yield a logistics framework that is more resilient, more efficient, and more responsive to both everyday supply-demand fluctuations and large-scale disruptions.

Numerous studies in the past five years have explored optimization and resilience in supply chains, particularly those involving perishable goods. These works span various domains, including inventory modelling, location-based planning, and hybrid decision-making strategies under uncertainty. Das et al. [1] proposed a two-warehouse inventory model that integrates spoilage behaviour under lockdown disruptions using a Weibull distribution, highlighting the temporal dimension in supply chain resilience. In parallel, Ekanayake et al. [2] addressed the spatial aspect by developing a population-density-based location planning model, applying network centrality metrics and Borda Count for efficient distribution of perishable goods. Other works further reinforce this duality. Rasouli et al. [3] and Babaei et al. [11] applied integer programming and budget-constrained models in team and logistics optimization, echoing the utility of binary formulations in selection problems. Chung and Kwon [4] incorporated sustainability into logistics optimization for perishables, offering green logistics strategies that align with environmental objectives. Yusuf et al. [5] and Tirkolaee et al. [6] introduced hybrid AI-based forecasting and inventory modelling frameworks, addressing uncertainties in demand and perishability. In the domain of decision support systems, Darvish et al. [7] and Dash & Mondal [13] integrated fuzzy multi-criteria decision-making models to help managers select appropriate logistics strategies under multiple conflicting objectives. Similarly, Daryanto and Ardiansyah [12] introduced robust stochastic location-inventory optimization models for short life-cycle products, underscoring the growing demand for spatial-temporal integration in supply chain design. From a broader analytical perspective, studies such as Mohammadi et al. [14] and Das & Mondal [15] used VIKOR and MCDM-optimization hybrids in logistics and resource allocation under constraints, suggesting pathways to extend location-inventory models. Meanwhile, Salama and Sabri [10] analysed risk mitigation in fresh food logistics during disruptions, reinforcing the urgency of building responsive systems.

In addition to supply chain-specific literature, foundational modeling approaches from football optimization [3], [9], [11] have been adapted in the current research to represent 0/1 decision-making logic. Furthermore, regional modelling studies by Sinulingga et al. [16], Silalahi et al. [17], and Sofiyah et al. [18] provide local insight into applied logistic systems and managerial automation, particularly within Indonesian contexts. Mathematical and engineering-based modeling contributions from Tulus et al. [19], [20], and Gultom et al. [21] offer relevant perspectives on multi-criteria modeling, sustainability prioritization, and wave-based simulation, all of which inform the computational backbone of integrated logistics planning. Sofiyah et al. [22] and Erwin et al. [23] demonstrated the value of AI and dynamic modeling for real-time responsiveness, while Marpaung and colleagues in [24]–[38] contributed extensively to computational frameworks, encryption, decision modeling, and energy systems relevant to sustainable and secure logistics environments. Collectively, these studies confirm the current literature's fragmented but highly innovative approach to solving spatial and temporal optimization in supply chains. However, there remains a gap in integrated models that simultaneously address perishable inventory control and strategic location planning precisely the contribution this paper aims to make.

The objectives of this study are fourfold. First, it seeks to analyse the mathematical and conceptual structure of the location planning model, particularly its application of spatial centrality for optimizing OFC placements. Second, it evaluates the effectiveness of the two-warehouse inventory model in mitigating supply chain disruption impacts through dynamic demand forecasting and spoilage control. Third, it conducts a comparative analysis to determine the strengths, limitations, and domain-specific suitability of each model, especially in terms of urban scalability, system complexity, and responsiveness. Finally, the study proposes an integrative framework that blends the two models into a unified system capable of leveraging population-based spatial logic while incorporating risk-adjusted inventory control to inform future logistics infrastructure development and crisis-preparedness policies.

2. METHODS

To illustrate the research trend in logistics models for perishable goods, a bibliometric analysis was conducted using Scopus-indexed publications from 2001 to 2025. The analysis reveals how academic interest in this field has evolved, particularly in response to global events such as the COVID-19 pandemic and the rapid advancement of supply chain technologies. The keyword combinations used for this analysis included "perishable goods," "supply chain," "logistics," "location planning," and "inventory management." Figure 1 presents the number of documents published per year, highlighting the temporal progression and growing importance of the topic within the research community.

