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An Integrated Mixed-Integer Linear Programming–Simulation Framework for Network Design and Operations Optimization in Iraq's Date-Fruit Supply Chain

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ABSTRACT

Iraq's date-fruit supply chain faces persistent inefficiencies arising from a dispersed collection network, imbalanced processing capacity, and limited cold chain and logistics infrastructure. This paper proposes an optimized operational model of mixed-integer linear programming (MILP), constraint-based scheduling, and discrete-event simulation. The MILP model formulates the network structure of data collection and processing centers to optimize total logistics costs. The scheduling component generates feasible harvest and processing plans under perishability, labor availability, and capacity constraints. Simulation is used as a method of analyzing complex systems. The proposed models and simulation demonstrate a 42% and 28% reduction in data transportation distance and cost, respectively, and an improvement in facility utilization from 58% to 93%. The scheduling models demonstrate a 22% reduction in date harvesting and processing waiting time and an improvement of 26% in peak throughput. The simulation results demonstrate a 36.5% and 14.2% reduction in post-harvest date losses and an improvement in the shelf life of deluxe dates.

1. INTRODUCTION

Iraq has been one of the world's leading date producers for a long time, with date palms not only being a major agricultural commodity but a key part of the country's heritage as well. With more than 16 million date palm trees and a production level of more than 600,000 tons per year, the date industry remains a strategic part of the country's agricultural economy [1]. Despite this high potential for date production, the industry continues to demonstrate high levels of supply chain inefficiencies [2-4].

The date fruit industry in Iraq has a fragmented structure, which includes a large number of small-scale farmers, diverse harvesting methods, limited storage facilities, and underdeveloped transportation networks [5, 6]. This problem is further compounded by low acceptance and application of modern technology, variable quality controls, and limited market access to global markets [7, 8]. This has led to significant post-harvest losses and reduced value addition.

Operational research has been widely utilized as a scientific tool for decision-making for complex supply chain issues using mathematical modeling, optimization, and simulation techniques [9]. In agri-food supply chains, network optimization, scheduling, and simulation techniques have proven their ability to cut costs, manage resources, and increase efficiency in food supply chain networks, but most current literature assumes relatively stable institutional environments, logistics structures, and infrastructures, which are not commonly found in transition economies such as Iraq after conflict [10, 11].

The Iraqi date supply chain has its own set of characteristics, which differ from those of traditional agri-food chains. These include fragmented collection networks with multiple actors, unbalanced geographies of processing, low refrigerated storage and transport networks, and large administrative and logistical lead times for both local and export chains [12-16]. In addition, security constraints add their own uncertainties, which are not usually considered in traditional supply chain optimization approaches [17]. Therefore, despite the insights gained from existing operations research (OR) applications, their direct application to the Iraqi dates sector is limited.

The current literature on the subject of date supply chain analysis and design has been limited to isolated issues like cost reduction, maintaining product quality, or export chain design and execution, and was generally carried out under more peaceful and stable regional conditions [18]. There is, however, an identified knowledge gap regarding the formulation of holistic models to deal simultaneously and comprehensively with the design and execution of the network strategy and the treatment of overall uncertainties under the particular Iraqi conditions. To address this gap, in this study, an integrated operational framework using mixed-integer linear programming (MILP), a constraint programming approach to harvesting and processing, and discrete event simulation to handle dynamics and disruption scenarios has been proposed. Unlike other approaches that focus on each of these aspects in isolation, in this proposed framework, strategic, tactical, and operational levels are integrated into a single framework. By considering local realities and constraints in the analytical framework, this study aims to provide a more practical and application-oriented approach to enhance efficiency and economic viability in the Iraqi date supply chain.

2. METHODOLOGY

2.1 Research design

This study uses both qualitative (fieldwork) and quantitative (modeling and simulation) methods. The study was undertaken in three of the major date-producing governorates in Iraq (Basra, Karbala and Baghdad) to reflect a range of production systems and supply chain configurations.

2.2 Data collection

A mixed-method data collection approach was used, where both primary and secondary sources were used to create depth of understanding and triangulate findings.

2.2.1 Primary data collection

Data was collected through structured interviews with 85 stakeholders across the date value chain: 32 date producers (12 small-scale, 15 medium-scale, and 5 large-scale), 18 processors with varying technological capacities, 14 distributors and traders (domestic and export-based), 8 exporters with international market experience, and 13 government officials representing relevant ministries and regulatory agencies. For each interview (60–90 minutes), a semi-structured interview format was adopted that included both qualitative and quantitative questions. Cost structures, perceived barriers to efficiency, decision-making processes, quality management practices, operational procedures, and technological capabilities were discussed.

Process mapping workshops were organized with four distinct supply chain participant groups (farmers, processors, distributors, and exporters), with each workshop including 8–12 participants. Using value stream mapping methodologies, these facilitated sessions identified the processes, value- and non-value-adding activities, time spent in each activity, and decision points and information flows. Root cause analysis techniques were used to coactively explore inefficiencies in the supply chain with participants.

Conduct time-motion studies on critical supply chain activities like harvesting, sorting, packing, loading/unloading, transportation, processing, and storage. This necessitates a minimum of 30 observations for each activity, utilizing standardized time study templates to document process disaggregation, total duration, time variability, and quality outcomes. Particular attention was given to interface points between supply chain stages where handover inefficiencies commonly occur.

2.2.2 Secondary data collection

The research supplemented primary data with extensive secondary sources:

Ministry of Agriculture reports and statistics provided historical production data (2015–2023), regional yield variations, variety distributions, land utilization patterns, and policy initiatives. Particular emphasis was placed on the Agricultural Development Plans (2018–2023) and the Date Palm Rehabilitation Project documentation, which contained baseline assessments and intervention targets.

