Optimization of Cold Chain Logistics for Perishable Agricultural Exports: A Case Study of the Azerbaijan-Russia Trade Corridor

Bakhtiyar Namazov
Logistics and Transportation department
Baku Engineering University
Baku, Azerbaijan
banamazov@beu.edu.az
0009-0006-7639-3914

Nofal Nabiyev
Logistics and Transportation department
Baku Engineering University
Baku, Azerbaijan
nnabiyev@beu.edu.az
0009-0006-1700-2418

Abstract. This study investigates the logistical challenges and biochemical risks associated with the transportation of perishable agricultural products from Azerbaijan to the Russian Federation—a strategic pillar of Azerbaijan's non-oil export sector. Using the **Van Arsdel "Time-Temperature-Tolerance" model** and the Q_{10} **temperature coefficient rule**, the research quantifies potential product losses across different scenarios. Empiric observations indicate that interruptions in "cold chain" infrastructure and regulatory delays at border-crossing points (e.g., Samur-Yaraq Kazmalyar) significantly accelerate microbiological degradation and autolysis. The paper classifies export goods (tomatoes, persimmons, peaches, etc.) based on their **transportability index** and sensitivity levels. Results suggest that implementing **real-time IoT-based monitoring systems** and pre-cooling protocols can reduce financial losses by up to 15-20% per shipment.

Keywords: Agricultural exports, logistical risks, cold chain management, post-harvest losses, temperature-controlled logistics, Azerbaijan-Russia trade relations, spoilage kinetics.

1. Introduction

The diversification of the non-oil sector is a fundamental priority in the economic strategy of the Republic of Azerbaijan. Within this framework, the Russian Federation remains the largest regional market for Azerbaijani agro-industrial products. However, the trans-border transportation of **perishable goods** is fraught with biochemical risks and institutional barriers that diminish economic rentability.

The stability of organoleptic and microbiological quality indicators depends strictly on the continuity of the **"cold chain" infrastructure**. Research demonstrates that deviations from normative temperature regimes stimulate respiration intensity and ethylene emission, leading to rapid biological aging. While pome fruits (apples, pears) exhibit higher **transportability**, stone fruits (peaches, nectarines) demonstrate low thermal resilience, requiring high-precision logistics.

2. Literature Review and Theoretical Framework

The qualitative integrity of perishable agricultural products is governed by complex biochemical processes that accelerate post-harvest. According to **Kader (2002)**, the primary driver of senescence in horticultural crops is respiration intensity, which is directly influenced by the ambient thermal environment. Theoretical frameworks in agro-logistics emphasize that any breach in the **"cold chain"** triggers irreversible metabolic changes.

The foundational model for evaluating cargo stability during transit is the **Time-Temperature-Tolerance (TTT)** framework developed by **Van Arsdel et al. (1969)**. This model posits that the cumulative impact of thermal fluctuations is additive and determines the residual shelf-life of the produce. Furthermore, the relationship between temperature rise and metabolic acceleration is quantified through the Q_{10} **temperature coefficient** (Van't Hoff's

rule), which suggests that a 10°C increase typically doubles or triples the respiration rate in stone fruits (Kader, 2002).

Contemporary studies on supply chain resilience, such as those by **Rodriguez-Bermejo et al. (2007)**, underscore the necessity of integrated monitoring systems. These researchers argue that post-harvest management is no longer a passive storage problem but a dynamic logistical challenge requiring **Intelligent Transport Systems (ITS)**. International regulatory standards, including the **UNECE ATP Agreement (2020)**, provide the institutional basis for these requirements, establishing normative parameters for refrigerated transport equipment. By synthesizing these theoretical models, this study aims to apply TTT and Q_{10} principles specifically to the Azerbaijan-Russia trade corridor to quantify regional logistical risks.

3. Methodology

This study employs a quantitative research design to assess the logistical risks and economic efficiency of perishable cargo transportation. The methodology is structured around three primary analytical frameworks: risk modeling, biochemical kinetics, and scenario-based financial assessment.