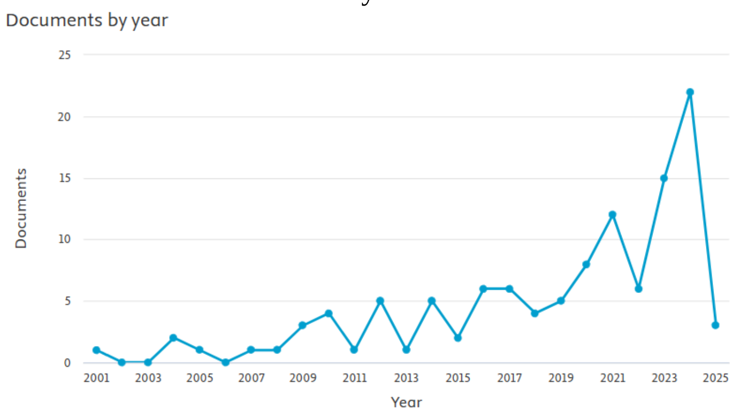

Figure 1. Number of published documents

As shown in Figure 1, scholarly output on logistics and supply chain modelling for perishable goods remained relatively low and stable between 2001 and 2017, averaging fewer than five documents per year. However, beginning in 2018 and accelerating sharply after 2020, the number of publications increased significantly, peaking in 2024 with more than 20 published studies. This surge aligns with heightened interest in pandemic-induced supply chain disruptions, the expansion of e-commerce logistics, and the emergence of digital solutions such as IoT, AI, and GIS in supply chain optimization. The bibliometric trend reflects a clear shift toward interdisciplinary approaches that integrate operations research, data science, and sustainability to address the multifaceted challenges of perishable goods logistics.This study adopts a descriptive-analytical research design to conduct a comparative evaluation of two advanced logistics models within the context of perishable goods supply chain management. The methodology is structured in five key stages: literature mapping, article selection, data processing, model comparison, and integrative framework development. To initiate the review process, the study employed bibliometric analysis using VOSviewer, a powerful tool for constructing and visualizing bibliometric networks. This step enabled the identification of co-occurrence patterns and thematic clusters related to logistics, perishable goods, location planning, and inventory optimization. The analysis revealed dominant research directions, emerging subfields, and relevant keyword associations that informed the selection of models for review. Following the thematic mapping, a systematic literature search was conducted through the ScienceDirect database using a set of predefined keywords and Boolean logic combinations. The search focused on peer-reviewed, open-access journal articles published between 2022 and 2024. To ensure methodological rigor, the article selection followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. This process involved four stages: identification, screening, eligibility, and inclusion. Out of 3,578 initially retrieved articles, a series of filters were applied based on relevance, methodological depth, and topical focus narrowing the pool to two high-impact articles: one introducing a population-density-based location model, and the other proposing a two-warehouse inventory system for disruption management.

The next phase involved qualitative comparative analysis of the selected models. Each model was examined in terms of its conceptual framework, mathematical formulation, input-output structure, underlying assumptions, and domain applicability. Special attention was given to the operational objectives of each model spatial efficiency in the first, and temporal adaptability in the second. Strengths and limitations were assessed using an analytical matrix to identify complementarities and integration opportunities. To enhance practical relevance, the study incorporated real-world case illustrations, such as food distribution networks in urban centers and inventory performance during COVID-19 lockdowns. These case contexts provided applied insights into how the models perform under actual constraints and uncertainty. The comparative findings were then synthesized to propose a hybrid logistics framework that integrates spatial centrality-based location optimization with dynamic, risk-aware inventory management. Finally, the validity and scalability of the integrated framework were evaluated based on its potential for digital augmentation using real-time data streams, such as Geographic Information Systems (GIS), Internet of Things (IoT) sensors, and e-commerce demand platforms. This approach ensures that the proposed model is not only conceptually sound but also practically responsive and adaptable to the evolving dynamics of modern supply chains for perishable goods. To better understand the thematic landscape and scholarly development related to logistics models for perishable goods, this study employed a bibliometric analysis framework. The process involved multiple structured stages using VOSviewer software, starting from data extraction in BibTeX format from selected academic databases, followed by visualization and analysis of co-occurrence patterns among key bibliographic elements. This method allows researchers to uncover publication trends, author productivity, and keyword clusters, which serve as a foundation for identifying dominant research areas and emerging gaps. The complete flow of this bibliometric analysis is presented in Figure 2.

