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AN ANALYSIS OF OPERATIONAL COLD CHAIN EFFICIENCY IN THE FOOD SUPPLY CHAIN: A CASE STUDY OF THE RIYADH REGION

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ABSTRACT

This study provides an economic and technical assessment of cold and freezing storage warehouses in the Riyadh region, focusing on their role in improving food supply chain efficiency. Data were collected from 60 facilities, with Riyadh City accounting for 88.3% of the sample, reflecting its central role in the sector. Results reveal wide variation in facility characteristics, including room count, storage capacity, and workforce size, with an average storage capacity of 3,078.95 tons. Larger warehouses demonstrated clear economies of scale, reducing unit storage costs. Market orientation is predominantly domestic, with 84.88% of storage serving local demand and only 20.61% allocated to exports, highlighting underutilized export potential. Financial analysis showed an average monthly net profit of SAR (Saudi Riyal) 194,000 (51,733 USD), with variable costs comprising 93.08% of total expenses. Regression results confirmed that the number of rooms, years of experience, and workforce size significantly and positively influence.

Keywords: Cold and freezing storage, Operational efficiency, Storage capacity, Economies of scale, Operational costs.

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1. INTRODUCTION

Food security has become a global strategic priority amid recurring fluctuations in agricultural production, disruptions in food supply chains, climate-related pressures, and volatility in international food markets. These challenges have increased the importance of strengthening domestic food systems, reducing post-harvest losses, and improving the infrastructure required to preserve agricultural products from production through distribution. Cold-chain infrastructure is particularly important for perishable food products because maintaining appropriate storage temperatures helps preserve product quality and safety while reducing deterioration and food losses (Aditjandra et al., 2025). In this context, the operational performance of refrigerated storage facilities is increasingly recognized as an integral component of sustainable and resilient food supply chains.

The importance of cold storage is further reinforced by the rapid expansion of Saudi Arabia’s cold chain warehousing market. Recent market estimates indicate that the sector was valued at approximately USD 2.5 billion in 2025 and is projected to reach USD 6.7 billion by 2034, representing a compound annual growth rate of 11.51%. Frozen storage accounted for approximately 55% of the market in 2025, while private warehouses accounted for around 60%. Moreover, the Northern and Central Region, centred around Riyadh, accounted for approximately 30% of the national market, reflecting Riyadh’s strategic role as a major distribution and logistics hub (IMARC Group, 2025).

In Saudi Arabia, dates hold substantial economic, nutritional, and cultural importance and represent a major agricultural commodity with considerable domestic and export potential. The country ranks among the world’s leading date producers, with annual production exceeding 1.5 million tons from approximately 36 million palm trees (National Centre for Palms and Dates, 2024). Despite this substantial production base, the proportion of production allocated to export markets remains relatively limited, averaging 8.96% between 2000 and 2021 and reaching 20.3% in 2021 (Alamri et al., 2024). Recent Saudi evidence has further emphasized the importance of post-harvest

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management to the economic performance of the date sector. Alhamdan et al. (2024a) identified technological progress in date marketing and storage as an important determinant of date-related food security and recommended expanding modern post-harvest transportation and storage technologies as well as refrigerated warehouse capacity to accommodate growing production and marketable surpluses.

Temperature and humidity control during storage are among the most important factors affecting the preservation of dates, particularly moist varieties that are susceptible to physicochemical and microbial deterioration. Cooling and freezing technologies can extend shelf life, maintain sensory and nutritional characteristics, and facilitate longer storage periods required for domestic distribution and international trade. The importance of shelf-life management is also reflected at the consumer level in Saudi Arabia. AlShaikh et al. (2024) reported that, for dates, 33.3% of surveyed consumers always checked expiry dates and 45.3% did so sometimes, indicating that shelf-life information represents a relevant consideration in consumer handling of date products. Packaging conditions are also relevant because their effectiveness interacts with storage temperature and environmental conditions. Alhamdan et al. (2024a) demonstrated that storage temperature and packaging type significantly influence the moisture, bioactive compounds, phenolic components, and mineral characteristics of Saudi date cultivars during extended storage. These findings reinforce the importance of considering cold-storage performance as an integrated system involving temperature, humidity, packaging, and facility design rather than refrigeration alone.

Recent research has increasingly examined methods for improving date preservation. Alqahtani et al. (2025) reviewed preservation methods at the Khalal stage of date maturity, highlighting conventional cold storage alongside emerging preservation techniques. Experimental studies by Noutfia et al. (2025a, 2025b) demonstrated the effects of prolonged frozen storage and relative humidity on the qualitative characteristics and storage stability of Mejhoul dates, emphasizing the need for precise environmental control. Cherif et al. (2021) similarly highlighted the importance of storage conditions in maintaining Deglet Nour date quality. Complementary approaches involving edible coatings have also been investigated; Ghafoor et al. (2022) examined chitosan-based coatings for refrigerated Barhi dates, while Mohammed et al. (2024) evaluated optimized gum Arabic-based coatings for preserving Hilali dates during cold storage. Collectively, these studies demonstrate considerable progress in understanding product-level preservation, although they provide less evidence on the operational and economic performance of the storage facilities in which such preservation takes place.

