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A Hybrid Distribution Network Model for Cost, Quality and Distribution Optimization in Perishable Goods Supply Chains

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ABSTRACT

The entrenched role of syndicates and intermediaries in the perishable goods sector inflates prices through artificial scarcity and hoarding, creating significant affordability challenges. Addressing these issues is critical amid rising global demand for fresh produce, which is highly vulnerable to quality degradation due to Supply Chain (SC) inefficiencies and inadequate cold storage practices. Consequently, formulating an SC Distribution Network (SCDN) becomes imperative to optimize distribution planning, mitigate quality deterioration, and ensure the sustainability of the SC. This research proposes an advanced SCDN architecture by developing a mixed-integer linear programming (MILP) model tailored for multi-echelon scenarios. The model aims to minimize overall SC costs, reduce cold storage expenses, and preserve the freshness of perishable goods through an efficient and hybrid distribution channel. The proposed model integrates competing objectives by addressing a multi-criteria problem via the weighted sum method (WSM) and is executed using the GUROBI optimizer in Python. Two case studies centred on the distribution of Mango and Jack fruits in Bangladesh validate the model's practicality. The findings highlight the strategic importance of optimal distribution center placement and a dual supply strategy, with plants meeting 63% of mango and 53% of jackfruit demand, reducing reliance on intermediaries by advocating direct shipping to markets while bypassing cold storage. This study further highlights the model's robustness and offers critical managerial insights, facilitating informed decision-making in the complex landscape of perishable product supply chains.

1. INTRODUCTION

The perishable goods sector is increasingly burdened by systemic inefficiencies, with syndicates and intermediaries exploiting market dynamics to artificially inflate prices through hoarding and engineered scarcity. These practices not only exacerbate affordability challenges but also disrupt the equitable distribution of essential fresh produce. At the same time, the growing global demand for perishable commodities, such as fruits and vegetables, highlights critical vulnerabilities in SC operations [1, 2]. Inadequate cold storage infrastructure, inefficient handling processes, and fragmented distribution networks contribute significantly to quality degradation and economic losses [3, 4]. Addressing these multifaceted challenges requires a strategic and robust approach to SCDN design, aimed at optimizing distribution efficiency, preserving product quality, and enhancing SC sustainability [2]. This research seeks to bridge these gaps by offering a comprehensive and innovative solution to the pressing issues in perishable SC management.

The role of intermediaries, or syndicates, in inflating prices for perishable goods is a significant issue in many developing countries, including Bangladesh. These middle entities often manipulate supply and demand by creating artificial scarcity or hoarding products, which drives up prices and reduces affordability, particularly for essential goods. Research indicates that intermediaries contribute significantly

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to price hikes, with some estimates suggesting that they are responsible for up to 80% of the price increase in the consumer goods market [5]. Furthermore, the management of perishable goods in retail outlets, such as superstores, adds another layer of complexity. Moreover, the government of Bangladesh has acknowledged the existence of syndicates for perishable products. Not only have they confirmed this, but they have also stated that breaking these syndicates is extremely challenging and difficult [6]. Later, the Agriculture Minister of Bangladesh highlighted the potential rise of syndicates due to a reduction in perishable commodities production for 2024, indicating that such syndicates may manipulate market prices [7]. These created higher costs make fresh produce less accessible to lower-income households, who often turn to local markets instead. Moreover, as global populations continue to grow and urbanize, the demand for food is reaching unprecedented levels, with forecasts predicting a 50% increase in food demand by 2030 [8]. This surge in demand, particularly for fresh produce, presents significant challenges for the agricultural sector, especially in managing perishable goods. However, recent research has mainly focused on various aspects of perishable goods SCs, such as reducing lead times [1], improving inventory management [9], minimizing carbon emissions [10], and enhancing sustainability [11]. However, addressing the unique challenges posed by perishable goods requires a holistic approach that balances cost optimization with quality preservation and tackle syndicates.

The perishable food SC also faces challenges such as inadequate infrastructure, technological gaps, and logistical inefficiencies. These issues contribute to significant food waste, which not only reduces industry profitability but also exacerbates food insecurity and environmental degradation. According to the United Nations, the global population is projected to reach 9.8 billion by 2050, intensifying the need for efficient food SCs to ensure safety, quality, and sustainability [12]. Currently, food losses account for one-third of global food production, equating to 1.3 billion tons annually [13]. In 2011, 492 million fruits and vegetables were wasted due to SC inefficiencies, with the environmental cost of this waste including the loss of 300 million barrels of oil and 230 cubic kilometres of water [14]. These losses raise ethical concerns, especially given the global hunger crisis. Mismanagement of perishable products leads to the waste of valuable natural resources, further exacerbating the environmental impact [15]. Despite the severity of these challenges, the issue of food waste has not been adequately addressed [16]. With the world population expected to grow, it is crucial to tackle these challenges to reduce food waste and ensure a sustainable food supply.

Given the challenges of perishable goods markets, efficient SC management is essential for ensuring that products reach consumers in optimal condition and at competitive prices. This study examines the challenges faced by SC networks for perishable products and explores opportunities for optimization. Key factors influencing the SC include the selection of appropriate distribution centres (DC), transportation routes, and inventory management practices. Suboptimal facility locations can result in increased transportation costs, delays, and inefficiencies in product handling [9]. Given the limited shelf life of perishable products, timely delivery is critical, and the location of DC has a direct impact on the overall efficiency of the SC [1]. This research develops an SC network model for mangoes and jackfruits, focusing on minimizing total costs, optimizing delivery lead times, and selecting optimal cold storage locations across various cities in Bangladesh.