Industry association databases, particularly from the Iraqi Date Producers Association and the Federation of Iraqi Chambers of Commerce, provided market pricing data, quality standards information, export statistics by destination, and industry structure information. These databases included monthly wholesale price indices for different date varieties and grades across multiple domestic markets.

All retrieved data were subjected to quality assessment processes to verify data through cross-reference between different sources, outlier detection, and expert validation with industry experts. Information was consistently coded, stored, and retrieved throughout the analysis process by following data management protocols.

2.3 Development of operational research models

Based on the gathered data, three complementary operational research models were built:

2.3.1 Network optimization model

This study proposes a MILP model for solution generation to optimize the network configuration consisting of collection centers, processing facilities and distribution hubs. The model aims to minimize overall logistics costs while satisfying demand constraints, as well as operational limitations on infrastructure.

This is mathematically expressed as: Minimize

$$Z = \sum_i \sum_j C_{ij} X_{ij} + \sum^k F^k Y^k + \sum_i \sum^k T_i^k V_i^k \quad (1)$$

Subject to:

$$\textit{Capacity constraints: } \sum_i X_{ij} \leq CAP_j Y_j \textit{ for all } j \quad (2)$$

$$\textit{Flow conservation: } \sum_j X_{ij} = \sum^k V_i^k \textit{ for all } i \quad (3)$$

$$\textit{Demand satisfaction: } \sum_i V_i^k \geq D^k \textit{ for all } k \quad (4)$$

$$\textit{Binary decision variables: } Y_j \in \{0,1\} \textit{ for all } j \quad (5)$$

where,

- X_{ij} represents the quantity of dates flowing from production region *i* to facility *j*.
- Y^k is a binary variable indicating whether facility *k* is operational.
- V_i^k represents the quantity of dates flowing from facility *i* to market *k*.
- C_{ij}, F^k, and T_i^k stand for transportation costs, facility operating costs and distribution costs, respectively.

To enhance clarity and consistency with the nomenclature presented at the end of the manuscript, the index sets, modeling assumptions, and objective function structure of the MILP formulation are explicitly summarized below. All symbols and variables referenced in this subsection are defined in the Nomenclature section.

The model employs three primary index sets: production regions indexed by $i \in I$, collection or processing facilities indexed by $j \in J$, and domestic or export markets indexed by $k \in K$. Decision variables include the quantity of dates transported from the region i to facility $j(X_{ij})$, the quantity shipped from the facility i to market $k(V_{ik})$, and the binary facility-opening variable (Y_j), as defined in the Nomenclature.

The MILP formulation is developed under a set of simplifying yet practical assumptions summarized in Table 1. Transportation costs (C_{ij}), facility operating costs (F^k), and distribution costs (T_{ik}) are assumed to be linear with respect to flow volumes, which is appropriate for the aggregated planning level considered. Market demand (D^k) is treated as deterministic and represented by average historical values, while uncertainty effects are addressed separately through simulation. Facility capacities (CAP_j) are assumed fixed within the planning horizon, reflecting existing infrastructure limitations, and inventory carryover between periods is not explicitly modeled in the MILP formulation.

The objective function, Z, seeks to optimize the overall system cost by summing up all the costs into a unified monetary objective, measured in a consistent unit of value (USD). The use of a single objective cost minimization paradigm is utilized to keep the model objective transparent and to eliminate the subjective influence that may be introduced through the use of direct weighing factors. Since all costs have been normalized using the common unit of value, weighing or scaling is unnecessary at this point. Trade-offs and the impact of uncertainties will be explored using the discrete event simulation mode.

Table 1. Index sets and modeling assumptions for the mixed-integer linear programming (MILP) formulation

Element	Description
$i \in I$	Production region index
$j \in J$	Collection or processing facility index
$k \in K$	Market or distribution hub index
X_{ij}	Quantity transported from region $i$to facility j
V_{ik}	Quantity transported from facility $i$to market k
Y_j	Binary variable indicating whether facility j is opened
Cost structure	Linear in flow volumes
Demand representation	Deterministic (D^k)
Capacity limits	Fixed (CAP_j)
Objective	Minimize total cost Z
Cost normalization	Unified monetary units (USD)
Uncertainty handling	Addressed via simulation

2.3.2 Harvest and processing scheduling model

To this end, they developed a constraint programming model to optimize harvesting schedules and processing operations. The model considers ripening patterns, labor availability, processing capacity, and perishability constraints.

To optimize harvesting and processing operations under perishability and resource constraints, a constraint programming model is formulated to determine feasible and efficient schedules. All symbols used in this subsection are consistent with the Nomenclature.

Decision Variables

- S_a: start time of activity a (harvesting, sorting, processing, packaging).
- $A_{a,r} \in \{0,1\}$: binary variable indicating assignment of activity a to resource r (labor team or machine).
- L_t: number of labor units allocated at the time slot t.

Constraints

- Precedence Constraints

Processing activities must follow harvesting and handling operations:

$$S_{a'} \geq S_a + p_a \forall (a \prec a') \tag{6}$$

where, p_a is the processing duration of the activity a.

- Capacity Constraints

Resource usage at any time cannot exceed available capacity:

$$\sum_a A_{a,r}(t) \leq CAP_r \forall r, t \tag{7}$$

- Labor Availability Constraints

$$L_t \leq L^{\max} \forall t \tag{8}$$

- Perishability Constraints

The elapsed time between harvesting and processing is limited to preserve quality:

$$S_{\text{proc}} - S_{\text{harv}} \leq T^{\max} \tag{9}$$

Objective Function

The scheduling objective is to minimize system delay and quality loss, expressed as the minimization of total waiting time between harvesting and processing:

$$\min \sum_{a \in A} (S_{\text{proc},a} - S_{\text{harv},a}) \tag{10}$$

Alternatively, tardiness relative to preferred processing windows can be minimized when applicable.