Beyond product quality, the design and operation of cold-storage facilities have substantial implications for energy use and economic efficiency. Karacan et al. (2023), based on data from 67 cold-storage facilities, examined relationships between energy consumption and facility characteristics such as storage capacity and volume and found that operating conditions could increase energy consumption by up to 30%. Their findings underline the importance of considering facility scale, operating practices, and refrigeration-system performance when evaluating storage efficiency. Similarly, Park et al. (2023) and Niu et al. (2024) demonstrated the potential of optimized control strategies and advanced control approaches to reduce energy consumption in cold-storage operations. Appropriate facility design is also important; Kshirsagar et al. (2025) emphasized the role of thermal insulation, temperature regulation, ventilation, and energy-efficient design in improving the sustainability of cold-storage infrastructure. More recently, Zanoni et al. (2026) showed that energy consumption in refrigerated warehouses is closely linked to warehouse filling levels and storage temperature, highlighting the interaction between capacity utilization, energy efficiency, product quality, and operating costs. Recent studies further demonstrate that refrigerated warehouse efficiency increasingly depends on the integration of energy management, environmental monitoring, intelligent decision-support technologies, and advanced thermal-control strategies. In particular, IoT- and AI-enabled systems provide opportunities for real-time monitoring of temperature and other environmental conditions, early detection of temperature deviations, predictive assessment of operational risks, and improved management of temperature-sensitive food supply chains (Gupta & Jain, 2026; Müller et al., 2026; Taguta et al., 2026). Alongside these digital technologies, recent developments in thermal and operational management offer additional opportunities to improve energy efficiency. Forouzanfar et al. (2026) demonstrated that logistics-aware temperature-setpoint scheduling can coordinate refrigeration demand with warehouse activities, thereby reducing refrigeration energy consumption and peak electrical demand while maintaining appropriate storage conditions. Similarly, Ouaouja et al. (2026) showed that integrating phase-change materials into refrigerated-storage walls can improve product temperature stability and contribute to reductions in electricity costs when combined with demand-response strategies. Collectively, these advances indicate a transition from conventional reactive cold-storage management toward integrated, data-driven, predictive, and energy-efficient systems, with potential benefits for product quality, operational efficiency, resource utilization, and long-term economic performance.

These operational considerations are particularly relevant to Saudi Arabia, where high ambient temperatures place additional demands on refrigerated food logistics. Ali et al. (2023), examining sustainability initiatives in frozen-food warehouses in the Saudi context, highlighted the importance of green operations, energy and resource conservation, and warehouse management practices in improving sustainability performance. Technological

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development also offers opportunities to improve control and monitoring. Alshdadi et al. (2024) designed and implemented an Internet-of-Things-based system for monitoring temperature and humidity during cold-chain storage and transportation under Saudi conditions, demonstrating the feasibility of real-time monitoring using sensors, communication technologies, and cloud-based systems. This complements the broader findings of Wang and Du (2025) and Protopappas et al. (2025), who emphasized the potential of Internet-of-Things-based monitoring to improve cold-chain visibility, energy management, and operational decision-making. In the Saudi context, Khan et al. (2025) highlighted the importance of cold-chain infrastructure for maintaining the quality of agricultural products, including dates, while improving distribution efficiency and export competitiveness. The authors also identified limited evidence on the operational costs and economic effectiveness of cold-chain implementation in Saudi Arabia, indicating a need for more detailed economic assessments of refrigerated storage facilities.

Although the existing literature provides valuable evidence on date preservation, cold-storage technologies, energy management, sustainable warehousing, and digital monitoring, an important empirical gap remains. Much of the date-specific literature focuses on product quality under controlled storage conditions, whereas studies of cold-chain operations often emphasize energy technologies or system-level sustainability. Facility-level evidence linking physical warehouse characteristics, operational capacity, workforce and managerial experience, environmental control, cost structures, revenues, and economies of scale remains comparatively limited, particularly for refrigerated and frozen food warehouses in Saudi Arabia. This distinction matters because improving product preservation alone does not determine whether the underlying storage infrastructure operates efficiently or whether existing capacity is economically suited to production, domestic distribution, and export requirements (Table 1).

Accordingly, this study analyzes the operational and economic efficiency of cooling and freezing storage warehouses in the Riyadh region, a major food storage and distribution hub in Saudi Arabia. Specifically, it examines differences in facility characteristics, including the number of storage rooms, total storage capacity, workforce size, and years of operational experience; evaluates the cost and revenue structure of the facilities; identifies the principal determinants of operational capacity; and assesses whether differences in facility scale are associated with differences in storage cost per ton. By integrating technical, operational, and economic dimensions at the facility level, the study seeks to provide empirical evidence to support more efficient investment in cold-storage infrastructure, strengthen export readiness, and enhance the cold chain's contribution to food security in Saudi Arabia.