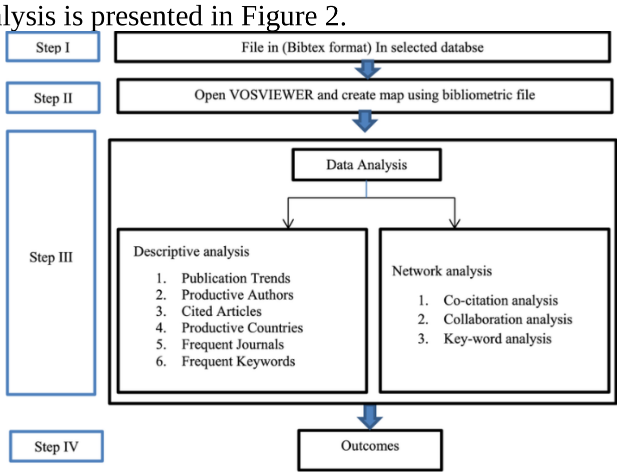

Figure 2. Review framework

As shown in Figure 2, the bibliometric analysis consists of four sequential steps. Step I involve data collection, specifically exporting metadata in BibTeX format from databases such as Scopus or ScienceDirect. In Step II, VOSviewer is used to visualize bibliographic networks based on this data. Step III is divided into two major analysis branches: descriptive and network-based. The descriptive analysis identifies publication volume over time, productive researchers and countries, frequently cited articles, and common keywords. Meanwhile, network analysis explores deeper relationships, including co-citation patterns, collaborative author networks, and thematic keyword mapping. Finally, Step IV consolidates these insights into meaningful outcomes that guide model selection and highlight the research community's focal areas. This structured bibliometric approach provides the empirical foundation for selecting the two core models reviewed in this study.

3. RESULTS AND DISCUSSION

To further explore the intellectual structure and thematic focus of recent research on perishable goods logistics, a keyword co-occurrence analysis was conducted using VOSviewer. This approach identifies how frequently and in what contexts key terms appear together in published articles, thereby revealing interconnected research domains. The analysis focuses on keywords extracted from titles and abstracts of articles published between 2022 and 2024, with a minimum occurrence threshold to ensure relevance and clarity. Figure 3 presents the resulting bibliometric map, where node size reflects keyword frequency, edge thickness indicates co-occurrence strength, and color gradients represent the average publication year of each term.

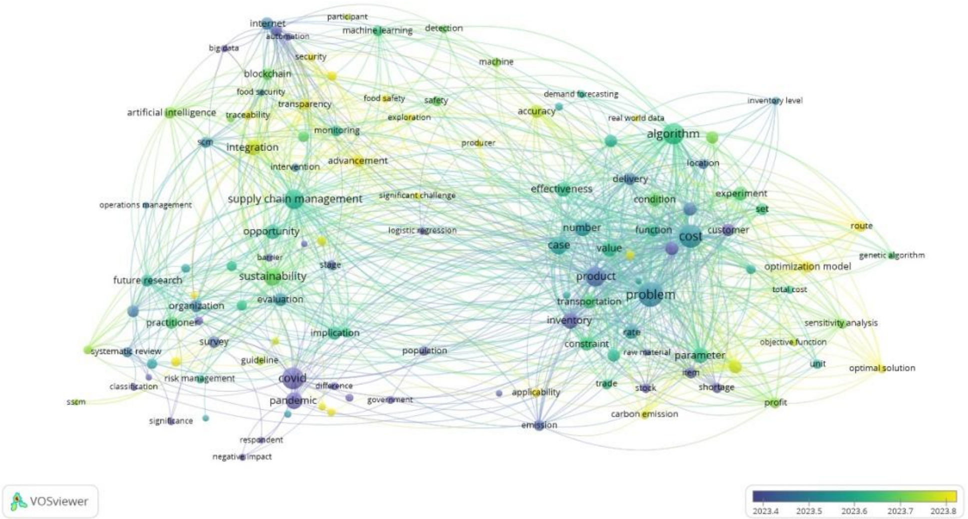

Figure 3. VosViewer output

As illustrated in Figure 3, several dominant thematic clusters emerge. Terms like supply chain management, sustainability, cost, problem, and inventory form the central nodes, indicating their foundational role in the research landscape. Surrounding these are tightly linked clusters reflecting specialized themes: algorithmic modeling (e.g., optimization model, genetic algorithm, sensitivity analysis), technological integration (blockchain, artificial intelligence, machine learning), and contextual triggers (COVID, pandemic, disruption). Notably, the color gradient shows a temporal evolution of interest, with recent years (light yellow) highlighting newer areas such as traceability, blockchain, and carbon emissions, indicating an increasing concern with transparency and sustainability in perishable supply chains. The visualization supports the selection of the two core models reviewed in this study by confirming the dual emphasis in current literature on spatial and temporal optimization within perishable goods logistics.

