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Multi-Objective Optimization in Sustainable Supply Chains: A Review of Methods and Applications for Perishable Products

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Abstract

Sustainable supply chain management for perishable products is a complex issue requiring balance between economic performance, environmental impact, and social responsibility. This study conducts a systematic literature review of multi-objective optimization methods used in designing sustainable supply chains for perishable products. The main objective is to identify and analyze various optimization methods such as Lexicographic Goal Programming (LGP), Multi-Choice Goal Programming (MCGP), Weighted Goal Programming (WGP), and Augmented ε-constraint (AEC) in the context of perishable product supply chains. Using the PRISMA method, 146 references were identified from Scopus and Google Scholar databases, which were then filtered down to 11 final articles for in-depth analysis. The results show that each method has distinct characteristics and advantages - LGP is effective for hierarchical optimization with clear priorities, MCGP provides flexibility in target selection, WGP enables balanced optimization through weighting, while AEC produces more robust solutions for complex problems. These findings provide valuable insights for practitioners and researchers in selecting appropriate optimization methods for designing sustainable supply chains for perishable products. This study also identifies knowledge gaps and future research opportunities in sustainable supply chain optimization.

Keywords
Multi-objective optimization, Food supply chain network, PRISMA, Sustainability.

1. Introduction
Sustainable supply chain management (SSCM) has become increasingly important as organizations face growing pressure to balance economic performance with environmental and social responsibilities. The need for sustainability is particularly critical in the management of perishable products, such as fresh food and pharmaceuticals, due to their limited shelf lives and sensitivity to environmental conditions. Over time, advancements in optimization methods, green logistics, and technological innovations have shaped the current understanding of SSCM. However, challenges remain in addressing the trade-offs between cost, environmental impact, and service quality, underscoring the need for further exploration in this field.

Significant research has been conducted to enhance the efficiency and sustainability of supply chains for perishable goods. Studies have highlighted the application of multi-objective decision-making frameworks, such as Linear Programming (LP) and Mixed-Integer Linear Programming (MILP), which optimize multiple objectives simultaneously, including cost minimization, carbon footprint reduction, and service level improvement (Rodríguez-Escoto et al., 2024; Santos et al., 2024). Additionally, heuristic algorithms, such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), have been employed to identify Pareto-optimal solutions for conflicting objectives. Furthermore, approaches like green logistics, circular economy principles, and advanced forecasting techniques have been proposed to reduce waste and emissions, demonstrating considerable progress in meeting sustainability goals (Nagy & Szentesi, 2024).

Despite these advancements, critical gaps persist in the integration of real-time data, the adaptation of optimization models to fluctuating market conditions, and the implementation of SSCM practices across diverse geographical and cultural contexts. Research also emphasizes the need for scalable solutions to address challenges specific to perishable products, such as maintaining quality, minimizing spoilage, and balancing trade-offs between economic, environmental, and social objectives.

This study reviews the optimization methods commonly used in sustainable multi-period food supply chains, with a particular focus on perishable products and shelf life constraints. It explores the applications of these methods in designing sustainable supply chain networks and evaluates their effectiveness, strengths, and limitations. By synthesizing existing research, the study aims to provide insights into the current state of SSCM for perishable goods and identify areas requiring further investigation, contributing to a deeper understanding of how optimization techniques can enhance sustainability in supply chain operations.

2. Methods
2.1 Search Strategy and Inclusion-Exclusion Criteria
The aim of this study is to review the literature on designing a sustainable multi-period food supply chain network that considers product shelf life. The systematic PRISMA search method was applied to identify relevant literature from the Scopus and Google Scholar databases. The combination of keywords used in the search included "food supply chain," and "multi-period optimization," and "sustainability," with filtering applied to titles, abstracts, and keywords in each document. The literature search focused on publications from 2014 to 2024.

The inclusion criteria for this literature search were studies published in English and research that specifically addresses sustainable food supply chain design while incorporating shelf-life constraints. Additionally, the studies must involve valid and verified models. The exclusion criteria included reports, news articles, and undergraduate theses, as well as studies that do not focus on sustainable food supply chain optimization.