This formulation enables the coordination of harvesting and processing schedules while explicitly accounting for perishability, labor limitations, and equipment capacity. The resulting schedules are subsequently evaluated under uncertainty using the discrete-event simulation model.

2.3.3 Simulation of inventories and transportation

AnyLogic simulation software was used to create a discrete-event simulation model and to analyze the dynamic behavior of the system under uncertainty. The model incorporates the following components:

- Stochastic components for yield variability, processing times, and demand uncertainties
- Temperature-dependent quality degradation functions
- Transportation network disruption scenarios and capacity constraints
- Weather influencing production and demand

Stochastic labor-related variations and security-induced transportation disruptions are intentionally excluded from the MILP formulation, which addresses deterministic strategic decisions, and are instead incorporated into the discrete-event simulation model. Such an intentional split allows for the modeling of realistic probabilistic events while still having an optimization framework with good solution characteristics.

2.4 Integration of data to model and treatment of variability

The qualitative and quantitative data collected in this study were incorporated into the optimization and simulation models in a way that synchronized the results of the observations with the formulation of the models. Data obtained from the structured interviews were used in determining the cost factors in the MILP model. particularly with respect to transportation costs, facility operation costs, capacity utilization rates, labor availability, and administrative lead times.

The time studies were used to represent the processing time behavior in the scheduling and simulation models. The empirical processing times for the critical operations were used to estimate the mean and variability parameters, which were then translated into probability distributions for the discrete-event simulation model. The distributions were chosen based on the results of the goodness-of-fit tests, and the parameters were estimated using the sample mean and standard deviation.

To incorporate the uncertainties and variabilities of the performance of the system, simulation experiments were carried out through a series of replications. The key performance measures, such as waiting times, utilization ratios, post-harvest levels of loss, and the performance of the inventory, were presented through 95% confidence intervals. In some cases, the results are presented as the average value ± standard deviation to demonstrate the model's sensitivity to the stochastic variability.

2.5 Model validation and scenario analysis

The developed models were validated using historical data from 2020 to 2023, as well as through expert evaluation conducted with industry partners. The following five scenario analyses were carried out:

- Baseline (current system configuration)
- Optimization of collection center locations
- Establishment of a cohesive cold chain
- Enhanced organizational coordination and information sharing
- Comprehensive intervention strategy

3. RESULTS

3.1 Supply chain mapping and bottleneck analysis

The paper highlights a detailed analysis of the Iraqi dates' chain of operations from the production process until the date of their final delivery in the exported markets and has identified the six major bottlenecks in the chain as the sources of inefficiency in the operations of the chain. The sources of inefficiency are described in Table 2.

Table 2. Supply chain bottleneck analysis in Iraqi date production

Bottleneck Category	Key Indicators	Current Status	Impact on Supply Chain Performance
Collection System Fragmentation	Number of intermediaries per region	4–7 intermediaries	22% cost increase in first-mile logistics
	Average batch size at collection	250–450 kg	Quality inconsistency, 15% rejection rate
Processing Capacity Distribution	Regional capacity allocation	67% Baghdad, 18% Basra, 15% other	35% underutilization in non-peak seasons
	Peak season capacity utilization	127% (theoretical)	Processing delays of 3–5 days
Cold Chain Coverage	Temperature-controlled volume	23% of total volume	Post-harvest losses of 25–40%
	Cold storage capacity	15,200 tons	Covers only 18% of premium varieties
Information Flow	Price information variance	35% between regions	Suboptimal selling decisions, 18% revenue loss
	Access to market information	32% of farmers	Limited bargaining power for producers
Transportation Infrastructure	Average farm-to-facility time	8.5 hours	Quality degradation begins before processing
	Road quality assessment	58% adequate	30% increase in transportation damage
Export Documentation	Required approvals/certificates	12 distinct documents	15–30 days processing delays
	Documentation cost	$1,250–1,850 per shipment	Reduced competitiveness in export markets

One of the key issues is the fragmentation of the logistics system, resulting in a series of middlemen between the farmers and the source areas (on average, 4–7 middlemen for each source area). Such a situation has contributed to the increase in the first-mile logistics costs of 22% over the optimal network and has also caused quality variability, with the rejection rate averaging 15%. Moreover, the quantity collected per point is small, ranging between 250 and 450 kg.

The distribution of processing capacities is uneven in the country, with an estimated 67% of the capacity found in the Baghdad area. This causes suboptimal use in the off-peak periods (estimated to be 35%) and severe congestion in the harvesting periods, which require theoretical utilization factors of 127%. This, in turn, causes delays with the processing lines, which amount to 3–5 days and greatly influence the products' qualities.

Another major risk is presented by the limitations of the cold chain. This is because only 23% of the total production volume is handled under cold chain distribution. This has resulted in a substantial level of post-harvest losses of between 25% and 40%. The cold storage capacity of the current infrastructure supports only 18% of elite date varieties.

Inefficient information flow is an additional factor worsening the performance of the supply chain. The variance of price information is on average 35% per region, which results in below-optimal sales and an estimated 18% loss of producer revenues. Only 32% of the farmers enjoy good market information.

Another critical factor is the constraint posed by the available means of transport infrastructure. This is evident in that the average farm-to-facility transport time is estimated to be 8.5 hours, which is unacceptably high for the retention of quality, especially in the high-quality varieties. The road condition assessments reveal that not more than 58% of the roads are of acceptable quality, leading to a 30% increase in transport-related losses.

Requirements for export documentation also form a bottleneck. Each shipment requires 12 different documents and approvals, leading to processing delays of 15–30 days. The cost involved, ranging from USD 1,250 to 1,850 per shipment, significantly reduces export competitiveness. In addition, the mapping activity highlights the vulnerability of the supply chain with respect to labor availability and security-related disruptions. Labor availability is a concern with respect to harvesting and processing, while transportation routes are threatened by episodic incidents of insecurity and administrative closure.