To ensure methodological rigor and transparency in the article selection process, this study followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. PRISMA enables structured identification, screening, eligibility assessment, and inclusion of literature based on predefined criteria. The initial search was conducted in the ScienceDirect database, targeting peer-reviewed, open-access research articles published between 2022 and 2024. The process involved several stages of refinement to isolate articles that specifically address logistics modeling in the context of perishable goods. Figure 4 illustrates the complete flow of literature selection using the PRISMA model.

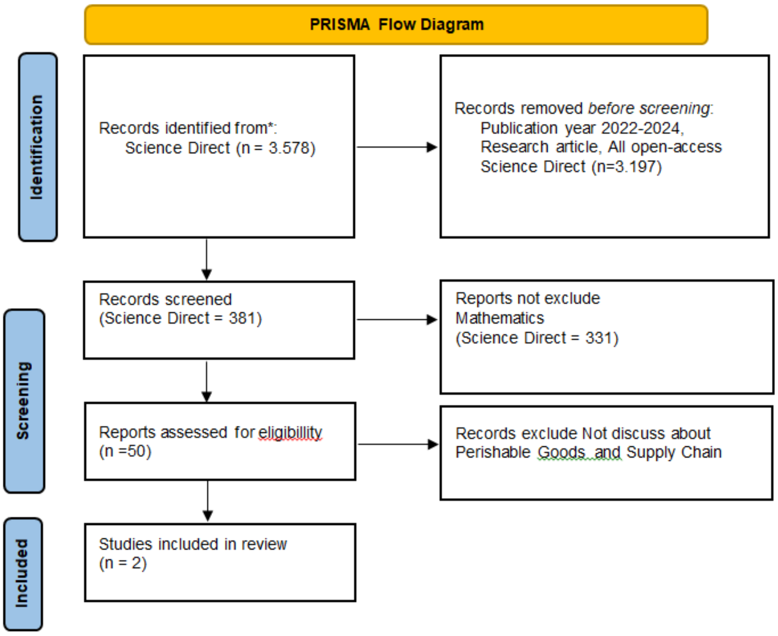

Figure 4. PRISMA flow diagram

As shown in Figure 4, the initial search yielded 3,578 records. After applying initial exclusion filters such as publication date, document type, and open-access availability 3,197 records were removed. From the remaining 381 articles, a further 331 were excluded for falling outside the study's thematic focus (primarily mathematical or unrelated to supply chain logistics). The final eligibility screening involved a close reading of 50 articles, out of which only two met the full inclusion criteria: addressing perishable goods logistics and proposing formal models applicable to location planning or inventory disruption management. These two studies form the core of the comparative analysis presented in this review.

3.1. Model 1: Location Planning Based on Population Density

The first model under review is a spatial decision-support tool developed by Ekanayake et al. (2023) that employs a population-density-driven approach to determine the optimal placement of Order Fulfilment Centres (OFCs). The model integrates multiple centrality measures including closeness, betweenness, and eigenvector centrality to evaluate the importance of each node in a logistical network. These measures are aggregated using the Borda Count method to rank candidate locations based on their proximity to demand clusters, overall network accessibility, and traffic throughput potential. The model's primary strength lies in its spatial efficiency, as it minimizes transportation distance and cost while enhancing service accessibility in densely populated urban areas. However, the model assumes static demand and fixed infrastructure, limiting its responsiveness in rapidly changing or disrupted environments.

3.2. Model 2: Two-Warehouse Inventory Management

The second model, proposed by Das et al. (2022), introduces a temporal risk-mitigation strategy through a two-warehouse inventory system. It distinguishes between Owned Warehouses (OWs) and Rented Warehouses (RWs), allocating inventory based on spoilage probability and demand volatility during normal and disrupted conditions. The model uses a Weibull distribution to represent perishability and adjusts stock levels dynamically in response to demand fluctuations and lockdown events. This approach enables cost optimization by minimizing inventory loss and storage overhead while maintaining service levels. Its core advantage is adaptability to real-time disruptions, though it does not account for the geographic distribution of demand or transport-related emissions.