The research questions guiding this review are as follows:
Q1: What methods are commonly used in analyzing and optimizing sustainable multi-period food supply chain models that account for product shelf life?
Q2: How are these methods applied to support the design of sustainable food supply chain networks?
Q3: What are the strengths and limitations of each method?

2.2 Data Analysis
Based on the literature search results, this study identified 353 references relevant to the specified keywords. These references were gathered from two main sources: Scopus (25 references) and Google Scholar (328 references). The identified studies were categorized into two main groups based on their research objectives:

1. Studies focusing on the development and application of methods to understand and optimize the dynamics of sustainable food supply chains for perishable products.
2. Studies evaluating the effectiveness of strategies and practices in managing sustainable food supply chains.

A detailed analysis of the selected studies allows the researcher to:

1. Identify various optimization methods applied in the context of sustainable supply chains for perishable products.
2. Understand the strengths and weaknesses of each method in addressing the challenges of perishability and sustainability.
3. Synthesize findings on the effectiveness of these methods in supporting decision-making related to supply chain optimization.
4. Highlight knowledge gaps and opportunities for future research in optimizing sustainable supply chains.

This analysis provides a comprehensive understanding of the role of optimization methods in enhancing the performance and sustainability of food supply chains across different levels, from local to global. The study employs a Systematic Literature Review (SLR) approach to identify and analyze studies relevant to optimization challenges in sustainable food supply chains for perishable products.

The selection process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. An initial search of the two databases identified 353 publications relevant to the research topic. After removing 73 duplicate entries, 280 publications remained for further screening. The remaining publications were reviewed based on their titles, abstracts, and keywords to ensure they met the established inclusion criteria. As a result, 227 publications were excluded for not focusing on the application of optimization methods in sustainable supply chains or for not using valid and verified models.

Next, the eligibility of the remaining 53 publications was thoroughly evaluated to ensure their quality and relevance. From this evaluation, 33 publications were excluded because they were literature reviews or incomplete articles containing only abstracts. Ultimately, 20 publications were selected as they met the criteria and were deemed relevant to the research topic. The PRISMA flowchart for the literature search process is illustrated in Figure 1.

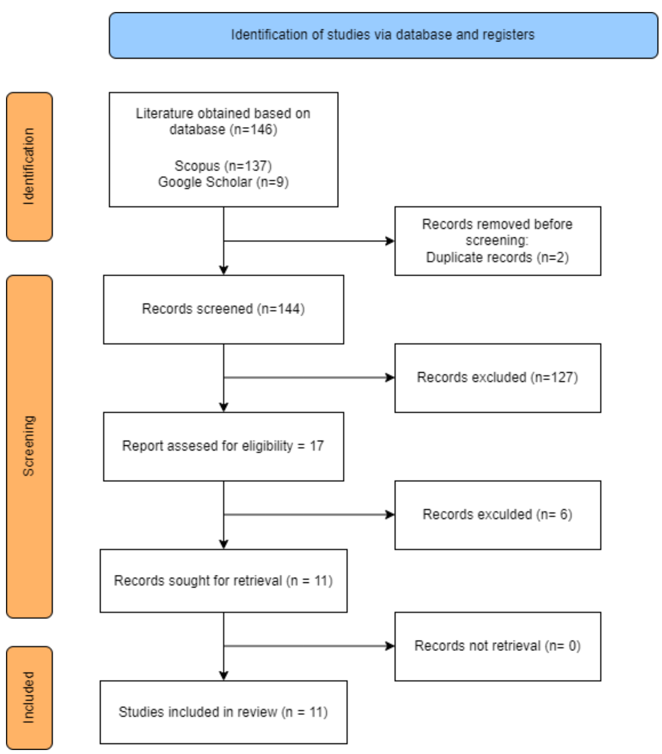

Figure 1. Steps for systematic literature review using PRISMA method

3. Result and Discussion

3.1 Result

The references used in this study encompass various research on the application of optimization methods and their effectiveness in enhancing the sustainability and efficiency of supply chains for perishable commodities. Examples of these commodities include pharmaceutical products, dairy products, vaccines, fresh food, fresh agricultural products, and meat products such as beef and chicken, as well as vegetables like shallots and garlic. The selected research topics cover areas such as pharmaceutical supply chains optimized using Lexicographic Goal Programming, dairy product logistics enhanced by Lexicographic Goal Programming, and vaccine distribution modeled using Weighted Goal Programming.