The contributions of this research lie in its novel approach to optimizing the perishable goods SC through a hybrid distribution network model. By integrating multi-echelon SC design with MILP model, the study provides a comprehensive framework for addressing cost, quality, and distribution optimization in perishable product SCs. This research offers valuable insights into the strategic placement of DCs, the trade-offs between cost efficiency and responsiveness, and the potential for reducing waste and improving product quality in dynamic SC environments.

The rest of this article is organized as follows: Section 2 reviews the relevant literature. Section 3 illustrates the problems, including problem statement and mathematical model development with relevant assumptions. Model validation, including data collection, results analysis, robustness test and managerial implications are presented and discussed in Section 4. Finally, concluding remarks and future research directions are presented in section 5.

2. LITERATURE REVIEW

The literature review is organized into two subsections for clarity and focus. Section 2.1 provides an in-depth analysis of recent studies related to the perishable food SC, highlighting key advancements and methodologies. Section 2.2 identifies and summarizes the critical research gaps that remain unaddressed.

2.1 Related Works

The perishable goods sector faces systemic inefficiencies, including market manipulation, inadequate cold storage, and fragmented distribution networks, leading to price inflation, quality degradation, and economic losses. Despite growing global demand, the literature lacks exploration of integrated SCDN design, sustainable cold chain solutions, and strategies to counteract market manipulation. These unexplored gaps require urgent attention to enhance efficiency, sustainability, and equity in perishable SC management.

Study by [17] designed a distribution network for perishable products involving production plants, cold storage DCs and customer zones. A tri-objective mathematical model was developed to optimize cold storage size, shipping quantities, and minimize costs and lead time. Another study by [9] optimized a hybrid perishable food SC from production centres to retailers, aiming to find optimal DC locations, traffic-efficient routes, inventory levels, and pricing strategies to minimize costs and environmental impacts. An operational model to assist growers of perishable crops in making short-term production and distribution decisions during harvesting was formulated [18]. Their model worked on providing the best trade-off between the freshness of crops and the cost of added labour and transportation. The objective was to maximise the profit, considering the cost of the rejected shipment. This was a mixed-integer problem solved by a CPLEX solver [1]. A single source multi-product, multi-stage SC network problem was developed by [19], where authors

Table 1. Summary of the related studies

Model / Area of Study [References]	Model Characteristics						Hybrid Distribution Network			Objective Function		Solution Approach
	Multi-product	***Cold storage***	***Optimal Location***	***Waste Minimization***	***DC size***	***Delivery Lead Time***	***Plant to DC***	***DC to market***	***Plant to market***	***Facility Cost***	***Transportation Cost***	
Vehicles location-routing problems [23]	×	×	✓	×	×	×	×	×	×	×	×	PSO and Variable Neighborhood Search
TES incorporation to the cold system for energy saving [24]	×	✓	×	×	×	×	×	×	×	✓	✓	NSGA-II algorithm
Location-routing model [25]	×	×	✓	✓	×	×	×	×	×	×	×	Constraint Programming
Refrigerated automated warehouse [26]	✓	✓	×	✓	×	×	×	×	×	✓	✓	Biogeography-based optimization
Distribution planning model [27]	✓	×	×	×	×	×	×	×	×	✓	✓	IRP
Inventory routing [28]	✓	×	✓	×	×	×	×	×	×	✓	✓	LP metrics method
Closed-loop SC MILP model [29]	×	×	✓	×	×	×	×	×	×	✓	✓	GA and PSO
Location-routing-inventory [30]	✓	×	✓	×	×	×	×	×	×	✓	✓	Modified PSO
Production-inventory-routing [31]	×	×	✓	✓	×	✓	×	×	×	✓	✓	Exact and WSM
Distribution planning MILP [1]	✓	✓	×	✓	✓	✓	×	×	×	✓	✓	Exact and WSM
Perishable foods SC network [21]	×	×	✓	✓	✓	×	×	×	×	✓	✓	LIRP, MINLP
Sustainable and resilient SC [9]	×	×	×	×	✓	✓	×	×	×	✓	✓	LIR
Planning the harvest and distribution of perishable products [18]	✓	×	✓	×	×	✓	×	×	×	×	×	Planning model
Sustainable and resilient SC [20]	×	×	✓	✓	✓	×	×	×	×	✓	✓	MINLP
Closed-loop location routing inventory problem [32]	×	×	✓	×	✓	×	×	×	×	✓	✓	CL-LRIP
Perishable product SC network [10]	×	×	×	✓	×	×	×	×	×	×	×	Fuzzy approach
Green closed-loop SC [33]	✓	✓	✓	✓	✓	✓	×	✓	×	✓	✓	NSGA-II algorithm
Resilience for unnecessary perishable foods [34]	×	×	×	×	×	×	×	×	×	✓	✓	Agent-based modeling approach
Hybrid SCDN (**Proposed**)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	MILP

solved it by using a Genetic Algorithm (GA) to prove that a steady-state GA can find better heuristic solutions. A recent study by [20] designed an SC with multiple production centres (PC), suppliers, DC and retailers aiming to optimize PC and DC placement for maximum profit by minimizing setup, raw material, transportation, and environmental costs. The objective functions balanced short-term tactical and long-term strategic goals, considering both direct PC-retailer shipments and indirect PC-DC-retailer shipments with price-dependent demand.