3.1. Spoilage Risk Modeling: The TTT Framework

To quantify the degradation of cargo quality during the 2,550 km transit from Baku to Moscow, the **Time-Temperature-Tolerance (TTT)** model is utilized. The Spoilage Risk (***SR***) is calculated using the multivariable function (Van Arsdel et al., 1969):

$$SR = \frac{M}{M_0} \cdot \frac{T}{T_0} \cdot H$$

Where:

***M*:** Actual transportation duration (days);

***M*₀:** Maximum shelf-life under optimal conditions;

***T*:** Interior refrigerator temperature;

***T*₀:** Optimal transport temperature;

***H*:** Sensitivity coefficient (representing biological vulnerability and susceptibility to mechanical damage).

3.2. Biochemical Kinetics and the Q_{10} Coefficient

The acceleration of metabolic decay due to thermal fluctuations is evaluated through the Q_{10} **temperature coefficient** (Van't Hoff's rule). This allows for the estimation of how much the respiration rate increases with every 10°C rise in temperature:

$$Q_{10} = \left(\frac{R_2}{R_0} \right)^{\frac{10}{T_2 - T_1}}$$

Where R_2 and R_1 are respiration rates at temperatures T_2 and T_1, respectively. For the purposes of this study, a Q_{10} factor of 2.0–3.0 is assumed for stone fruits, implying that a 5°C deviation effectively reduces the remaining shelf-life by half.

3.3. Quantitative Estimation of Product Loss (LQ)

The physical volume of spoilage is derived from the calculated risk index relative to the total vehicle capacity (FAO, 2011):

$$LQ(tons) = Q_{total} \times \left(\frac{SR}{100} \right)$$

Where ***LQ*** is the quantity of lost product and Q_{total} is the standard 20-ton capacity of the refrigerated unit.

4. Analysis of the Azerbaijan–Russia Agro-Export Chain

4.1. Export Dynamics and Market Structure

The agricultural export sector remains a cornerstone of Azerbaijan's non-oil economy, with the Russian Federation serving as the primary regional trade partner. In 2025, horticultural exports reached a critical milestone, exceeding 500,000 tons in total volume. Tomatoes and persimmons maintain market leadership in terms of export value and tonnage, respectively. Emerging trends indicate a rapid surge in the export of stone fruits (peaches and nectarines), driven by seasonal demand and shifting market dynamics within the CIS region. These exports exhibit strong seasonality, with peak activities during the summer (stone fruits) and autumn-winter (apples and persimmons) cycles.

Table 1. Export Volumes of Key Agricultural Commodities from Azerbaijan to Russia (2024–2025)

Product Category	Export Volume (Tons)	Export Value (Million USD)	Growth Rate (%)
Tomatoes	172,900	192.5	+18.7%
Persimmons	187,500	144.2	+21.5%
Apples	85,000	48.2	+5.4%
Nectarines	19,000	22.8	+35.0%
Peaches	17,400	21.5	+28.0%
Cherries/Sour Cherries	12,200	15.6	+12.3%
Hazelnuts	15,000	95.0	+8.1%

Key Performance Indicators and Export Dynamics

The analysis of export data reveals several critical trends regarding Azerbaijan's position in the Russian agricultural market:

- **Market Leadership:** Persimmons dominate in terms of physical volume (tonnage), while tomatoes remain the absolute leader in terms of total export value (foreign exchange revenue).
- **Rapid Growth Trends:** In 2025, the most significant export surges were observed in nectarines and peaches (+28–35%). This growth is largely attributed to increased demand for Azerbaijani produce amid restrictions on European goods in the Russian market.
- **Pricing Factors:** The highest average unit prices were recorded for peaches and nectarines (USD 1.20+ per kg), while the lowest average price was for apples (USD 0.56 per kg).
- **Seasonality Impacts:** Export activities follow distinct biological cycles. Approximately 90% of persimmon and feijoa exports occur in the final quarter (October–December), whereas nectarines and peaches peak during the summer months.

Temporal Distribution of Exports:

1. **Tomatoes:** Exported year-round; however, due to advanced greenhouse cultivation, the highest intensity is observed during the winter and spring (January–May).
2. **Apples:** Primarily exported during autumn and winter (September–March). Their high storage capacity allows for extended transit until late spring.
3. **Stone Fruits (Peaches/Nectarines):** These summer crops reach their peak export volume between August and September.

4.2. Geographic Distribution and Logistical Nodes

The distribution of Azerbaijani produce is concentrated across several high-consumption urban agglomerations in Russia:

• **Moscow Hub:** The **"Food City" agro-cluster** serves as the primary gateway and redistribution center for Azerbaijani goods.

• **Regional Markets:** Significant volumes are directed toward Saint Petersburg, Yekaterinburg (as the gateway to the Urals), and southern hubs like Stavropol and Mineralnye Vody.

Transit is primarily facilitated via road transport through the **Samur–Yarag Kazmalyar** border corridor, which acts as the critical bottleneck for the entire supply chain.