Research on fresh food supply chains applies Weighted Goal Programming, while studies on fresh agricultural products utilize Weighted Goal Programming (WGP) and Minimax Goal Programming (MGP) to balance sustainability and efficiency. Healthcare industry supply chains are often analyzed using Weighted Goal Programming, and the dairy industry leverages the augmented ε-constraint method for optimal resource allocation. Similarly, the supply chains for meat products are enhanced through the augmented ε-constraint method, while the distribution of vegetables is modeled using multi-choice goal programming. Lastly, ε-constraint methods are applied to optimize operations in the meat industry.

These studies also emphasize the importance of accurate data collection, usability, and the potential for continuous monitoring to support sustainable supply chains and ensure efficient management of perishable products. A more detailed explanation is provided in Table I.

Table 1. Literature Filtering Results

No	References	Exact methods	Perishable products	Sustainability			Results
				Economic	Environmental	Social	
1	Alireza Roshani (2024)	LGP	Pharmaceutical	✓	✓	✓	Reduce total costs by 5.48%, Increase network resilience by 31.9%, Optimize the balance between sustainability dimensions
2	Jouzdani (2021)	MCGP	Dairy Products	✓	✓	✓	An improvement in costs of 15% can reduce environmental impact by up to 51%, Optimal use of refrigeration can significantly reduce product damage.
3	Hashemi-Amiri et al (2023)	WGP	Poultry	✓		✓	The model can integrate supplier selection, production scheduling and routing decisions, handle demand uncertainty with the DRCC approach.
4	Yakavenka et al (2020)	WGP, MGP	Fresh Agricultural Products	✓	✓	✓	Method of producing better solutions in terms of minimizing costs and environmental impact. There is a trade-off between time and cost where costs go down, time tends to go up
5	Isaloo & Paydar (2020)	WSM, WGP	Healthcare Industry	✓	✓		Method consistently gives the best results for various problem sizes from 6 test problems conducted

6	Hemmati et al (2023)	AEC	Dairy Industry	✓	✓		The model provides a robust solution to uncertain parameters such as demand, transportation costs, and product damage levels.
7	Foroozesh et al (2022)	AEC 2, RPP	Meat Products	✓	✓		The proposed RPP-I model shows better performance with a decrease in the standard deviation of the CO2 emission objective function by 44.91%, an increase in facility utilization by 22.12%.
8	Abbas et al (2023)	MCGP	Vegetables	✓	✓	✓	The model successfully optimized distribution center locations, vehicle allocation, delivery routes, use of refrigeration facilities.
9	Fathollahzadeh et al (2024)	AEC	Meat Industry	✓		✓	Model effectively reduced environmental impacts by approximately 2.5% at the cost of a 5% decrease in profits.
10	Goli & Tirkolaee (2023)	WSM, AEC	Dairy Products	✓		✓	AEC shows the best performance compared to WSM because it provides a higher TPS value, has the lowest HA value 0.245
11	Entezari et al (2024)	AEC 2	Blood	✓		✓	The model successfully reduced total costs by 5.48%, Reduced blood shortages by 53.22%, Delivery time efficiency by up to 2 hours

Remarks:
LGP : Lexicographic Goal Programming
MCGP : Multi-Choice Goal Programming
WGP : Weighted Goal Programming
MGP : Minimax Goal Programming
WSM : Weighted Sum Method
AEC : Augmented ε-constraint
RPP : Robust possibilistic programming

3.2 Discussion

The analysis in Table 1 of the optimization methods used in the reviewed studies reveals distinct strengths, weaknesses, and best applications for each method in the context of sustainable supply chain design for perishable products. Lexicographic Goal Programming (LGP) prioritizes objectives hierarchically, ensuring higher-priority goals are optimized before addressing secondary ones. This method, as demonstrated by Alireza (2024) in pharmaceutical supply chains, effectively reduced costs by 5.48% and increased network resilience by 31.9%. While LGP is well-suited for scenarios with clearly defined priorities, such as healthcare and pharmaceuticals, it is inflexible when all objectives are equally important.