The primary obstacles in perishable food SCs have been identified by studies, and these include reducing post-harvest loss, optimizing revenue, and ensuring consumer satisfaction. Risk management in perishable food SCs has become essential due to the perishable nature of goods and their short shelf lives; research has focused on detecting obstacles and reducing them. The most popular optimization techniques are linear programming models because of their versatility and capacity to handle a broad range of constraints and goals in perishable SC management. That's why those are frequently employed in the optimization of the food SC. Perishable SC managers employ Solvers to address optimization challenges, which frequently call for users to express real-world issues mathematically [10]. Authors in [22] introduced an integrated approach, known as LIRP, to optimize an SC Network for perishable products. It focused on minimizing costs by addressing key challenges such as determining optimal DC quantity and locations, allocating retailers to DCs, and optimizing vehicle routes from DCs to retailers while considering product perishability using mixed-integer nonlinear programming (MINLP) model. Authors in [22] introduced a multi-objective mixed integer programming (MOMIP) model to minimize three key objectives: net present value of SC cost, road traffic congestion, and fuel consumption. This approach was compared to goal programming (GP), where decision-makers set target values for each objective.

A non-linear mathematical model for perishable products was demonstrated by [35], where Authors solved the model using a heuristic Lagrangian Relaxation algorithm. The objective function minimized the total annual cost, comprising holding inventory and safety stock cost, ordering cost, transportation cost, and fixed installation cost of DCs. The model offered a trade-off between having a longer lifetime and reducing inventory costs. A model considering the transportation route, inventory, demand from retailers, and product freshness was proposed by [10] to determine the locations of distribution centres and focusing on minimizing the carbon emissions to develop a sustainable SC management system. Authors in [36] proposed a vehicle routing model to determine optimal routing, load and shipping times for delivering perishable foods to customers. Authors in [37] introduced a multi-objective model considering cost, greenhouse gas emission, and a novel priority index for social sustainability. The research included a mathematical model, a solution methodology using multi-objective fuzzy programming, and a case study on surgical instrument SCs. Results optimize product flow, vehicle visits, and prioritize objectives while considering cost uncertainties and qualitative factors for robust and sustainable SC management. Another study by [32] introduced a mathematical model for a Closed Loop Location Routing Inventory Problem. They integrated a few real-world situations in the developed model such as applying multi-compartment trucks with simultaneous pickup and delivery, and the risk of traffic. The study conducted by [33] presented a multi-objective mathematical model for closed-loop SC management that considers perishable products, quality deterioration, and a bundling strategy to reduce costs, risk, emissions, and delivery time under uncertain demand conditions, and compares the performance of the proposed non-dominated sorting GA (NSGA-II) with the multi-objective particle swarm optimization (MOPSO). A recent study by [34] modelled and simulated an agent-based resilient SC for unnecessary perishable foods to evaluate the impact of strategies like consumer behaviour tracking, discounts, product safety awareness, robotics, blockchain, and supporting suppliers on SC resilience, finding that 30% discount and 40% robotics were the most effective strategies in improving SC resilience.

2.2 Research Gaps

Several critical research gaps, as reported in the comparative Table 1, persist in optimizing perishable goods SCs. First, there is a lack of integrated models that balance cold chain sustainability, cost reduction, and quality preservation, particularly in resource-limited settings. Additionally, strategies to mitigate market manipulation by intermediaries are underexplored, and the use of real-time data for dynamic rescheduling in response to demand fluctuations and spoilage remains limited. Another gap is the need for models that simultaneously address economic, environmental, and quality objectives in perishable food SCs.

Moreover, the impact of intermediaries on cost and product freshness is insufficiently studied, and waste reduction strategies across the entire cold chain are lacking. While optimization techniques like linear programming and genetic algorithms are common, hybrid approaches that address multi-objective challenges are underdeveloped. Finally, emerging technologies such as blockchain, AI, and IoT have not been adequately explored for improving transparency and decision-making in perishable goods SCs. Addressing these gaps will enhance efficiency, sustainability, and equity in perishable food SCs.

3. PROBLEM STATEMENT

We examine an SC encompassing plants, DCs, and markets, as depicted in Figure 1, where products are transported from plants to DCs for quality preservation in refrigerated storage before being distributed to markets. A critical aspect of this SC involves selecting the most profitable locations for establishing refrigerated DCs from potential sites and determining whether to ship products directly from plants to markets. These decisions are pivotal for minimizing total costs while maintaining product quality.

In this hybrid SC, direct shipments from plants to markets occur when there is a pre-order and the delivery time is within a specified threshold. Otherwise, products are routed through DCs before reaching the market. To address these decisions, we developed a MILP model, a mathematical optimization technique that identifies the optimal solution for a problem where some decision variables are constrained to be integers, while others can be continuous.

3.1 Problem Definition and Assumptions

To develop an optimization model for this SC problem, we consider an SC comprising a set $\mathcal{F} = \{1, 2, \ldots, F\}$ of F non-homogeneous products, indexed by f, a set $\mathcal{P} = \{1, 2, \ldots, P\}$ of P potential plants, indexed by p, a set $\mathcal{D} = \{1, 2, \ldots, D\}$ of D potential DCs, indexed by d, and a set $\mathcal{M} = \{1, 2, \ldots, M\}$ of M markets, indexed by m.

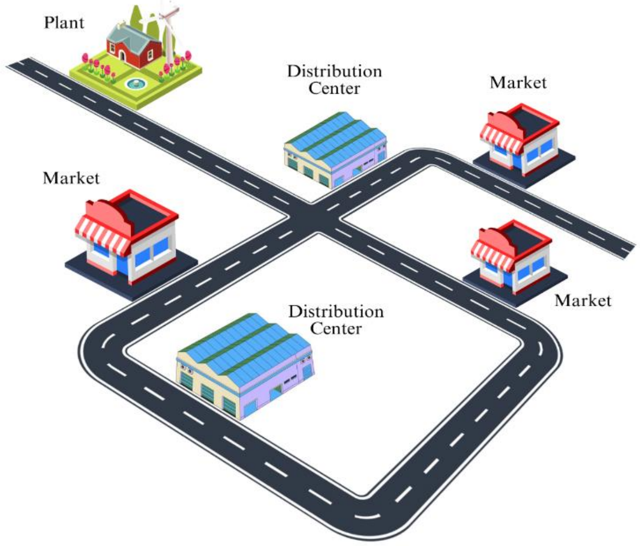


Fig. 1. General framework for an SC Network

The capacity constraints in the SCDN are imposed on each plant and DC, denoted by Q_{fp} and K_{fd}, respectively. Given the set of potential DCs, the fixed cost associated with establishing a DC at location d for product f is represented by F_{fd}. Product flow, a critical component of any SCDN, incurs shipping costs, which are defined as C_{fpd} from plant to DC, C_{fdm} from DC to market, and C_{fpm} from plant to market. The distribution network for each product is further characterized by T_{fpm}, representing the time duration from the end of production at plant p to the shipment arrival at market m for product f.