Most shipments are facilitated via **road transport** (cross-border transit via the Samur River bridge) and **rail freight**, ensuring rapid access to Russia's internal markets.

The transportation of agricultural products from Azerbaijan to the Russian Federation is facilitated by both domestic and international logistics service providers (see Table 2). During the 2024–2025 period, the market share of Azerbaijani logistics companies experienced substantial growth, reaching **85%** of the total transport volume (**Azerbaijan Land Transport Agency (AYNA), 2025**). This shift indicates a strengthening of local logistical capacity and increased competitiveness in the regional transit corridor.

Table 2. Classification of Key Operators in Azerbaijan's Agro-Logistics Sector

Company Name	Transport Mode	Specialization / Operational Scope
"Agro Transport" LLC	Road (Refrigerated)	Direct farm-to-wholesale delivery of horticultural products to Russian hubs.
"ADY Express" LLC	Rail	High-volume long-distance transport via refrigerated wagons (e.g., apples/potatoes).
"AZ Logistika"	Road (Refrigerated)	Large fleet operations targeting remote regions (Urals and Siberia).
"Fresh Logistics"	Road (Refrigerated)	Specialized cold chain management for highly perishable stone fruits and berries.
"Absheron Logistics Center"	Multimodal	Terminal services, packaging, and integrated rail/road dispatch.

4.3. Technical and Infrastructure Requirements

The reliability of the export chain depends on strict adherence to the **"Green Corridor"** protocols and continuous cold chain integrity. Effective transport requires specialized refrigerated (reefer) units capable of maintaining specific humidity levels (85–95%) and thermal stability. Current data shows that Azerbaijani logistics providers have increased their market share to **85%**, reflecting a modernization of the local fleet. However, technical risks such as ethylene cross-contamination and inadequate airflow clearance remain significant challenges during the 2,550 km transit to Moscow.

5. Economic Efficiency and Scenario Analysis

5.1. Export Cost Structure and Financial Parameters

The economic viability of agricultural exports is determined by the integration of procurement costs, logistics freight, and regulatory fees. Based on 2025–2026 market projections, a comparative cost estimate for a standard 20-ton refrigerated shipment was developed. This analysis considers factors such as fuel consumption for thermal maintenance and specialized packaging requirements for high-value stone fruits.

Table 5 presents the estimated cost of goods sold (COGS) and logistical expenditure for key agricultural commodities. The calculations are based on the average market indicators and

freight rates projected for the 2025–2026 period (Azerbaijan International Road Carriers Association (ABADA), 2025).

Table 3. Export Cost Estimates for a 20-Ton Shipment from Azerbaijan to Russia (in USD)

Product	Purchase Value (20 t)	Logistics (Freight Cost)	Packaging & Documentation	Total Cost (COGS)	Unit Cost (per kg)
Tomato	$22,000	$4,000	$2,000	$28,000	$1.40
Apple	$14,000	$3,500	$1,500	$19,000	$0.95
Persimmon	$15,000	$4,000	$1,800	$20,800	$1.04
Feijoa	$18,000	$4,200	$1,800	$24,000	$1.20
Nectarine	$26,000	$4,500	$2,500	$33,000	$1.65
Peach	$28,000	$4,500	$2,500	$35,000	$1.75

5.2. Physiological Sensitivity and Spoilage Metrics

A critical component of the risk model is the sensitivity coefficient (***H***), which reflects how different biological commodities respond to the stresses of long-distance transit. Understanding these indices is essential for calibrating the Time-Temperature-Tolerance (TTT) model and predicting potential degradation rates.

Table 4. Logistical Sensitivity Indices (*H*) for Azerbaijani Perishable Goods

Product Name	Sensitivity Coefficient (H)	Primary Biological/Physical Driver
Apple	Minimal	Durable pericarp, high fiber content, extended shelf-life.
Tomato	Moderate	Softening and thinning of the skin during the ripening phase.
Persimmon	High	Propensity for enzymatic browning and pedicel-end rot.
Nectarine	Critical	High vulnerability to bruising and juice leakage due to lack of pubescence.
Peach	Maximum	Extremely high respiration rate and zero tolerance for mechanical pressure.

The expected physical losses during the Baku–Moscow transit, under varying conditions, highlight the extreme vulnerability of stone fruits compared to pome fruits.