Table 1: Summary of recent studies

Author(s) & Year.	Focus Area	Key Findings
Aditjandra et al. (2025)	Sustainable cold-chain infrastructure	Positions refrigerated infrastructure within sustainable logistics planning
Alhamdan et al. (2024a)	Date packaging and storage temperatures	Demonstrates interaction between packaging, temperature, and date quality
Alhamdan et al. (2024b)	Economic impact of date losses in Saudi Arabia	Links storage technology and warehouse capacity with food security
Ali et al. (2023)	Sustainability of frozen-food warehouses in Saudi Arabia	Links warehouse operations, energy/resource conservation, and sustainability performance
Alqahtani et al. (2025)	Review of preservation methods at Khalal stage	Identifies gaps in storage and future trends for quality preservation.
Alshdadi et al. (2024)	Smart cold-chain monitoring in Saudi Arabia	Demonstrates real-time temperature/humidity monitoring under Saudi conditions
Cherif et al. (2021).	Deglet Nour storage conditions	Demonstrates optimal conditions to minimize quality loss.
Ghafoor et al. (2022).	Chitosan coatings on Barhi dates	Coatings improve refrigerated storageperformance.
Karacan et al. (2023)	Energy management in 67 cold stores	Relates energy use to capacity, volume, and operating conditions
Kshirsagar et al. (2025)	Energy-efficient cold-storage design	Highlights insulation, temperature control, and sustainable facility design
Mohammed et al. (2024)	Preservation of dates during cold storage	Examines complementary preservation technologies
Niu et al. (2024).	Control strategies in cold storage	Energy consumption is reduced through optimized controls.
Noutfia et al. (2025a).	Frozen storage of Mejhoul dates	Prolonged frozen storage affects qualitative characteristics.
Noutfia et al. (2025b).	Humidity-controlled storage	Humidity significantly influences functional compounds and image features.
Park et al. (2023)	Advanced control of cold-storage energy use	Demonstrates potential energy savings through intelligent control
Protopappas et al. (2025)	IoT services for food supply chains	Low-cost monitoring enhances cold chain transparency.
Wang & Du (2025).	IoT monitoring for cold chain logistics	Improves efficiency and energy management in storage and transport.

2. MATERIALS AND METHODS

This study employed a cross-sectional design to evaluate the operational and economic performance of cooling and freezing warehouses in the Riyadh region. We collected primary data through structured field surveys, semi-structured interviews, and direct facility observations. We pre-tested the survey instrument to ensure clarity and reliability. We distributed 102 questionnaires; after screening for completeness, we included 60 valid responses in the analysis. We obtained informed consent from all participants, and responses were anonymized to protect confidentiality. The King Saud University Research Ethics Committee reviewed and approved the study protocol in accordance with the Declaration of Helsinki (1964, amended 2008). The dataset comprised facility-level characteristics, including:

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- Structural variables: number of storage rooms, storage capacity (metric tons), and building characteristics.
- Operational variables: workforce size, years of experience, type of products stored, and presence of environmental control systems (temperature and humidity).
- Economic variables: fixed costs (building, refrigeration, ventilation, and insurance), variable costs (labour, energy, packaging, water, fuel, lubricants, sterilization, and maintenance), monthly revenues, and net returns.

Technical specifications of storage facilities were also assessed, including insulation materials, temperature ranges, and availability of chilled and frozen storage rooms. As reported in recent cold chain research (Alqahtani et al., 2025; Alqahtani & Fikry, 2026; Noutfia et al., 2025a, 2025b), such variables are crucial determinants of both product quality and economic sustainability.

Descriptive statistics (mean, standard deviation and coefficient of variation) were calculated to summarize facility characteristics. Multiple linear regression was applied using the Ordinary Least Squares (OLS) method to examine the effect of structural and operational factors on storage capacity (dependent variable). The explanatory variables included number of rooms (X_1), years of experience (X_2), workforce size (X_3), and dummy variables for temperature (d_1) and humidity control (d_2). Model fit was assessed through R^2, F-tests, and variance inflation factors to check multicollinearity. Similar approaches have been adopted in food supply chain efficiency studies (Park et al., 2023; Niu et al., 2024). The regression equation was:

$$Y = C + b_1X_1 + b_2X_2 + b_3X_3 + b_4d_1 + b_5d_2 + \varepsilon \quad (1)$$

Additionally, one-way analysis of variance (ANOVA) was used to compare the average storage cost per ton across four facility-size categories: <10 rooms, 10–19 rooms, 20–29 rooms, and ≥30 rooms. The choice of categories followed the observed distribution in the data and aligns with earlier postharvest efficiency research (Cherif et al., 2021). Normality of residuals was tested using the Kolmogorov–Smirnov test (Conover, 1999) and the Shapiro–Wilk test (Mendes & Pala, 2003), while homogeneity of variance was confirmed using Levene's test (Derrick et al., 2018).

An economic evaluation was conducted to analyze the cost–return structure of the warehouses. Annual fixed and variable costs were compared with monthly revenues to derive net profitability. Sensitivity analysis was applied to simulate the effect of changes in energy costs and labour expenditures, following approaches used in recent cold chain energy optimization studies (Niu et al., 2024; Wang & Du, 2025). This combination of statistical and economic tools captured both the technical and financial dimensions of efficiency.

Field surveys also recorded technical specifications of refrigeration and freezing rooms, including insulation materials (polystyrene, rockwool, polyurethane), average thickness, temperature ranges, and room dimensions. All surveyed facilities operated both chilled (0–15°C) and frozen storage (−18 to 0°C) but lacked flash-cooling systems, a limitation consistent with findings from previous work on date storage (Mohammed et al., 2024; Noutfia et al., 2025b). These technical observations provide practical insight into the current limitations of storage infrastructure in the Riyadh region.