In this hybrid SCDN, decisions regarding product flow across the SC, the selection of DC locations, and the configuration of condition-based SC networks for each product are made. However, the following assumptions are made while developing the proposed optimization model.

- Products are initially shipped from the plant to the DC and subsequently from the DC to the market.
- In the case of pre-orders, products are shipped directly from the plant to the market immediately after production.
- Multiple plants can supply products to a single DC.
- Products can be distributed to a market from various plants and DCs.
- The degradation of products is assumed to be linear over time.
- Product shortages are not considered in the model.

3.2 Mathematical Model

In this section, an optimization model of DSCN proposed for perishable goods, aiming to simultaneously minimise a set of SCDN costs (f_1), presented in Equation 1. Section 3.2 introduces the essential indices, parameters and decision variables of the proposed model.

a) *Indices*:

f=non-homogeneous product, $f \in \mathcal{F} = \{1, 2, \ldots, F\}$

p=plant, $p \in \mathcal{P} = \{1,2, \ldots, P\}$

d= potential DC site, $d \in \mathcal{D} = \{1, 2, \ldots, D\}$

m=market, $m \in \mathcal{M} = \{1, 2, \ldots, M\}$

b) Input Parameters:

Q_{fp} = Capacity of plant p for product f

K_{fd} = Potential capacity of DC at site d for product f

B_{fm} = Annual demand from market m for product f

F_{fd} = Fixed cost of locating a DC at site d for product f

C_{fpd} = Shipping cost for one-unit product f from plant p to DC d

C_{fdm} = Shipping cost for one-unit product f from DC d to market m

C_{fpm} = Shipping cost for one-unit product f from plant p to market m

T_{fpm} = Time duration from plant p production end to market shipment m for product f

M = Threshold value of time for direct shipping from plant to market

c) *Decision Variable*:

X_{fpd} = Quantity of product f shipped from plant p to DC d

X_{fdm} = Quantity of product f shipped from DC d to market m

X_{fpm} = Quantity of product f shipped from plant p to market m

Y_{fd}=1, if DC is located at site d for product f; otherwise, Y_{fd}=0.

W_{fpm}=1, if product f shipped directly from plant p to market m; otherwise, W_{fpm}=0.

d) *Objectives*: The objective function 1 is optimized by rigorously adhering to the constraints outlined in 2 through 8. This approach ensures that the optimization process is fully aligned with the defined parameters, thereby achieving a solution that is both feasible and optimal within the established framework.

$$f_1 = \sum_{f \in \mathcal{F}} \sum_{d \in \mathcal{D}} F_{fd} Y_{fd} + \sum_{f \in \mathcal{F}} \sum_{p \in \mathcal{P}} \sum_{d \in \mathcal{D}} C_{fpd} X_{fpd} + \sum_{f \in \mathcal{F}} \sum_{d \in \mathcal{D}} \sum_{m \in \mathcal{M}} C_{fdm} X_{fdm} + \sum_{f \in \mathcal{F}} \sum_{p \in \mathcal{P}} \sum_{m \in \mathcal{M}} C_{fpm} X_{fpm} W_{fpm} \quad (1)$$

e) Subject to:

$$\sum_{d\in\mathcal{D}} X_{fpd} + \sum_{m\in\mathcal{M}} X_{fpm}Y_{fpm} \le Q_{fp}, \quad \forall f \in \mathcal{F}, \forall p \in \mathcal{P} \tag{2}$$

$$\sum_{p\in\mathcal{P}} X_{fpm} - \sum_{m\in\mathcal{M}} X_{fdm} \ge 0, \quad \forall f \in \mathcal{F}, \forall d \in \mathcal{D} \tag{3}$$

$$\sum_{m\in\mathcal{M}} X_{fdm} \le K_{fd}Y_{fd}, \quad \forall f \in \mathcal{F}, \forall d \in \mathcal{D} \tag{4}$$

$$\sum_{d\in\mathcal{D}} X_{fdm} + \sum_{p\in\mathcal{P}} X_{fpm}W_{fpm} = B_{fm}, \quad \forall f \in \mathcal{F}, \forall m \in \mathcal{M} \tag{5}$$

$$T_{fpm}(2W_{fpm} - 1) \le M(2W_{fpm} - 1), \ \forall f \in \mathcal{F}, \forall p \in \mathcal{P}, \forall m \in \mathcal{M} \tag{6}$$

$$X_{fpd}, X_{fdm}, X_{fpm} \ge 0, \quad \forall f \in \mathcal{F}, \forall p \in \mathcal{P}, \forall d \in \mathcal{D}, \forall m \in \mathcal{M} \tag{7}$$

$$Y_{fd}, W_{fpm} \in \{0,1\}, \forall f \in \mathcal{F}, \forall p \in \mathcal{P}, \forall d \in \mathcal{D}, \forall m \in \mathcal{M} \tag{8}$$

Constraint 2 enforces that the total quantity shipped from a plant must not exceed its production capacity. Constraint 3 ensures that the quantity dispatched from a DC cannot surpass the volume it receives from plants. Similarly, Constraint 4 limits the total outbound shipments from a DC to its maximum handling capacity. Constraint 5 mandates that the quantity delivered to a market must fully satisfy its demand. Constraint 6 governs direct shipments, prohibiting them when the shipping time exceeds the maximum allowable threshold and permitting them when the shipping time is within acceptable limits. Lastly, Constraint 7 stipulates that all decision variables must be non-negative, while Constraint 8 defines the binary nature of certain variables.