3.2 Network optimization results

As a result, our network optimization model resulted in significant changes in supply chain configuration and performance metrics (see Tables 3 and 4). The optimization analysis determined that the network could be optimized from the current 28 collection centers and 8 processing facilities to 12 strategically located collection centers and 5 optimally located processing facilities with no adverse impact on service levels or capacity.

This network rationalization results in substantial efficiency gains (Table 3), including a 42% reduction in average transportation distance (from 187 km to 108 km) and a corresponding 28% reduction in transportation costs (from 48.5 to 34.9 USD per ton). As illustrated in Figure 1, the optimized network configuration reduced the average transportation distance by approximately 42%, indicating a substantial improvement in logistics efficiency.

The more efficient facility distribution enables a 35% improvement in average facility utilization rates, increasing from 58% to 93%. Perhaps most critically for product quality, the farm-to-processing time was reduced by 51%, from 8.5 to 4.2 hours, which substantially improves the ability to preserve inherent product quality. As illustrated in Figure 2, the significant reduction in transportation costs achieved through network optimization, with costs decreasing from 48.5 to 34.9 USD per ton.

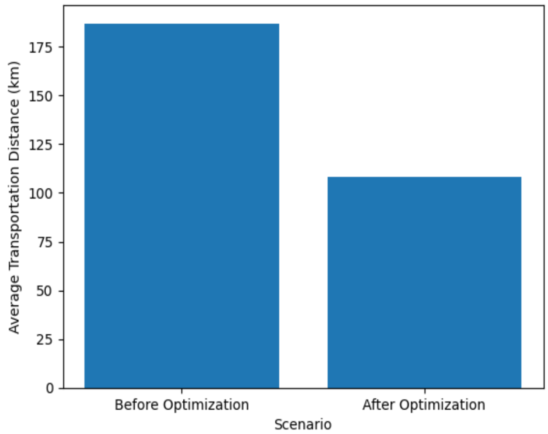

Figure 1. Transportation distance reduction after network optimization

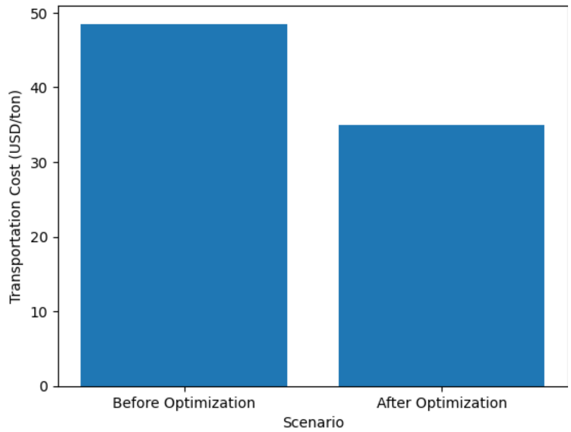

Figure 2. Transportation cost reduction following supply chain network optimization

Table 3. Network optimization model results summary

Parameter	Current Network	Optimized Network	Improvement (%)
Number of collection centers	28	12	57% reduction
Number of processing facilities	8	5	38% reduction
Average transportation distance (km)	187	108	42% reduction
Transportation cost (USD/ton)	48.5	34.9	28% reduction
Average facility utilization (%)	58	93	35% improvement
Farm to processing time (hours)	8.5	4.2	51% reduction

Table 4. Optimal facility location and capacity allocation

Region	Collection Centers	Annual Capacity (tons)	Processing Facilities	Processing Capacity (tons)
Baghdad	4	48,000	2	85,000
Basra	3	35,000	1	60,000
Karbala	3	32,000	1	45,000
Diyala	1	22,000	1	40,000
Babil	1	18,000	0	0
Total	12	155,000	5	230,000

Table 5. Sensitivity analysis results for the network optimization model

Parameter Variation	Impact on Transportation Cost	Impact on Facility Utilization	Impact on Overall Cost Savings
Fuel price +15%	+8.3%	No significant change	24.5% (vs. baseline 28%)
Fuel price -15%	-7.6%	No significant change	31.2% (vs. baseline 28%)
Demand +20%	+4.2%	+12.8%	25.7% (vs. baseline 28%)
Demand -20%	-5.7%	-10.5%	24.3% (vs. baseline 28%)
Combined worst-case scenario	+12.5%	-10.5%	19.8% (vs. baseline 28%)

Table 6. Harvest and processing scheduling optimization results

Performance Metric	Before Optimization	After Optimization	Improvement
Average wait time between harvest and processing (hours)	31.5	24.6	22%
Processing equipment utilization (%)	65.3	77.1	18%
Labor costs (USD/ton processed)	42.5	36.1	15%
Peak season throughput (tons/day)	780	985	26%
Average processing cycle time (hours)	28.5	22.3	22%

Table 7. Optimized harvest schedule by variety and region

Variety	Region	Harvest Window (Current)	Optimized Harvest Window	Processing Priority	Quality Impact
Zahdi	Baghdad	Sept. 10–Oct. 5	Sept. 15–Oct. 1	High	+12% grade A yield
Khadrawi	Baghdad	Aug. 25–Sept. 20	Aug. 28–Sept. 15	Medium	+8% grade A yield
Barhi	Basra	Aug. 5–Aug. 30	Aug. 10–Aug. 25	Highest	+15% grade A yield
Halawi	Karbala	Sept. 5–Oct. 1	Sept. 10–Sept. 25	Medium	+10% grade A yield
Maktoom	Diyala	Sept. 15–Oct. 10	Sept. 20–Oct. 5	Low	+7% grade A yield

Table 4 presents the proposed facilities and their optimal geographical distribution and capacity allocation. A total of 2 processing facilities, with 85,000 tons of processing capacity, will support 4 collection centers in the Baghdad region, with an annual capacity of 48,000 tons. 3 collection centers would be located in Basra and Karbala, and 1 in each of Diyala and Babil, with processing facilities in all regions except for Babil. This distribution organizes transportation efficiency and capacity utilization per client, as well as cleaning each production area adequately.