Multi-Choice Goal Programming (MCGP), on the other hand, allows multiple acceptable levels for goals, offering flexibility in decision-making. Studies like Jouzdani (2021) and Abbas (2023) showcased its application in dairy and vegetable supply chains, achieving cost improvements of up to 15% and environmental impact reductions of 51%. However, its increased computational complexity limits its use to problems requiring significant flexibility, such as refrigeration and route optimization in food supply chains.

Weighted Goal Programming (WGP), which assigns weights to each objective based on their importance, provides balanced solutions but requires careful weight assignment, which may be subjective. Hashemi (2023) demonstrated its effectiveness in poultry supply chains by integrating supplier selection, production scheduling, and routing decisions. Yakavenka (2020) highlighted its application in fresh agricultural products, where it effectively minimized costs and environmental impacts, albeit with trade-offs between time and cost.

Minimax Goal Programming (MGP) focuses on minimizing the maximum deviation from target goals, ensuring equitable trade-offs among objectives. Yakavenka (2020) showed its capability to balance conflicting goals in agricultural supply chains, particularly when fairness is critical. However, its approach may lead to suboptimal solutions for individual objectives.

The Weighted Sum Method (WSM), a simple and intuitive approach, combines multiple objectives into a single weighted objective function. It has been applied effectively in healthcare supply chains, as noted by Isaloo (2020), providing consistent results across problem sizes. However, Goli (2023) found that the method struggles with non-convex Pareto frontiers and is outperformed by more advanced techniques like Augmented ε-Constraint (AEC).

Augmented ε-Constraint (AEC) improves upon the standard ε-constraint method by avoiding weakly optimal solutions and ensuring well-distributed Pareto solutions. Hemmati (2023) applied AEC to dairy supply chains, demonstrating its robustness against uncertain parameters like demand and transportation costs. Similarly, Fathollahzadeh (2024) showed its effectiveness in the meat industry, reducing environmental impacts by approximately 2.5% at the cost of a 5% decrease in profits. Although computationally intensive, AEC is ideal for complex supply chains requiring detailed trade-off analysis.

Each method offers unique benefits and trade-offs, making them suitable for specific supply chain scenarios. LGP and MCGP are ideal for prioritizing objectives and handling flexibility, respectively. WGP and MGP balance conflicting goals effectively, while WSM and AEC cater to straightforward and complex trade-offs. RPP stands out for its robustness in uncertain environments, particularly in the context of perishable goods. The choice of method depends on the supply chain's complexity, objectives, and the level of uncertainty involved.

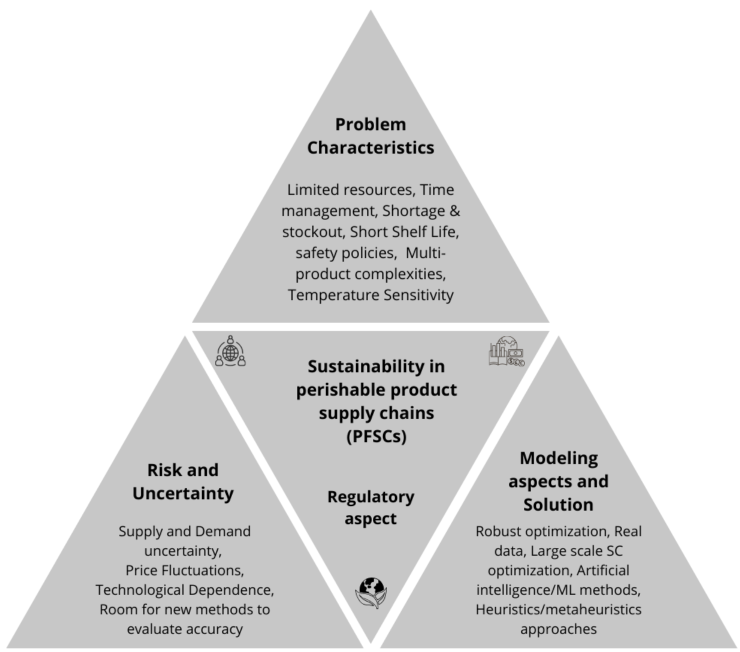

Figure 2. Challenges and considerations in designing and managing sustainable PFSCs

The triangular diagram in Figure 2 illustrates the multiple challenges and considerations in designing and managing sustainable supply chains for perishable products (PFSCs), highlighting three primary dimensions. Problem Characteristics reflect the unique complexities of PFSCs, including the short shelf life of perishable products, which demands precise time management to minimize spoilage and waste. Limited resources, such as transportation and storage capacities, exacerbate the challenge of managing shortages and stockouts. Additionally, adhering to safety policies and handling diverse multi-product supply chains introduce further complexity, particularly for temperaturesensitive goods requiring robust cold chain systems. These issues highlight the need for integrated approaches to effectively manage perishable goods.