4. MODEL VALIDATION

The developed optimization model is validated through two distinct case studies, each involving highly significant perishable goods. Both products are locally produced and distributed nationwide, providing a relevant and practical context for evaluating the model's effectiveness in managing SC complexities associated with perishable items.

4.1 Data Collection

Data for this study was primarily sourced from the Yearbook of Agricultural Statistics, Bangladesh Sangbad Sangstha (BSS), and relevant academic publications. To validate the proposed hybrid SCDN for perishable goods, an illustrative example was constructed utilizing this data. The focus was on two highly popular seasonal perishable fruits, mangoes and jackfruits, and the model incorporated data from seven supply sources, ten DCs, and fifteen market zones. Detailed data for the case study are presented in Table 2, Table 3, and Table 4 summarizing plant capacities, DC locations, and market demands, respectively.

Table 2. Plant Capacity

Mango		Jackfruit	
Plant	***Production Capacity (Tons)***	***Plant***	***Production Capacity (Tons)***
Rajshahi (MP1)	240283	Khagrachari (JP1)	40675
Chapai Nawabganj (MP2)	144761	Rangamati (JP2)	43860
Naogaon (MP3)	48161	Tangail (JP3)	66500
Dinajpur (MP4)	44833	Gazipur (JP4)	101751
Habiganj (MP5)	23056	Kushtia (JP5)	75134
Kushtia (MP6)	57858	Pabna (JP6)	29106
Cumilla (MP7)	23821	Nilphamari (JP7)	30945

Table 3. DC Locations

Mango			Jackfruit		
DC	***Storage Capacity (Tons)***	***Fixed Cost (BDT)***	***DC***	***Storage Capacity (Tons)***	***Fixed Cost (BDT)***
Puthia (MD1)	20000	48000000	Gazipur (JD1)	8000	19200000
Natore Sadar (MD2)	18000	43200000	Rajshahi (JD2)	10000	24000000
Shibganj (MD3)	10000	24000000	Rangpur (JD3)	7000	16800000
Bogura Sadar (MD4)	9000	21600000	Jashore (JD4)	13000	31200000
Sirajganj Sadar (MD5)	12000	28800000	Kushtia (JD5)	9000	21600000
Khulna Sadar (MD6)	8000	19200000	Patuakhali (JD6)	12000	28800000
Mymensingh Sadar (MD7)	12000	28800000	Chattogram (JD7)	5000	12000000
Sylhet Sadar (MD8)	15000	36000000	Chandpur (JD8)	6000	14400000
Barisal Sadar (MD9)	17000	40800000	Sunamganj (JD9)	14000	33600000
Barguna Sadar (MD10)	14000	33600000	Jamalpur (JD10)	4000	9600000

Table 4. Market Demand

Mango		Jackfruit	
Market	***Demand (Tons)***	***Market***	***Demand (Tons)***
Natore (MM1)	25000	Dinajpur (JM1)	12000
Rajshahi (MM2)	30000	Thakurgaon (JM2)	15000
Sirajganj (MM3)	20000	Chuadanga (JM3)	10000
Pabna (MM4)	15000	Jashore (JM4)	14000
Ishwardi (MM5)	15000	Bagerhat (JM5)	10000
Chapainawabganj (MM6)	25000	Bhola (JM6)	5000
Naogaon (MM7)	20000	Patuakhali	8000

		(JM7)	
Sylhet (MM8)	10000	Sylhet (JM8)	7000
Khulna (MM9)	18000	Feni (JM9)	12000
Dhaka (MM10)	30000	Cumilla (JM10)	6000
Chattogram (MM11)	22000	Kishoreganj (JM11)	13000
Barisal (MM12)	14000	Chattogram (JM12)	19000
Rangpur (MM13)	16000	Dhaka (JM13)	17000
Kushtia (MM14)	13000	Khulna (JM14)	15000
Netrokona (MM15)	17000	Mohanganj (JM15)	9000

Several assumptions were made to streamline cost calculations. It was assumed that the average truck mileage is 20 kilometres per litre of diesel, with the diesel cost in Bangladesh set at 106 Taka (BDT) per litre. Accordingly, the shipping cost was estimated at approximately 5 BDT per kilometre per unit of product. Shipping costs from plants to DCs, DCs to markets, and directly from plants to markets were calculated by multiplying the respective distances by 5 BDT per kilometre. Lead times for different markets were estimated using Google Maps, taking into account the delay between production completion and order placement. Lead time, in this context, refers to the time required for a product to be transported from the plant to the market after an order is placed. For markets with pre-orders, this time delay was assumed to be zero. The total time duration from all plants to all markets was calculated as:

$$\textit{Total time duration} = \textit{Time delay} + \textit{Lead time} \quad (9)$$

Mangoes, once harvested, can be stored at room temperature for only 1-2 days before ripening begins, necessitating refrigeration in DCs after this period. As a result, the threshold time for direct shipping from plant to market was set at 24 hours to ensure product freshness.

4.2 Computing Environment

To solve the proposed MILP model, the Gurobi Optimizer was employed within a Python 3.11 environment. All experiments were conducted on a PC equipped with an Intel Core i5 processor and 8 GB of RAM.