The sensitivity analysis shown in Table 5 further confirms that the network optimization model is robust to different scenarios. Even adjusting for a 15% fuel price increase, we still achieve cost savings of 24.5% versus a baseline of 28%. In a similar vein, demand fluctuations of ±20% have an overall cost savings impact of less than 4 percentage points. Even the combined worst-case scenario (higher fuel prices and lower demand) ensures a cost cut of 19.8%, assuring model resilience against potential market and cost changes.

3.3 Schedule optimization for harvesting and processing

The optimization of harvest and processing scheduling showed meaningful operational improvement, as shown in Tables 5-7. As indicated in Table 6, this optimization reduced the average wait time between harvesting and processing by 22% (from 31.5 to 24.6 hours), which is crucial for preserving product quality. Processing equipment utilization increased by 18% (from 65.3% to 77.1%), while labor treatment costs decreased by 15% (from $42.5 to $36.1 per ton processed). In addition, peak-season throughput increased by 26% (from 780 to 985 tons per day) without requiring additional capital investment, reflecting improved scheduling and resource allocation.

The optimized harvest scheduling by variety across the regions is presented in Table 7. Focusing on small windows of harvest for specific varieties in each of those regions had a profound effect on the quality improvements. For instance, in Basra, focusing the Barhi variety harvest on August 10–25 (compared with the current August 5–30 window) increased Grade A yield by 15%. Similar improvements were observed across other major varieties, where optimized harvest windows, typically 5–10 days shorter than current practice, resulted in 7–15% more Grade A output.

An analysis of the critical path of processing operations (Table 8) highlighted critical bottlenecks requiring intervention. The most significant bottleneck was drying (8.0 hours), followed by receiving and sorting (2.5 hours) and packaging (1.5 hours). The model identified specific interventions for each critical path component. Upstream drying platform upgrades, additional downstream sorting stations, and packaging automation address the largest constraints.

Table 8. Critical path analysis for processing operations

Process Step	Duration (Current)	Critical Path Status	Bottleneck Severity	Recommended Intervention
Receiving and sorting	2.5 hours	Critical	High	Additional sorting stations
Washing	1.0 hours	Non-critical	Low	No immediate action
Hydration	3.5 hours	Critical	Medium	Parallel processing
Drying	8.0 hours	Critical	Highest	Upgraded drying technology
Fumigation	12.0 hours	Critical	Medium	Expanded capacity
Grading	2.0 hours	Non-critical	Low	No immediate action
Packaging	1.5 hours	Critical	High	Automation upgrade

3.4 Simulation results of the inventory and transportation

As demonstrated via Tables 9-11, our simulation modeling of inventory management and transportation systems uncovered significant room for improvement, especially within the cold chain implementation and inventory optimization arenas.

The results of the modeling for various scenarios on the cold chain implementation are presented in Table 9. In the baseline situation, post-harvest losses are high (36.5%), and product quality scores are relatively low (6.2 out of 10). Losses without cold chain solutions stand at 23% with quality scores of 6.5. Partial implementation of cold chain solutions reduces losses to 25.8% and improves quality scores to 7.5, while full implementation achieves dramatic improvements with losses reduced to 14.2% and quality scores elevated to 8.7. Of particular note, the difference in premium variety shelf-life spans from 45 days in the baseline scenario to 112 days (149% improvement) when a cold chain is assumed throughout the food system. Full implementation results in a dramatic increase in the share of export quality output, rising from 35.5% to 67.8%, indicating a very high potential increase in export revenue.

As shown in Figure 3, full cold chain implementation resulted in a dramatic reduction in post-harvest losses, decreasing from 36.5% in the baseline scenario to 14.2%.

As shown in Table 10, inventory optimization resulted in a 28% reduction in average inventory levels (from 12,450 to 8,950 tons) and a 25% decrease in holding costs (from $32.5 to $24.4 per ton per month). Stockout incidents declined from 14 to 3 events per season (a 79% reduction), while inventory turnover improved from 6.5 to 9.2 cycles per year (a 42% increase). These improvements were primarily driven by enhanced demand forecast accuracy, which increased by 23% (from 74% to 91%). In addition, product waste due to overstocking decreased by 75% (from 8.3% to 2.1%).

Figure 4 highlights the efficiency gains in inventory management, where average inventory levels were reduced by approximately 28% following OR implementation.

The Baghdad–Basra highway closure is seen as a medium-risk event (about 15% chance), but the impact is significant if it happens, increasing lead times by approximately 72 hours and transportation costs by 45%. It also exhibits a low resilience score (3.5 out of 10), suggesting the system has limited ability to cope. Border crossing delays show the most likely disruption scenario (35% probability), with a moderate impact on lead time (+48 hours) and cost impact (+25%).