3.2. Comparative Matrix: Performance under Normal and Disrupted Conditions

To evaluate the practical and theoretical contributions of the two selected logistics models, a structured comparison was conducted based on a range of operational and strategic criteria. These include performance objectives, optimization metrics, environmental impact, and contextual applicability under both stable and disrupted conditions. The comparison enables a clear understanding of each model's capabilities and constraints, particularly in relation to spatial efficiency and temporal resilience. Table 1 summarizes the core distinctions and complementarities between the population-density-based location planning model and the two-warehouse inventory system for disruption management.

Table 1 Comparative Evaluation of Two Logistics Models for Perishable Goods

Criteria	Model 1: Location Planning	Model 2: Two-Warehouse Inventory
Objective	Spatial efficiency	Temporal resilience
Key Metrics	Centrality scores, Borda ranking	Spoilage rate, demand sensitivity
Scenario Suitability	Urban expansion, static networks	Pandemic/disruption response
Optimization Focus	OFC placement, route efficiency	Inventory turnover, loss minimization
Environmental Impact	Reduced emissions via route cuts	Neutral
Strengths	Network-wide coverage, scalability	Risk-responsive, adaptable, cost-saving
Limitations	Static demand assumptions	No spatial/transport logic
Integration Potential	High when combined with inventory	High when supported by geographic logic

As illustrated in Table 1, the two models address fundamentally different but interrelated aspects of logistics planning for perishable goods. The location planning model emphasizes spatial optimization using centrality metrics and is best suited for scenarios involving urban expansion or long-term distribution network design. In contrast, the two-warehouse inventory model focuses on temporal flexibility, adjusting inventory levels in response to demand shocks and spoilage risk, making it ideal for dynamic or disrupted environments such as pandemics. Importantly, both models show high integration potential—where spatial efficiency can be paired with risk-sensitive stock control to create a more adaptive and resilient logistics system. This synergy sets the foundation for the integrated framework proposed in the following section. To determine the optimal location, a multi-centrality score is calculated using the Borda Count method:

$$SAll(i) = Rank[W_{CC} \times SCC(i) + W_{BC} \times SBC(i) + W_{EC} \times SEC(i)]$$

where W_{CC},W_{BC}, and $W_{EC}$are the weights for each centrality measure.

This model's parameters include centrality measures (closeness, betweenness, and eigenvector) used to identify optimal distribution center locations based on population density distribution. Closeness centrality calculates the average shortest distance between a specific node and others, betweenness centrality assesses a node's role as a connecting path in the network, while eigenvector centrality evaluates a node's influence based on surrounding population density.

3.4. Two-Warehouse Inventory Model

This model focuses on inventory management across two types of warehouses: owned warehouses (OW) and rented warehouses (RW) during supply chain disruptions caused by lockdowns. The spoilage rate is calculated using a two-parameter Weibull distribution, while demand is dynamic, depending on time and conditions.

1. Weibull Distribution for Spoilage Rate:

$$RI_1(t) = e^{-qt^p}\left[X - t\left(\gamma + \frac{\delta t}{2}\right) - qt^{p+1}\left(\frac{\gamma}{p+1} + \frac{\delta t}{p+2}\right)\right]$$

where $RI_1(t)$ is the inventory level at the rented warehouse (RW) at time t, p and q is the scale parameter of the Weibull distribution, γ refers to the initial demand and δ represents the rate of change of demand.

2. Dynamic Demand During Lockdown:

$$RI_2(t) = e^{-qt^p}\left[t(\Delta d - \gamma)\left(\frac{1 + qt^p}{p+1}\right) - \delta t^2\left(\frac{1}{2} + \frac{qt^p}{p+2}\right) + X - S_T \Delta d\left(1 + \frac{qS_T^p}{p+1}\right)\right]$$

where Δd is the demand reduction during lockdown, and $S_T$is the start time of the lockdown.

3. Storage Costs:

$$C_{HRW} = E\int_{Sr}^{Er} RI_2(t)dt$$

where E is the storage cost per unit at RW time, E_T is the end of the lockdown. The model is designed to address sudden changes in demand and storage capacity. During disruptions, the model adjusts for reduced demand while preparing for a subsequent surge after the disruption ends.