4.3 Result Analysis

The optimal total cost calculated by the model is 799363070 BDT. Among all potential DC locations, the most profitable ones have been identified. Specifically, DCs should not be established in Mymensingh Sadar and Barguna Sadar for mango distribution, as detailed in Table 5. Instead, DCs will be strategically located in the remaining eight locations. For jackfruit, DCs will be established in nine locations, excluding Rangpur, as outlined in Table 2. Selecting all 10 DC locations for both products would result in a higher total cost of 877289310 BDT, which exceeds the calculated optimal cost, thus validating the appropriateness of our DC location selection.

The fulfilment of market demand for mangoes through both DCs and plants is presented in Table 6. In this case, the plants directly meet 63% of the total market demand, while the remaining 37% is supplied via DCs, as depicted in Figure 2a.

Table 5. Profitable DC Locations

Mango		Jackfruit	
DC Location	***Decision***	***DC Location***	***Decision***
MD1	✓	JD1	✓
MD2	✓	JD2	✓
MD3	✓	JD3	×
MD4	✓	JD4	✓
MD5	✓	JD5	✓
MD6	✓	JD6	✓
MD7	×	JD7	✓
MD8	✓	JD8	✓
MD9	✓	JD9	✓
MD10	×	JD10	✓

Table 6. Fulfilment of Margo Demand

Market	Demand	From Plant	From DC
MM1	25000	25000	0
MM2	30000	30000	0
MM3	20000	20000	0
MM4	15000	0	15000
MM5	15000	15000	0
MM6	25000	25000	0
MM7	20000	0	20000
MM8	10000	10000	0
MM9	18000	0	18000
MM10	30000	30000	0
MM11	22000	0	22000
MM12	14000	14000	0
MM13	16000	0	16000
MM14	13000	13000	0
MM15	17000	0	17000
Total	290000	182000	108000

Similarly, for jackfruit, the fulfilment breakdown is presented in Table 7, with plants meeting 53% of the market demand and DCs covering 47%, as shown in Figure 2b. Direct delivery

Table 7. Fulfilment of Jackfruit Demand

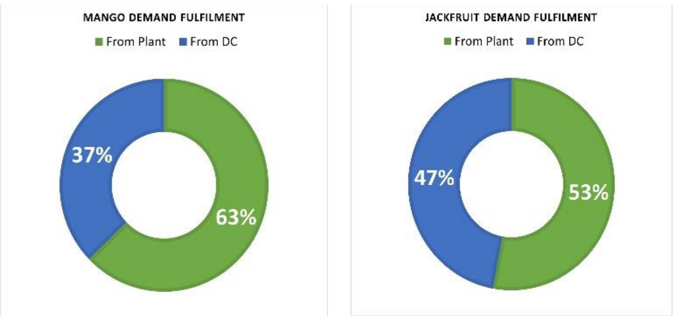
Market	Demand	From Plant	From DC
JM1	12000	12000	0
JM2	15000	15000	0
JM3	10000	0	10000
JM4	14000	14000	0
JM5	10000	10000	0
JM6	5000	0	5000
JM7	8000	0	8000
JM8	7000	0	7000

JM9	12000	12000	0
JM10	6000	0	6000
JM11	13000	13000	0
JM12	19000	0	19000
JM13	17000	0	17000
JM14	15000	15000	0
JM15	9000	0	9000
Total	172000	91000	81000

from plants to the demand zones significantly mitigates several challenges common in agricultural SCs, such as storage costs, product freshness, and issues related to syndicates at intermediate stages. Thus, this hybrid network enhances efficiency and reduces dependency on intermediaries, addressing these concerns to a great extent.

4.4 Sensitivity Analysis

The robustness of the proposed hybrid SCDN is evaluated by adjusting the values of specific parameters and comparing the outcomes with the initial results. This process allows for an assessment of the network's performance under varying conditions, ensuring its reliability and adaptability in different scenarios.



(a) Mango Demand (b) Jackfruit Demand

Fig. 2. Demand Fulfilment

a) *Different Values of Plant Capacity*: Table 8 presents the results of Tests 1, 2, 3, and 4, which explore the impact of varying plant capacities. The corresponding total costs for each test are depicted in Figure 3.

Table 8. Different Values of Plant Capacity

Mango				Jackfruit			
Plant	***Production Capacity (Tons)***			***Plant***	***Production Capacity (Tons)***		
	Initial	***Test 1***	***Test 2***		***Initial***	***Test 3***	***Test 4***
MP1	240283	241000	239000	JP1	40675	42000	38000
MP2	144761	145500	143000	JP2	43860	41000	45000
MP3	48161	47000	49000	JP3	66500	68000	64000
MP4	44833	43500	45000	JP4	101751	103000	100000
MP5	23056	23500	22500	JP5	75134	71000	77000
MP6	57858	59000	56500	JP6	29106	34000	27000
MP7	23821	22500	25500	JP7	30945	28000	33000

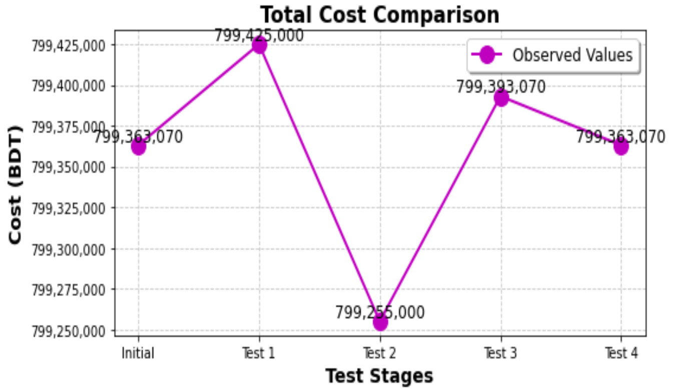


Fig. 3. Total Cost Comparison for Test 1, 2, 3 and 4

A thorough analysis reveals that the changes in total costs are minimal across all tests, demonstrating the model's strong reliability and adaptability under fluctuating plant capacities. Furthermore, the initially selected DCs for both products, as shown in Table 5, remain unchanged across all tests, even with adjustments to plant capacities, as indicated in Table 9. This consistency in DC selection and cost performance highlights the robustness of the model in maintaining cost efficiency, even when key operational parameters, such as plant capacity, are modified.