3. RESULTS & DISCUSSION

3.1. Descriptive Analysis of the Study Sample in the Riyadh Region

A total of 102 questionnaires were distributed to cooling and freezing storage facilities in the Riyadh region through direct interviews (n = 63) and electronic surveys (n = 39). Of these, 64 were returned, but four were excluded due to incomplete or inconsistent data, leaving 60 valid responses.

The geographical distribution of the facilities shows a strong concentration in Riyadh City (88.3%), followed by Al-Kharj (5.0%), Al-Dilam (3.3%), and Al-Muzahmiyya and Al-Sulayil (1.7% each). This concentration reflects the demographic and economic centrality of the capital, where population density and demand for food storage are highest. Al-Husseini (2000) reported similar findings, emphasizing the direct relationship between population clusters and the density of food-related services.

The economic and operational characteristics of the facilities (Table 2) highlight significant diversity. The average operational experience was 17.6 years (range: 1–40 years, C.V. 51.93%), reflecting the coexistence of newly established warehouses alongside long-standing ones. Storage capacity averaged 3,078.95 tons, ranging from 331 to 16,500 tons (C.V. 86.26%), showing significant structural differences across facilities. The number of rooms averaged 13.95 (C.V. 63.34%), and workforce size averaged 8.57 workers (C.V. 40.91%), confirming variation in operational scales. Such heterogeneity is economically relevant because facility size and storage capacity can influence energy requirements and operational performance. Karacan et al. (2023), based on data from 67 cold-storage facilities, demonstrated that storage capacity, facility volume, and operating conditions are closely associated with energy consumption, highlighting the importance of facility scale in evaluating cold-storage efficiency.

Most warehouses serve domestic markets (mean 84.88%), while exports accounted for only 20.61%. No facilities reported sales to manufacturing plants, indicating underutilization of processing opportunities. This result aligns with Ismaiel et al. (2016), who highlighted weak integration between storage and value-added processing in Saudi agribusiness.

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Table 2: Economic variables of cooling and freezing facilities

Variable	Minimum	Maximum	Mean	Std. Dev	C.V.
Years of Experience	1	40	17.58	9.13	51.93
Workforce Size	2	16	8.57	3.505	40.91
Total Capacity (in tons)	331	16,500	3,078.95	2,655.91	86.26
Number of Rooms	3	56	13.95	8.836	63.34
Purpose of Storage					
- Local Market Sales (%)	50	100	84.88	13.35	15.73
- Export (%)	10	50	20.61	11.34	55
- Sales to Factories for Manufacturing (%)	0	0	0	0	0

C.V.= Represents the coefficient of variation.

3.2. Operational Costs, Revenue and Net Profit of Cooling and Freezing Warehouses in the Riyadh Region

The economic performance of the warehouses is summarized in Table 3. Average monthly operational costs were SAR 64.49k (USD 17,197), with variable costs accounting for 93.08% (SAR 60.03k; USD 16,009) and fixed costs only 6.92% (SAR 4.46k; USD 1,189). The predominance of variable costs reflects the flexible nature of operational expenses that scale with service demand, consistent with findings by Jedermann et al. (2014), who stressed the importance of improving operational logistics to reduce waste and cost inefficiencies. This cost structure also reinforces the importance of energy and resource management in cold-storage operations. Karacan et al. (2023) showed that cold-store energy consumption is strongly influenced by facility characteristics and operating conditions, while Ali et al. (2023) emphasized energy and resource conservation as important components of sustainable warehouse performance. Average monthly revenues reached SAR 258.50k (USD 68,933), while net profits averaged SAR 194.00k (USD 51,733), demonstrating strong profitability and confirming the attractiveness of investment in this sector. On a per-room basis, costs averaged SAR 4,606.10 (USD 1,228) per month, while revenues averaged SAR 18,460 (USD 4,922), yielding a net return of SAR 13,860 (USD 3,696). This high margin underscores the sector's economic viability. It aligns with Alhamdan et al. (2018), who found that investing in advanced storage methods (e.g., freezing) is financially rewarding due to quality preservation and extended shelf life.

Table 3: Economic performance of refrigeration and freezing facilities in the Riyadh region (USD)

Item	Min	Max	Avg	Std. Dev.	%	Per Room
Fixed Costs						
– Building Cost	106,667	5,333,333	1,627,200	1,487,325	93.11	–
– Refrigeration Equipment	40,000	266,667	87,623	45,139	5.01	–
– Ventilation Equipment	6,667	66,667	26,293	15,185	1.50	–
– Insurance	2,667	13,333	6,485	2,365	0.37	–
Total Fixed Costs	156,000	5,680,000	1,747,600	310,002	100.0	–
Variable Costs						
– Labor Costs	30,400	290,667	104,213	46,110	60.89	–
– Electricity Consumption	6,400	80,000	39,627	16,274	23.15	–
– Storage Boxes	3,200	16,000	8,608	3,490	5.03	–
– Water Consumption	1,600	16,000	6,592	2,901	3.78	–
– Fuel Consumption	2,240	9,600	4,853	1,925	2.84	–
– Oils and Grease	640	9,600	3,635	2,189	2.12	–
– Sterilization Costs	640	6,400	3,099	1,344	1.81	–
– Maintenance Costs	2,400	18,667	7,787	3,515	0.38	–
Total Variable Costs	47,520	447,467	178,414	116,406	100.0	–
Monthly Financials						
– Total Costs	–	–	17,197	–	100.0	1,228
– Total Revenue	–	–	68,933	–	N.A.	4,922
– Net Return	–	–	51,733	–	N.A.	3,696

N.A.= Not available.