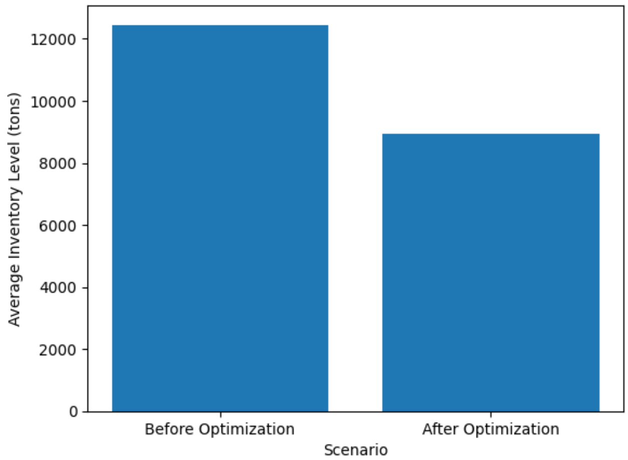

Figure 3. Impact of cold chain implementation on post-harvest losses

Table 9. Simulation results for cold chain implementation scenarios

Performance Indicator	Baseline	Partial Implementation	Full Implementation
Post-harvest losses (%)	36.5	25.8	14.2
Average product quality score (1–10)	6.2	7.5	8.7
Shelf-life for premium varieties (days)	45	75	112
Grade A output percentage	42.3	58.7	71.5
Export-quality percentage	35.5	51.2	67.8
Temperature excursion events (per month)	24.5	10.3	2.1

Table 10. Inventory management optimization results

Inventory Parameter	Current System	With Operations Research (OR) Implementation	Improvement
Average inventory levels (tons)	12,450	8,950	28% reduction
Inventory holding costs (USD/ton/month)	32.5	24.4	25% reduction
Stockout events (per season)	14	3	79% reduction
Inventory turns per year	6.5	9.2	42% increase
Product waste from overstocking (%)	8.3	2.1	75% reduction
Demand forecast accuracy (%)	74	91	23% improvement

Table 11. Transportation disruption scenario analysis

Disruption Scenario	Probability	Impact on Lead Time	Impact on Cost	Mitigation Strategy	Resilience Score (1–10)
Baghdad–Basra highway closure	Medium (15%)	+72 hours	+45%	Alternative routing	3.5
Border crossing delays	High (35%)	+48 hours	+25%	Buffer inventory	5.2
Processing facility downtime	Low (8%)	+120 hours	+60%	Backup facilities	6.8
Seasonal flooding	Medium (20%)	+36 hours	+30%	Early shipment	7.1
Political instability	Medium (25%)	+96 hours	+55%	Distributed storage	4.3

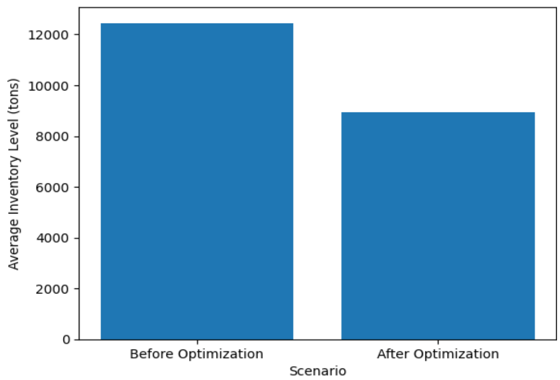

Figure 4. Reduction in average inventory levels after operational research implementation

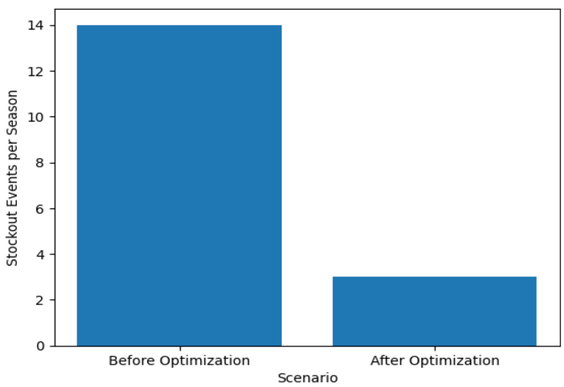

Figure 5. Reduction in stockout events after operational research implementation

As illustrated in Figure 5, the optimized inventory system significantly reduced stockout events from 14 to only 3 occurrences per season.

3.5 Economic impact analysis

The economic impact analysis of the operational research implementation scenarios presents compelling evidence for investment, as detailed in Tables 12-14.

As illustrated in Table 12, even this lowest level of implementation scenario, which only includes network optimization, incurs an $8.2 million expense but generates $22.7 million in annual benefits, yielding a payback period of just 1.3 years. The comprehensive implementation scenario requires the most significant investment ($14.5 million) while producing the most substantial annual benefits ($31.4 million) and a Return on Investment (ROI) period of 2.2 years. The 5-year Net Present Value (NPV) amounts from USD 45.6 million for the basic scenario to USD 62.4 million for comprehensive implementation, while Internal Rates of Return (IRR), from 32.5% to 42.5%, grossly exceed conventional investment return benchmarks.

As shown in Table 13, the largest share (39.2% or $12.3 million per year) of total benefits comes from post-harvest loss reduction, followed by quality premium increases (27.1% or $8.5 million) and operating cost reductions (18.5% or $5.8 million). The effects of both revealed market access and inventory cost improvements, accounting for 10.2% and 5.0% of the total value creation, respectively, emphasize the importance of multidimensional value creation from the deep operational research implementation.

Table 12. Economic impact analysis of operational research implementation scenarios

Implementation Scenario	Initial Investment (USD millions)	Annual Benefits (USD millions)	ROI Period (years)	NPV (5-year, USD millions)	IRR (%)
Network optimization only	8.2	22.7	1.3	45.6	42.5
Cold chain enhancement	12.6	26.8	1.6	51.2	37.8
Information systems	10.5	24.5	1.5	48.7	39.2
Comprehensive implementation	14.5	31.4	2.2	62.4	32.5

Note: ROI = Return on Investment; NPV = Net Present Value; IRR = Internal Rates of Return

Table 13. Benefit breakdown by category (comprehensive implementation)