Risk and Uncertainty dimension underlines the unpredictability in supply and demand, which significantly impacts PFSC operations. Price fluctuations and dependency on technology, such as monitoring and transportation systems, further add to the uncertainty. These risks require the adoption of advanced forecasting techniques and robust optimization frameworks to mitigate disruptions and enhance accuracy. Addressing these risks is vital for maintaining operational stability and minimizing losses in the supply chain.

Modeling Aspects and Solutions, focuses on leveraging advanced techniques to address the complexities of PFSCs. The integration of large-scale data enables better decision-making, while advanced tools like artificial intelligence (AI), machine learning (ML), and heuristic/metaheuristic methods improve the efficiency and sustainability of supply chain operations. Robust optimization ensures that uncertainties in supply, demand, and other parameters are effectively managed, enabling the design of resilient and adaptive supply chain networks.

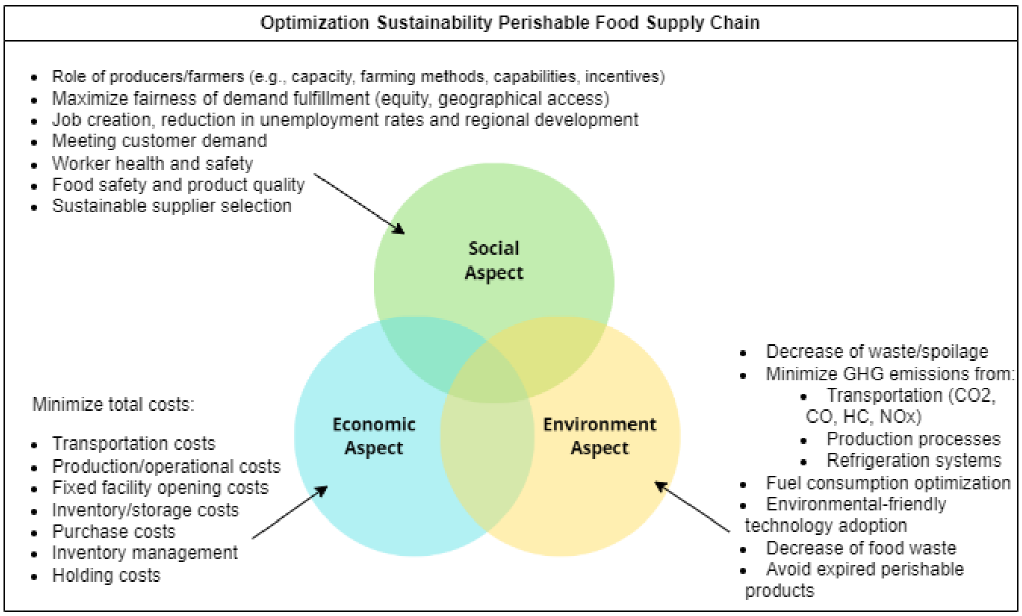

Figure 3. Challenges and considerations in designing and managing sustainable PFSCs

The Figure 3 highlights the three core dimensions of sustainability in the optimization of a perishable food supply chain. The social dimension emphasizes the role of the supply chain in promoting equity, community welfare, and public health. It considers the role of producers and farmers, focusing on their capacity, farming methods, and the incentives needed to enhance productivity and regional development.

The economic dimension focuses on cost efficiency and the financial viability of supply chain operations. Minimizing transportation costs, production costs, and operational expenses is a primary goal, ensuring that the supply chain remains competitive while delivering value. Additionally, effective inventory management and cost control help mitigate the financial risks associated with perishable goods, such as spoilage and overstocking. The economic aspect emphasizes a balance between cost reduction and maintaining product availability, ultimately ensuring profitability without compromising service quality.