3.3. Factors Affecting the Operational Capacity of Cooling and Freezing Warehouses

To identify the determinants of operational performance, a multiple linear regression model was estimated with operational capacity (measured in tons during the storage season) as the dependent variable. The explanatory variables included the number of rooms (X_1), years of experience (X_2), workforce size (X_3), and two control dummies representing temperature control (d_1) and humidity control (d_2).

The model results (Table 4) show that it is statistically significant at the 1% level ($F = 16.31$, $p < 0.01$), with an adjusted R^2 of 0.565. This indicates that the explanatory variables together account for approximately 56% of the observed variation in warehouse capacity. The number of rooms, years of operational experience, and workforce size all had positive and statistically significant effects, contributing 160.45, 58.34, and 158.52 tons, respectively, for each additional unit. These findings highlight the role of infrastructure, institutional learning, and human resources in enhancing cold chain efficiency. Similar observations were made by Jedermann et al. (2014), who emphasized that scaling infrastructure and improving labour coordination are critical for reducing food losses. The significant positive

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effect of the number of rooms is also consistent with the broader evidence that facility scale and storage capacity are important determinants of cold-storage operational characteristics (Karacan et al., 2023).

Table 4: Regression results for factors affecting operational capacity of refrigeration and freezing facilities

Variable	Coefficient	Std. Error	t-Statistic	p-Value	VIF
Constant	-1,561.95	2,148.12	-0.73	0.47	–
Number of Rooms (X_1)	160.45	33.04	4.86	0.00	1.64
Years of Experience (X_2)	58.34	26.87	2.17	0.03	1.29
Workforce Size (X_3)	158.52	76.14	2.08	0.04	1.37
Temperature Control (d_1)	101.10	1,936.88	0.05	0.96	3.48
Humidity Control (d_2)	-301.74	2,333.89	-0.13	0.90	3.43

Source: Field study sample data. Model fit statistics: $R^2 = 0.602$; Adjusted $R^2 = 0.565$; F-statistic = 16.31 ($p < 0.01$); Durbin–Watson = 2.03; AIC = 17.87.

In contrast, environmental control variables were not statistically significant. Temperature control (d_1) showed a positive but weak effect (+101.1 tons), while the absence of humidity control (d_2) reduced capacity by 301.74 tons. These coefficients should therefore not be interpreted as evidence of statistically established effects on operational capacity. Nevertheless, temperature and humidity remain technically important for maintaining storage conditions and product quality. This is consistent with Alhamdan et al. (2018), who found that inadequate temperature and humidity regulation accelerates quality loss in stored dates, thereby indirectly limiting adequate storage capacity (Fig. 1). More recent evidence supports this technical importance: Alhamdan et al. (2024a) demonstrated that storage temperature and packaging conditions influence quality attributes of Saudi date cultivars during prolonged storage, while Alshdadi et al. (2024) demonstrated the feasibility of real-time temperature and humidity monitoring in Saudi cold-chain storage and transportation using Internet-of-things technologies.

Importantly, all Variance Inflation Factor (VIF) values were below the threshold of 10, confirming that multicollinearity was not an issue and that the estimated coefficients are robust. The Durbin–Watson statistic (2.03) further suggests no serial correlation in the residuals, enhancing the reliability of the model.

3.4. Analysis of Variance for Storage Cost per Ton Based on Differences in Storage Capacities

The one-way ANOVA test was applied to examine whether storage costs per ton vary significantly across warehouse capacity categories. Results (Table 5) indicate statistically significant differences ($F = 3.665$, $p = 0.018$), confirming that storage capacity is a key determinant of cost efficiency.

Table 5: Analysis of variance tests for comparing the average storage cost per ton between categories

Test/Indicator	Category 1	Category 2	Category 3	Category 4	Significance Result
Normality Test (K–S)	0.184 (p=0.089)	0.237 (p=0.060)	0.286 (p=0.137)	0.271 (p=0.192)	Acceptable
Normality Test (S–W)	0.340 (p=0.065)	0.851 (p=0.041)	0.840 (p=0.130)	0.856 (p=0.177)	Acceptable
Homogeneity (Levene)	–	–	–	–	1.516 (p=0.220)
ANOVA	–	–	–	–	F=3.665 (p=0.018)
LSD Pairwise Differences	Cat1–Cat2 = 10.90 (ns)	Cat1–Cat3 = 18.43 (sig)	Cat1–Cat4 = 27.10 (sig)	Cat2–Cat3 = 7.53 (ns)	Cat2–Cat4 = 16.20 (sig)

Source: Field study sample data. Note: ns = Not significant, sig = Significant at 5% level.

Pairwise comparisons using the LSD test show that warehouses with ≥30 rooms (category 4) achieved significantly lower unit storage costs than those in smaller categories, with reductions of SAR 27.10 thousand, 16.20 thousand, and 8.68 thousand relative to categories 1, 2, and 3, respectively. Significant differences were observed between category 4 and categories 1 and 2, but not with category 3. This suggests that once a certain threshold of storage capacity is reached, cost advantages stabilize and additional rooms alone may not further reduce per-unit costs.