Benefit Category	Annual Value (USD millions)	Percentage of Total Benefits	Key Drivers
Post-harvest loss reduction	12.3	39.2%	Temperature control, reduced handling damage
Quality premium increase	8.5	27.1%	Grading standards, faster processing
Operating cost reduction	5.8	18.5%	Optimized transportation, labor efficiency
Market access improvement	3.2	10.2%	Documentation streamlining, quality consistency
Inventory cost reduction	1.6	5.0%	Improved forecasting, faster turnover
Total benefits	31.4	100%	

Table 14. Employment and socioeconomic impact

Sector	Direct Jobs Created/Enhanced	Indirect Jobs	Skill Development Impact	Community Welfare Impact
Farming operations	450–650	300–450	Medium	High
Collection and transportation	200–300	150–200	Medium	Medium
Processing and packaging	350–500	250–350	High	Medium-High
Distribution and marketing	200–350	300–400	Medium-High	Medium
Support services	0–0	200–300	Low-Medium	Low
Total impact	1,200–1,800	1,200–1,700	Medium-High	Medium-High

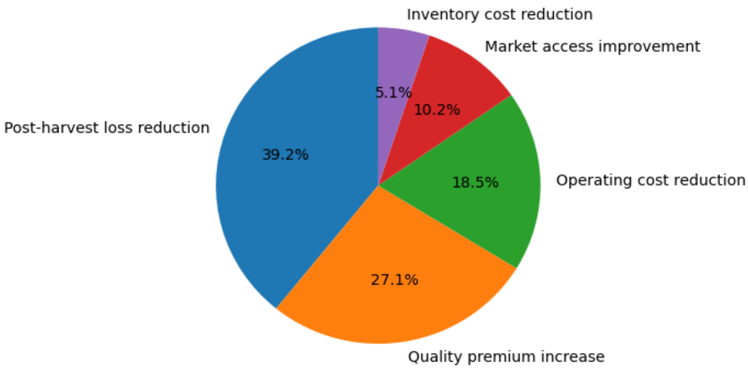

Figure 6. Annual benefit breakdown of comprehensive operations research (OR) implementation

Figure 6 presents the distribution of annual economic benefits, showing that post-harvest loss reduction represents the largest contribution, accounting for nearly 40% of total benefits.

Table 14 provides employment and socioeconomic impacts, with 1,200–1,800 direct jobs created across various sectors, with the most concentrated in feature farming operations (450–650 jobs) and processing/packaging (350–500 jobs). The project is expected to create 1,200–1,700 indirect jobs. The impact of skill development across sectors varies from medium to high, where the highest impact sector in this regard is processing and packaging operations. Assessments of effects on community welfare show medium to high generality, especially for farming operations with income stabilization and quality improvements representing highly relevant socioeconomic effects.

4. DISCUSSION

4.1 Integrated analysis of supply chain optimization opportunities

All operational research models produced similar results showing that there was a great potential for improvement to the overall date supply chain in Iraq. The insights from network optimization show that the current infrastructure is both underoptimized (too many dispersed collection points) and unbalanced (processing capacity not matching production zones). This is consistent with the bottleneck analysis that identified fragmented collection systems and processing capacity imbalance as the critical constraints.

Adding the scheduling optimisation results to the mix gives an even clearer picture of how these structural inefficiencies flow through the system. The unnecessary wait between the point of harvest and the point of processing (currently 31.5 hours) directly results from the poor configuration and allocation of network capacity. This geographical misalignment of facilities, combined with the processing bottlenecks highlighted in the critical path analysis (particularly in drying, receiving/sorting and packaging), causes inefficiencies throughout the post-harvest processing chain.

Such findings from simulation about the implementation of cold chain add to these by showing that structural and operational improvements could be enhanced as targeted technology investments. The reduction in post-harvest losses from 36.5% to 14.2% is transformative, especially when combined with a 51% decline in farm-to-processing time achieved through network optimization.

The results of inventory optimization further show how better forecasting and scheduling can simultaneously reduce inventory levels as well as stockout risk. Indeed, an 28% reduction in inventory levels and 79% reduction in stockout events yield a remarkable increase in working capital efficiency and service levels.

The economic analysis demonstrates the real-world impact of these improvements and shows that even when only implementing a single operational research component (i.e., network optimization) the financial gain far outweighs investments. The holistic strategy, with a higher investment cost upfront, is realized with increasingly significant returns across multiple socio-economic indicators.

4.2 Implementation challenges and practical considerations

Although the optimization models show significant potential benefits, there are several implementation challenges that need to be addressed. The network would need to be optimized through a hands-on process that would entail the complicated repurposing of existing assets, potentially including the closure of facilities and new construction. This creates logistical issues around investing sufficiently, planning for the transition, and managing stakeholders, in particular for facilities identified for consolidation.

The harvest scheduling optimization, though theoretically sound, would need coordinated deployment across many independent farmers. This fragmented production model, where hundreds of thousands of small-scale producers operate, creates coordination problems that cannot be solved by mathematical optimization alone. The arguments for creating much more tightly controlled harvesting timelines will rely on more robust agricultural extension services or farmer education, and likely incentive structures for compliance.

Cold chain adoption has both financial and technical hurdles. While the simulation indicates benefits are evident, the barrier of finding a 12.6-million-dollar investment should pose a significant barrier (Table 11). Some phased implementation approach, incentivising the adoption of premium varieties through dedicated export channels may represent more achievable path to transition, progressively expanding as investment capital allows.

The scenarios of transportation disruption highlighted in the simulation speak to wider infrastructure and security issues that go beyond just the date industry. Addressing the vulnerability of the Baghdad–Basra corridor would likely entail coordination with national transportation planning (and possibly security agencies).

The economic analysis shows strong returns on investment, but costs and benefits accrue to many players in the supply chain, while investments skyrocket with fewer participants. However, the costs and benefits here are misaligned, leading to a coordination problem that could require policy interventions or industry-wide cooperation mechanisms.