3.5. Combined Analysis

The combination of both models from the reviewed journals results in a comprehensive approach that can be applied to various logistics contexts for perishable goods. The location planning model from the first journal provides a framework for determining the optimal locations for order fulfillment centers (OFCs) based on the geographical distribution of demand. Meanwhile, the two-warehouse inventory model from the second journal offers a solution for managing inventory dynamically, particularly during supply chain disruptions such as pandemics. In terms of location planning, the centrality-based model is capable of determining distribution points that maximize spatial efficiency. For example, by using closeness centrality, the distribution system can be designed to minimize delivery distances and improve accessibility for customers in high-demand areas. This model is especially relevant for designing well-structured logistics networks in urban areas. However, it does not sufficiently address temporal factors such as seasonal demand fluctuations or sudden surges in demand, which can present challenges in managing perishable goods.

On the other hand, the two-warehouse inventory model allows for more adaptive inventory management by considering spoilage rates and dynamic demand patterns. During disruptions such as lockdowns, this model can accommodate reduced demand due to restrictions while preparing for an increase in demand once the restrictions are lifted. This approach ensures that inventory is available as needed, without overloading storage capacity. However, this model does not explicitly consider geographic aspects, meaning its implementation can be more effective if combined with the spatial analysis provided by the first model. The integration of both models can be applied to real-world scenarios, such as the distribution of fresh food products in major cities. The first step is to use the centrality-based model to determine the optimal location for the OFCs near areas with high demand. Then, the inventory model can be used to manage inventory at these OFCs, ensuring that products are delivered on time and remain fresh. This approach is also valuable for improving supply chain resilience when faced with sudden disruptions, such as natural disasters or global disturbances.

Moreover, the combination of these two models can support sustainability goals in the supply chain for perishable goods. By positioning the OFCs closer to the consumers, carbon emissions from transportation can be reduced. Meanwhile, better inventory management minimizes waste from spoilage or expiration. Both models can also be expanded by utilizing real-time data, such as actual demand data from e-commerce systems or geographical data from GIS systems, to enable more accurate and responsive decision-making.

Overall, the integration of both models provides strategic solutions that improve efficiency, adaptability, and sustainability in the supply chain for perishable goods. The combination of spatial and temporal analysis creates a holistic approach that is not only relevant for normal conditions but also capable of addressing challenges in crisis situations.

4. CONCLUSIONS

This study reviewed and comparatively analyzed two critical logistics models in the management of perishable goods: a population-density-based location planning model and a two-warehouse inventory system designed for disruption mitigation. Through bibliometric analysis and a structured PRISMA-guided literature selection process, the study identified and evaluated each model's structure, operational focus, and contextual applicability. The location planning model demonstrated significant advantages in spatial optimization, offering effective solutions for the strategic placement of Order Fulfillment Centers (OFCs) by leveraging centrality measures and Borda Count rankings. Its strengths lie in minimizing delivery distances and enhancing accessibility in densely populated regions. However, it operates under static demand assumptions and lacks responsiveness to real-time disruptions. In contrast, the two-warehouse inventory model exhibited strong capabilities in temporal adaptability, effectively managing spoilage risks and fluctuating demand through dynamic stock allocation across owned and rented facilities. Its resilience under crisis conditions such as pandemics and supply interruptions make it highly valuable for real-time decision-making. Nonetheless, it does not incorporate geographic considerations, thereby limiting its spatial efficiency. The comparative evaluation revealed that the two models are complementary rather than competitive. When integrated, they form a robust, multi-dimensional framework that combines the geographic precision of location planning with the adaptive strength of inventory modeling. This hybrid framework supports supply chain resilience against disruptions, promotes sustainability through reduced waste and emissions, and enhances responsiveness by aligning logistical infrastructure with dynamic market needs. From a strategic standpoint, the integration of these models is not only academically significant but also practically transformative. It offers a data-driven, scalable, and digitally adaptable solution for governments, logistics companies, and food distribution networks operating in complex and uncertain environments. Future research should explore the integration of these models with real-time technologies such as IoT sensors, GIS analytics, and AI-driven forecasting to enhance their predictive accuracy and operational deployment. Additionally, empirical testing of the hybrid framework in diverse urban and rural settings would provide further validation of its effectiveness across varying demographic and infrastructural conditions.

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