All assumptions of ANOVA were satisfied. Normality tests (Kolmogorov–Smirnov and Shapiro–Wilk) confirmed that the data followed acceptable distributions, while Levene's test ($p = 0.220$) indicated homogeneity of variances. This strengthens the robustness of the statistical inference.

These findings highlight the presence of economies of scale, where larger facilities are able to spread fixed costs over greater output volumes, thereby lowering per-unit storage costs. Similar evidence has been reported in cold chain logistics research, where scale efficiencies were identified as a significant factor driving cost reduction and competitiveness (Jedermann et al., 2014). Moreover, the results align with Abou Ayana et al. (2016), who stressed that improving post-harvest infrastructure and scaling facilities are essential for reducing waste and enhancing the profitability of perishable commodities such as dates. The observed scale effect is also compatible with Karacan et al. (2023), who demonstrated that cold-storage capacity and facility volume are closely associated with energy requirements and operating performance, suggesting that facility scale should be considered jointly with energy management when evaluating storage efficiency.

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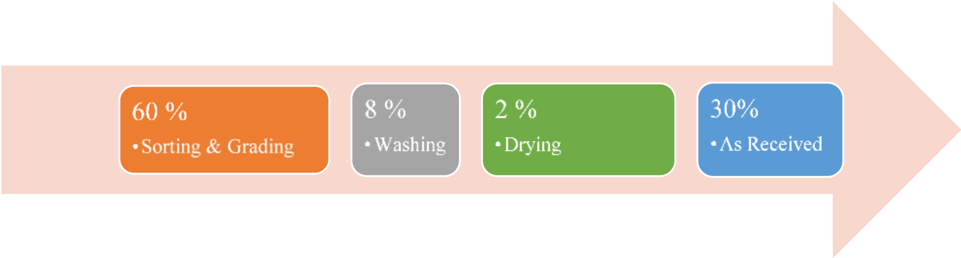

Fig. 1: Processes before storing in the cold storage.

Proper pre-storage handling is fundamental to reducing post-harvest losses and maintaining product quality. As illustrated in Fig. 2, most facilities emphasized sorting and grading (60%), while fewer applied washing (8%) or draying (2%), and 30% stored products directly "as received" without pre-treatment. This limited use of preventive handling steps may expose products, particularly dates, and other perishables, to accelerated spoilage, echoing Abou Ayana et al. (2016), who highlighted the importance of temperature and humidity control combined with cleaning and grading to preserve quality.

Fig. 2: Types of packaging materials used for food storage: (a) corrugated cardboard produce box; (b) corrugated cardboard boxes; and (c) reusable plastic crate.

Fig. 3 and 4 represent the packaging systems used. The survey revealed strong reliance on corrugated boxes, with or without polyethylene (PE) liners. Twenty-kilogram corrugated boxes (28%) and 4-kilogram corrugated boxes (16%) were most common, followed by 4-kg boxes with PE liners (15%) and 20-kg boxes with PE liners (6%). Larger containers such as 30-kg plastic boxes were rare (2%), while "other" forms accounted for one-third of packaging. The dominance of corrugated packaging suggests a trade-off between low cost and moderate protective performance. Aleid et al. (2014) previously demonstrated that packaging type and storage duration significantly affect quality attributes of Khalas and Sukkari dates, underscoring the need for broader adoption of lined packaging to minimize moisture loss and microbial risk. More recent evidence from Alhamdan et al. (2024a) further demonstrated that packaging type, in combination with storage temperature, affects physicochemical and bioactive characteristics of Saudi date cultivars during extended storage, reinforcing the importance of appropriate packaging selection as part of cold-chain management.

Storage facilities were primarily used for merchant trading (63.3%), followed by date processing (35%), with only 1.7% dedicated to leasing. All facilities stored dates, reflecting their central role in Saudi cold chains. However, many also stored other perishable products, such as potatoes (33.3%), meat (28.3%), fruits (15%), vegetables (13.3%), onions (10%), tomatoes (10%), and miscellaneous items (5%). This diversification highlights the multifunctional role of cold storage in Riyadh. The heavy presence of potatoes and meat aligns with Jedermann et al. (2014), who emphasized that multi-product cold chains offer efficiency gains but require strict monitoring technologies to avoid cross-contamination risks.

Table 6 summarizes technical characteristics. Average cold storage capacity was 2,375 tons with 9.7 rooms, while freezing storage averaged 704 tons with 4.2 rooms. Insulation practices showed polystyrene foam as the dominant material, averaging 18 cm thickness, while rockwool and polyurethane foam were less common (10 cm each). The similarity in insulation thickness across cold and freezing storage suggests standardization, but may not reflect optimal energy performance. Alhamdan et al. (2018) showed that freezing efficiency and quality preservation in Barhi dates improved significantly under optimized conditions, suggesting that beyond material thickness, factors such as insulation quality, room design, and airflow management are critical. This interpretation is further supported by Kshirsagar et al. (2025), who emphasized the importance of thermal insulation, temperature regulation, ventilation, and energy-efficient facility design in reducing thermal loads and improving cold-storage sustainability.