4.3 Comparative context and industry transformation potential

This sector presents both substantial challenges and significant opportunities for improvement compared with most other agricultural sectors that have undergone similar OR-based transformations. The baseline post-harvest loss rate of 36.5% is higher than averages seen across many other sectors, but this also indicates a larger potential value to be captured through improvements.

The decrease in transportation distance of 42% using network optimization is an improvement compared to other studies undertaken in different agricultural supply chains, where distance improvements generally fall between 20–35% [19-22]. As noted in this paper, the 28% reduction in inventory levels is far in excess of results typically seen on comparable optimization projects (typically offering 15–25%) reductions.

The socioeconomic impact estimates identify that, in addition to the direct economic benefits, operational research implementation could have a large role in rural development and employment generation. The projects will create 1,200–1,800 direct jobs, with important skills development impact, and will contribute significantly to Iraq's agricultural transformation and economic diversification objectives.

4.4 Trade-offs and limitations

While the proposed integrated framework of optimization and simulation results in significant efficiency and economic gains, the results also indicate important trade-offs and limitations that should be interpreted while deriving the implications of the results.

Optimization solutions work in favor of a more centralized solution that involves fewer collection and processing centers, which in turn greatly decreases the distance of transportation. However, centralization also poses a challenge in terms of a compromise between the goals of optimization and the objective of resilience, specifically in the Iraqi setting. A centralized approach to processing involves a higher level of vulnerability to security-related disturbances, road blockages, and instability in the region, which can lead to a compound effect in the event of a disturbance. Even then, the findings of the simulation study suggest that a compromise can be achieved between centralization and resilience through alternative routes and buffer storage.

The results obtained through simulations demonstrate the potential transformation associated with the implementation of cold chains in terms of minimizing post-harvest losses and extending shelf life. These associated benefits have been accompanied by significant capital outlays. The associated energy demands and power supply constraints can pose significant financial and technical challenges, especially in areas where infrastructure is less stable. Thus, the concept of a selective cold chain approach focused on superior varieties and export channels may be a pragmatic and financially viable approach compared to the implementation of cold chains.

The proposed framework is specifically designed with a focus on the Iraqi date sector's structure and security context. Although a general framework of integrating scheduling, simulation, and MILP is generic and can be applied to a wide variety of domains, specific numerical outcomes and solutions are best avoided from being generalized across agri-food chains and regions because of differences in various factors such as quality of infrastructure, governance, labor markets, and risk factors, which could have a material impact on both variables and outcomes. On the whole, the recognition of such trade-offs and limitations helps to increase the interpretability and relevance of the research to the actual optimization process**.**

4.5 Future research directions

This work highlights several important areas for future research. First, the simulation models could be adapted to include climate change scenarios, which will have a large impact on growing conditions, harvest timing, and transportation reliability in decades to come. The second area of opportunity to improve the network optimization is to apply a finer granularity to customer segmentation and service level differentiation, and it would be interesting to identify “best of breed” supply chains for premium export vs. more commoditized domestic consumption.

Moreover, subsequent studies could investigate the potential for coalescing digital technologies beyond the basic information systems simulated here, such as blockchain for traceability, Internet of Things for real-time monitoring, and Artificial Intelligence for demand forecasting. Technologies that could refine the benefits gained from the operational research models proposed in this paper.

Conversely, comparative analysis with other regional countries producing similar dates may identify valuable cross-national learning opportunities, including both supporting the industrialisation of countries supplying global consumers with desirable varieties and regional cooperation for export promotion

5. CONCLUSIONS

In this study, the applicability of using MILP, constraint-based scheduling, and discrete event simulation is assessed as a means of improving the efficiency and economic viability of the Iraqi dates' supply chain. The results indicate that, with the necessary infrastructure, the application of OR methods is viable for the reduction of transportation distances and costs, the problem of underutilization of facilities, delays in processing, and post-harvest losses.

However, it is important to recognize that the results depend on the modeling framework and data quality. To promote tractability, certain modeling assumptions have been made. These include linearity in cost functions, deterministic values in the optimization problem, and representative values for the distribution functions based on field observations. While uncertainty and disruptions have been modeled explicitly through simulations, it is possible that data quality and institutional variation may have affected the extent to which such benefits have been achieved.

In terms of implementation, the results indicate the achievable benefits for the short and long term. In the short term, the reorganization of the network and the optimization of harvesting and processing schedules would bring about significant benefits of efficiency with moderate investment. In the long term, the benefits of efficiency, which are related to the development of the cold chain, information systems, and structural changes, would require major investment and a steady energy source. While structural changes have the highest potential benefits, they are also more vulnerable in terms of investment and energy risks.

In general, this work provides an analytical tool for decision-making purposes and not a set of prescriptive answers. The benefit of this work is realized in enabling decision-makers to make informed trade-offs between efficiency, resilience, and investment viability during improvement strategy design for the Iraqi date supply chain.

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NOMENCLATURE

C_{ij}	Transportation cost from production region i to facility j
D^k	Demand at market k
F^k	Fixed operating cost of processing facility k
T_i^k	Distribution cost from facility i to market k
X_{ij}	Quantity of dates transported from region i to facility j
V_i^k	Quantity of dates transported from facility i to market k
Y_j	Binary variable indicating whether facility j is opened
Z	Objective function (total supply chain cost)
CAP_j	Capacity of processing facility j
t	Transportation or processing time
L	Post-harvest loss ratio
Q	Product quality score
I	Inventory level
HC	Inventory holding cost

Greek symbols

α	Quality degradation coefficient
β	Demand variability coefficient
λ	Arrival rate of harvested dates
μ	Processing rate
θ	Temperature deviation factor

Subscripts

i	Production region index
j	Collection or processing facility index
k	Market or distribution hub index
max	Maximum value
min	Minimum value
k	Market index
opt	Optimized value
base	Baseline (current system)