Table 9. DC Location for Test 1, 2, 3 and 4

Mango				Jackfruit			
DC	***Select Location***			***DC***	***Select Location***		
	Initial	***Test 1***	***Test 2***		***Initial***	***Test 3***	***Test 4***
MD1	✓	✓	✓	JD1	✓	✓	✓
MD2	✓	✓	✓	JD2	✓	✓	✓
MD3	✓	✓	✓	JD3	×	×	×
MD4	✓	✓	✓	JD4	✓	✓	✓
MD5	✓	✓	✓	JD5	✓	✓	✓
MD6	✓	✓	✓	JD6	✓	✓	✓
MD7	×	×	×	JD7	✓	✓	✓
MD8	✓	✓	✓	JD8	✓	✓	✓
MD9	✓	✓	✓	JD9	✓	✓	✓
MD10	×	×	×	JD10	✓	✓	✓

b) *Different Values of DC Capacity*: In the subsequent analysis, the model's robustness under varying DC capacities is assessed through four additional tests, with results presented in Table 10. The total costs for Tests 5, 6, 7, and 8 are reported in Figure 4. The analysis indicates that total costs remain largely unchanged across these tests, reinforcing the model's adaptability to fluctuations in DC capacities. Furthermore, the initial selection of DCs for both products, as displayed in Table 5, remains constant throughout all tests, even with changes in distribution capacities, as demonstrated in Table 11. This consistency further validates the model's capability to sustain cost efficiency under varying operational conditions.

Table 10. Different Values of Plant Capacity

Mango				Jackfruit			
DC	*Storage Capacity (Tons)*			*DC*	*Storage Capacity (Tons)*		
	Initial	*Test 5*	*Test 6*		*Initial*	*Test 7*	*Test 8*
MD1	20000	19500	21000	JD1	8000	7500	8500
MD2	18000	17000	20000	JD2	10000	11000	9500
MD3	10000	12000	13000	JD3	7000	7500	6500
MD4	9000	8500	8000	JD4	13000	11500	12000
MD5	12000	13000	10000	JD5	9000	8000	10000
MD6	8000	9000	11000	JD6	12000	13000	11000
MD7	12000	11000	14000	JD7	5000	6000	6500
MD8	15000	14000	13000	JD8	6000	7000	7500
MD9	17000	16500	15000	JD9	14000	13000	13500
MD10	14000	15000	13000	JD10	4000	4500	5000

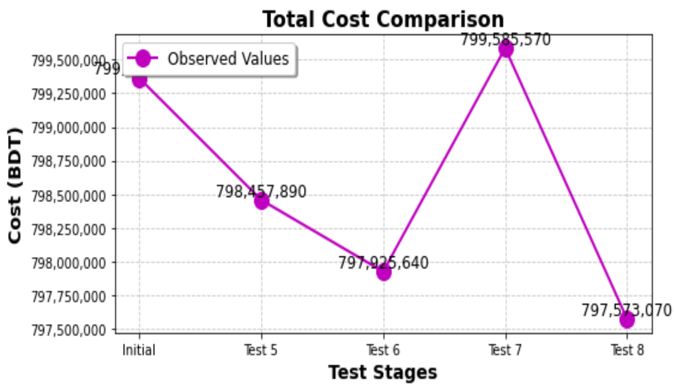


Fig. 4. Total Cost Comparison for Test 5, 6, 7 and 8

Table 11. DC Location for Test 5, 6, 7 and 8

Mango				Jackfruit			
DC	*Select Location*			*DC*	*Select Location*		
	Initial	*Test 5*	*Test 6*		*Initial*	*Test 7*	*Test 8*
MD1	✓	✓	✓	JD1	✓	✓	✓
MD2	✓	✓	✓	JD2	✓	✓	✓
MD3	✓	✓	✓	JD3	×	×	×
MD4	✓	✓	✓	JD4	✓	✓	✓
MD5	✓	✓	✓	JD5	✓	✓	✓
MD6	✓	✓	✓	JD6	✓	✓	✓
MD7	×	×	✓	JD7	✓	✓	✓
MD8	✓	✓	✓	JD8	✓	✓	✓
MD9	✓	✓	×	JD9	✓	✓	✓
MD10	×	×	×	JD10	✓	✓	✓

c) *Different Values of Market Demand*: A similar experiment was conducted under varying market demand conditions, yielding outcomes consistent with those previously observed. This investigation involved systematically adjusting market demand parameters while monitoring the corresponding results, as presented in Table 12, and Figure 5. The findings reaffirmed the model's robustness, as total costs remained stable despite fluctuations in market demand. This consistency underscores the model's adaptability and reliability in diverse scenarios, further validating its effectiveness in managing SC dynamics, as reported in Table 13. The results illustrate that the model can maintain cost efficiency and operational stability across a range of market conditions, demonstrating comprehensive applicability in real-world settings.

Table 12. Different Values of Plant Capacity.