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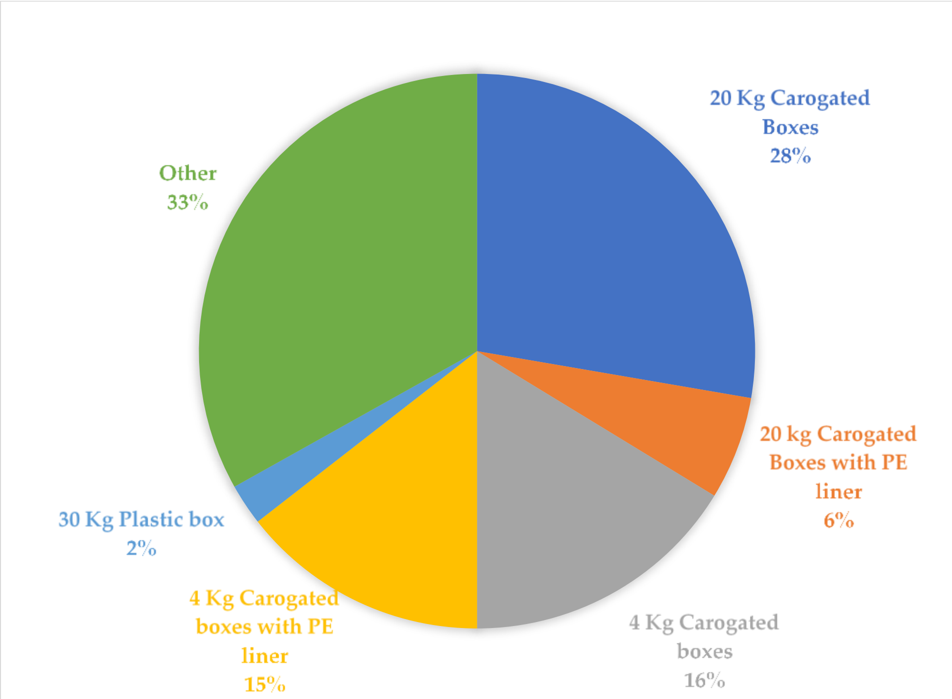

Fig. 3: Percentage of used packages in storage.

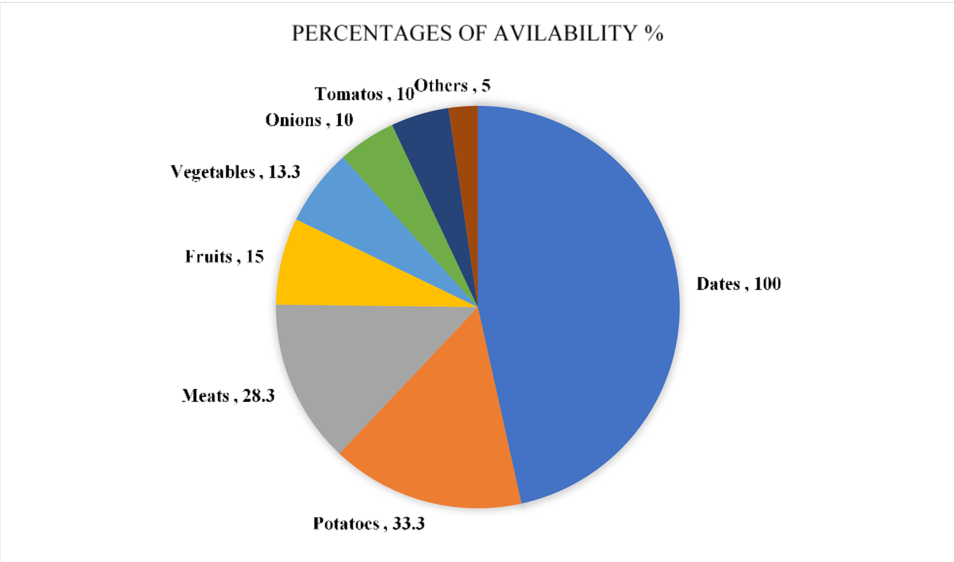

Fig. 4: Types of products stored in the refrigeration and freezing facilities.

Table 6: Technical specifications of cold and freezing storage facilities

Specification	Cold Storage	Freezing Storage
Temperature Range	0 to 15°C	-18 to 0°C
Average Capacity (Tons)	2,375.10 ± 2,192.21	703.85 ± 4,661.20
Average Number of Rooms	9.73 ± 76.00	4.22 ± 3.77
Polystyrene Foam (cm)	17.52 ± 6.11	18.09 ± 6.07
Rockwool (cm)	9.90 ± 1.50	9.85 ± 1.73
Polyurethane Foam (cm)	10.13 ± 1.87	10.65 ± 1.92
Other Materials (cm)	7.73 ± 1.07	7.88 ± 1.21