The environmental dimension centers on reducing the ecological footprint of supply chain operations. It focuses on minimizing greenhouse gas (GHG) emissions from transportation, production, and refrigeration processes, addressing pollutants such as CO_2, HC, and NOx. Strategies include optimizing fuel consumption, adopting environmentally friendly technologies, and implementing sustainable production processes. By decreasing food waste and adopting greener practices, the supply chain contributes to environmental conservation while supporting long-term sustainability goals. However, each method in multi-objective optimization has strengths and weaknesses as presented in Table 2.

Table 2. Literature Filtering Results

No	Methods	Strengths	Weaknesses
1	LGP	Ensures strict prioritization of objectives, optimizing higher-priority goals before lower-priority ones	Results are highly dependent on the priority order of objectives
			Less flexibility in accommodating changing priorities
			Calculation complexity increases with the number of objectives
2	MCGP	Provides flexibility in target selection	Higher computational complexity due to multiple choices per objective.
			Requires careful calibration of multiple acceptable levels.
3	WGP	Flexible in weighting objectives	Results are highly dependent on weight determination
		Allows balanced optimization by assigning weights to objectives.	Difficult to guarantee objectives optimality
			Requires expertise in weight determination
4	ε-constraint	Produces more robust solutions	High computational complexity
		Effective in multi-objective optimization	Requires precise augmented parameters
			Longer computation time
5	MGP	Balances objectives by minimizing the maximum deviation from the ideal values.	Requires additional computational effort to handle multi-objective trade-offs.
6	WSM	Simple and intuitive, combining objectives into a single optimization function.	Struggles with non-convex Pareto frontiers, potentially missing optimal solutions.

The Table 2 summarizes the strengths and weaknesses of various exact methods used in multi-objective optimization, providing insights into their applicability for sustainable supply chain design. Each method demonstrates unique characteristics that make it suitable for specific types of problems. Simpler methods like WSM are suitable for straightforward problems, while advanced methods like ε-Constraint and MGP are better suited for complex, multi-objective optimization challenges. Balancing strengths and weaknesses is essential to achieving optimal outcomes in sustainable supply chain design.

3.3 Future Research

Further studies are needed to explore the implementation of optimization methods across various scales, from local to global, and their impact on food supply chain policies. Investigating how the results of these methods can support decision-makers in formulating more effective strategies for sustainable supply chains is critical. Additionally, analyzing the challenges faced in different geographical and cultural contexts, as well as conducting case studies in developing countries, could provide deeper insights.

Long-term evaluations of the application of optimization methods are essential to ensure sustained benefits in managing perishable products within supply chains. Future research should also consider applying these methods in diverse policy scenarios, such as the impact of subsidies, trade regulations, and food assistance programs. This could provide a clearer understanding of the effectiveness and potential consequences of various interventions aimed at improving the sustainability and efficiency of food supply chains.

4. Conclusion

This literature review highlights the growing importance of multi-objective optimization methods in addressing the challenges of sustainable supply chain management for perishable products. The review identifies and evaluates various methods, including Lexicographic Goal Programming, Multi-Choice Goal Programming, Weighted Goal Programming, Augmented ε-Constraint, and others, emphasizing their strengths, weaknesses, and applicability in balancing economic, environmental, and social objectives. Through careful examination of 11 selected papers from an initial pool of 146 references, The review demonstrates that different optimization methods offer distinct advantages in addressing the complex challenges of sustainable perishable supply chains.

The findings reveal that while simpler methods like Weighted Sum Method and Weighted Goal Programming provide ease of implementation and computational efficiency, they often struggle with non-convex Pareto frontiers and achieving diverse trade-offs. Advanced methods such as Augmented ε-Constraint and Robust Possibilistic Programming excel in handling complex multi-objective scenarios and uncertainty but require higher computational resources and precise parameter settings. Furthermore, the integration of AI, machine learning, and real-time data presents significant opportunities for improving the adaptability and robustness of supply chain models.

Despite significant advancements, gaps remain in addressing certain aspects of sustainability. Limited attention has been given to the dynamic interactions between economic, environmental, and social objectives over time, as well as the impact of data size on model performance and results. Additionally, there is a need to explore hybrid approaches combining exact and heuristic methods to improve scalability for large-scale problems.

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