Mango				Jackfruit			
Markets	*Demand (Tons)*			*Markets*	*Demand (Tons)*		
	Initial	*Test 9*	*Test 10*		*Initial*	*Test 11*	*Test 12*
MM1	25000	24000	26000	JM1	12000	12500	11500
MM2	30000	31000	29000	JM2	15000	16000	14000
MM3	20000	21000	21500	JM3	10000	9000	8000
MM4	15000	16000	15500	JM4	14000	15000	12000
MM5	15000	14000	14500	JM5	10000	9500	11000
MM6	25000	26000	24000	JM6	5000	6000	4000
MM7	20000	19000	21000	JM7	8000	7500	7000
MM8	10000	10500	9000	JM8	7000	6000	7500
MM9	18000	19000	17000	JM9	12000	13500	14000
MM10	30000	29000	28000	JM10	6000	7500	5000
MM11	22000	21000	22500	JM11	13000	12500	14000
MM12	14000	13000	15000	JM12	19000	18000	20000
MM13	16000	17500	17000	JM13	17000	16000	18000
MM14	13000	14000	15000	JM14	15000	16500	14000
MM15	17000	16500	16000	JM15	9000	9500	10500

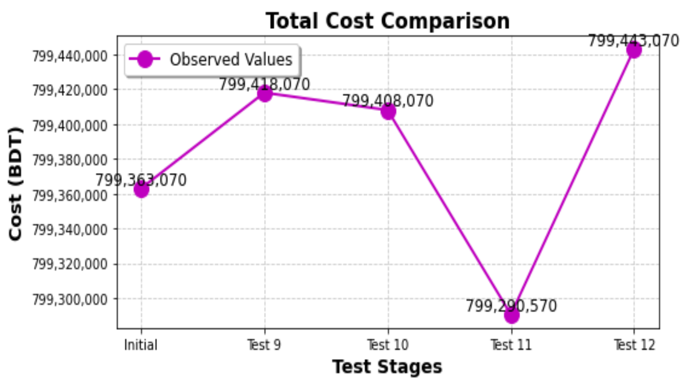


Fig. 5. Total Cost Comparison for Test 9, 10, 11 and 12

Table 13. DC Location for Test 9, 10, 11 and 12

Mango				Jackfruit			
DC	*Select Location*			*DC*	*Select Location*		
	Initial	*Test 9*	*Test 10*		*Initial*	*Test 11*	*Test 12*
MD1	✓	✓	✓	JD1	✓	✓	✓
MD2	✓	✓	✓	JD2	✓	✓	✓
MD3	✓	✓	✓	JD3	×	×	×
MD4	✓	✓	✓	JD4	✓	✓	✓
MD5	✓	✓	✓	JD5	✓	✓	✓
MD6	✓	✓	✓	JD6	✓	✓	✓

MD7	×	×	×	JD7	✓	✓	✓
MD8	✓	✓	✓	JD8	✓	✓	✓
MD9	✓	✓	✓	JD9	✓	✓	✓
MD10	×	×	×	JD10	✓	✓	✓

The findings illustrate that the model effectively maintains cost efficiency and operational stability across diverse market conditions, showcasing its comprehensive applicability in real-world settings.

4.5 Managerial Implications

The analysis of the optimal total cost, calculated at 799363070 BDT, yields several key managerial implications for SC management:

a) *Strategic Location of DCs*: Avoiding DC establishment in Mymensingh Sadar and Barguna Sadar for mango distribution, while focusing on eight other DC locations, can enhance cost efficiency. Similarly, excluding Rangpur for jackfruit distribution is essential, emphasizing the importance of economically viable site selection.

b) *Demand Fulfilment Efficiency*: The dual supply strategy, with plants meeting 63% of mango demand and 53% of jackfruit demand, reduces reliance on intermediaries. This hybrid network mitigates common challenges in agricultural SCs, such as storage costs and product freshness, while enhancing availability.

c) *Robustness and Adaptability*: Sensitivity analysis shows the model's robustness across varying plant and DC capacities, as well as market demands. The stability of total costs indicates that the hybrid SCDN can adapt to fluctuations without significant cost increases, ensuring reliability under uncertainty.

d) *Practical Applicability*: The model's effectiveness in sustaining cost efficiency and operational stability across various scenarios highlights its real-world applicability. Organizations can leverage these insights to optimize resource allocation and enhance SC responsiveness.

In summary, the findings advocate for a strategic approach to DC location selection and operational management that emphasizes adaptability and efficiency, positioning organizations to better navigate the complexities of modern SC dynamics.

5. CONCLUSION

This study undertook the complex task of optimizing the SC network for perishable products, addressing the delicate balance between maintaining product quality and achieving cost-efficiency. By harnessing the power of the MILP model, the research identified profitable DC locations and optimal shipment quantities, offering insights that have the potential to transform operational strategies and enhance profitability in the perishable goods sector. A sensitivity analysis was also conducted to assess the robustness of the MILP model, confirming its feasibility across different scenarios.

One of the study's most critical insights is the identification of optimal DC locations. In the dynamic and often unpredictable landscape of perishable product SCs, strategic DC placement is crucial for ensuring product quality and timely delivery. The research provides a strategic framework for businesses to optimize their distribution networks, thereby minimizing costs and reducing delays. Additionally, the study tackled the intricate problem of determining the ideal shipment quantities from plants or DCs to markets. In an environment where efficiency and responsiveness are frequently at odds, achieving this balance is essential. The MILP model facilitates this by enabling stakeholders to make data-driven decisions that align with both market dynamics and operational constraints. By implementing these findings, businesses can enhance SC resilience, reduce waste, improve customer satisfaction, and create opportunities for greater economic sustainability.

The study focused on the SC for mango and jackfruit in Bangladesh, providing valuable insights specific to this context. However, it did not account for factors such as traffic congestion, carbon emission reduction, advanced forecasting techniques, and dynamic pricing strategies. These elements offer additional avenues for future research and refinement of SC strategies.

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