The technical specifications of storage facilities in the Riyadh region revealed distinct differences between cold storage and freezing facilities (Table 6). Cold storage facilities operated at temperatures ranging from 0 to 15°C and exhibited larger average capacities (2,375.10 ± 2,192.21 metric tons) with more rooms (9.73 ± 76.00). In contrast, freezers operated at –18 to 0°C and had smaller average capacities (703.85 ± 4,661.20 metric tons) and fewer rooms (4.22 ± 3.77). The high standard deviations observed for both facility types underscore the heterogeneity in design and function, reflecting the coexistence of small-scale specialized units and large-scale distribution hubs. These findings are consistent with international literature emphasizing that cold storage is generally designed to handle bulk commodities requiring moderately cool temperatures, whereas freezers are often dedicated to products with strict preservation requirements, such as meat and poultry (Jedermann et al., 2014; Alhamdan et al., 2018). The observed variability highlights the importance of aligning facility design with commodity-specific

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requirements and market demand. Moreover, the greater room count in cold storage facilities suggests their role as multi-purpose hubs capable of storing diverse products, while freezers tend to serve more specialized storage needs. From an energy-management perspective, this heterogeneity is also relevant because differences in storage volume, capacity, and operating conditions can produce substantial differences in cold-store energy consumption (Karacan et al., 2023).

3.4.1. Fixed Costs of Refrigeration and Freezing Facilities: The analysis of fixed investment costs (Table 3) reveals substantial variation across facilities. The average total fixed costs amounted to SAR 6.55 million (USD 1.75 million), ranging from SAR 585 thousand (USD 156 thousand) to SAR 21.3 million (USD 5.68 million). Building construction dominated, representing 93.11% of total fixed costs with an average of SAR 6.10 million (USD 1.63 million). This finding aligns with observations in similar contexts where physical infrastructure is the primary fixed asset in cold chain logistics (Jedermann et al., 2014). Refrigeration equipment accounted for 5.01% of fixed costs (SAR 328.58 thousand; USD 87.6 thousand), ventilation systems for 1.50% (SAR 98.6 thousand; USD 26.3 thousand), and insurance for only 0.37% (SAR 24.32 thousand; USD 6.5 thousand). Financing costs were absent across all surveyed facilities, indicating that most warehouses are either self-financed or supported through government-backed investment programs. This absence of financing expenses reflects the broader Saudi agricultural sector context, where state subsidies and direct investments play a significant role in infrastructure development (Alamri et al., 2024).

3.4.2. Variable Costs of Refrigeration and Freezing Facilities: Annual variable costs averaged SAR 668.60 thousand (USD 178.3 thousand), with a wide range from SAR 178.2 thousand (USD 47.5 thousand) to SAR 1.678 million (USD 447.5 thousand). Labour was the largest expense, accounting for 60.89% of total variable costs (SAR 390.8 thousand; USD 104.2 thousand). This dominance underscores the sector's reliance on labour-intensive operations, particularly during peak harvest and storage seasons. On average, facilities employed three technical and seven non-technical workers, reflecting a dual need for specialized skills in equipment handling and general support staff. Electricity represented the second-largest cost component at 23.15% (SAR 148.6 thousand; USD 39.6 thousand), followed by storage boxes at 5.03% (SAR 32.28 thousand; USD 8.6 thousand). The relatively high contribution of electricity to variable operating costs is consistent with recent evidence from the Saudi cold-chain warehousing market, where energy and operating costs have been identified as major constraints on warehouse profitability. Saudi Arabia's hot climatic conditions require intensive and continuous refrigeration, increasing electricity demand and strengthening the economic case for investment in energy-efficient refrigeration and insulation technologies (IMARC Group, 2025). Other variable costs included water consumption (3.78%), fuel (2.84%), oils and grease (2.12%), sterilization (1.81%), and maintenance (0.38%). The relatively small share of maintenance suggests underinvestment in preventive care, which could raise long-term costs through higher energy inefficiency and equipment failures. Similar conclusions were drawn by Alhamdan et al. (2018), who noted that insufficient maintenance and environmental control undermine both storage efficiency and product quality in date freezing. Rental costs per pallet averaged SAR 85.31 (USD 22.75) for cold storage and SAR 91.56 (USD 24.42) for freezing storage, reflecting slightly higher operational expenses in facilities requiring lower temperatures. These Fig.s are consistent with regional cold chain market reports, which highlight that deep-freeze facilities incur disproportionately higher energy costs (Ken Research, 2023).

4. CONCLUSION

This study assessed the operational efficiency of cooling and freezing warehouses in the Riyadh region and identified the determinants of performance. The results demonstrate that economies of scale are evident in larger facilities, as they achieve lower storage costs per ton. Operational capacity was positively influenced by the number of rooms, years of experience, and workforce size, while profitability levels remain high across the sector. However, market orientation remains largely domestic, with export opportunities underexploited.

To strengthen the sector's contribution to national food security and economic diversification, several measures are recommended. First, strategic investments in larger and technologically advanced facilities are needed to enhance cost efficiency and service quality. Second, integrating modern temperature and humidity control systems will improve product preservation and align with global standards. Third, expanding storage infrastructure to underserved cities can ensure more equitable access to cold chain services. Finally, developing export-oriented marketing strategies will enhance international competitiveness and increase the sector's economic returns.

Declarations

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Author's Contribution: AMA, YAA, AAK: Conceptualization, Formal analysis, Methodology, Data curation, Software, Formal analysis. FA, SAG, SA: Supervision, Drafting of the original draft. JA, SBA, EA: Research, Drafting, Proofreading and Editing. AMA, YAA, AAK: Project management, supervision, final review. All authors approved the final version of the article.

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