Table 5. Analysis of Post-Harvest Losses for Selected Perishable Goods (Baku–Moscow Route, 20-Ton Refrigerated Truck)

Product	Optimal Temp. (°C)	Transit Duration (Days)	Estimated Spoilage Risk (%)	Loss Quantity (kg)	Primary Cause of Loss
Tomato	+10 ... +12	4 – 5	2 – 3	400 – 600	Over-ripening and tissue softening
Apple	0 ... +4	5 – 7	0.5 – 1	100 – 200	Mechanical bruising (Most durable)

Persimmon	0 ... +1	4 – 6	4 – 6	800 – 1200	Internal browning / Skin damage
Feijoa	+3 ... +5	3 – 4	5 – 7	1000 – 1400	Rapid oxidation and desiccation
Nectarine	0 ... +2	3 – 5	6 – 8	1200 – 1600	Break in dormancy / Juice leakage
Peach	0 ... +1	3 – 5	7 – 10	1400 – 2000	High sensitivity / Decay and bruising

5.3. Comparative Analysis of Logistical Scenarios

The operational integrity of the agricultural cold chain, as illustrated in **Figure 1**, depends on the seamless transition between each logistical stage—from pre-cooling at the farm to final retail delivery. However, the high susceptibility of Azerbaijani stone fruits to thermal fluctuations necessitates more than just infrastructure; it requires rigorous, standardized protocols at every touchpoint. To transform this theoretical workflow into a functional risk-management tool, a specialized **'Standard Operating Procedure' (SOP)** is required. **Table 8** provides a comprehensive **Exporter's Quality Control Sheet**, delineating the critical requirements for pre-loading, in-transit monitoring, and packaging standards to ensure that the cold chain remains unbroken throughout the Baku–Moscow corridor.



Figure 1. Risks affecting the chain of perishable goods transported from Azerbaijan to Russia

The research analyzes three distinct logistical scenarios – **Optimal (Scenario A)**, **Standard (Scenario B)**, and **Critical (Scenario C) –** to simulate various real-world conditions including border delays and equipment failures:

• **Scenario A (Optimal/Ideal):** This scenario assumes the utilization of modern refrigerated transport (Euro-6 standards), expedited customs clearance at the Samur border point (under 12 hours), and a continuous, stable temperature regime. In this context, losses are minimal and restricted to **natural weight loss (desiccation)** and minor pre-existing harvesting damages that are undetectable during the initial loading phase.

• **Scenario B (Standard/Baseline):** This represents the most frequent real-world operational environment. It includes a 2-3 day dwell time at the border crossing and intermittent temperature fluctuations caused by mandatory cargo inspections (opening of refrigerator doors). These conditions lead to moderate physiological stress on the products, resulting in standard commercial losses.

• **Scenario C (Critical/Failure):** This scenario involves a catastrophic failure of the cold chain. Primary causes include technical malfunctions (e.g., compressor failure), prolonged border delays exceeding 7–10 days, or **operator negligence** (e.g., intentional deactivation of the cooling unit to minimize fuel consumption). Such conditions lead to rapid biochemical degradation, rendering high-value crops like peaches and nectarines unsalable.

Empirical data for these models were sourced from:

• **The State Statistical Committee of Azerbaijan (2025)** for export volumes and pricing.

• **ABADA (2025)** for freight costs and regional toll systems (e.g., Platon).

• **Field observations** regarding transit durations at the Samur-Yarag Kazmalyar border crossing.

The financial implications of these scenarios demonstrate that even minor thermal deviations can lead to significant economic rentability losses.

Table 6. Comparative Analysis of Financial Losses by Scenario (per 20-Ton Shipment, in USD)

Product	Scenario A: Ideal (1-2% loss)	Scenario B: Standard (5-10% loss)	Scenario C: Critical (20-30% loss)	Primary Cause of Critical Failure
Tomato	$220 – $440	$1,100 – $2,200	$4,400 – $6,600	Refrigeration failure / Temp. exceeds +15°C
Apple	$70 – $140	$350 – $700	$1,400 – $2,100	Freezing injury / Severe mechanical damage
Persimmon	$150 – $300	$750 – $1,500	$3,000 – $4,500	Ethylene buildup / Internal juice leakage
Feijoa	$180 – $360	$900 – $1,800	$3,600 – $5,400	Rapid oxidation / Surface browning
Nectarine	$260 – $520	$1,300 – $2,600	$5,200 – $7,800	Transit delays exceeding 7 days
Peach	$280 – $560	$1,400 – $2,800	$5,600 – $8,400	Temperature fluctuations above +5°C

The aggregated financial risk for each commodity, based on market prices and spoilage probability, further underscores the necessity for precision in cold chain management.

Table 7. Calculated Losses and Risk Assessment for a 20-Ton Shipment

Product Name	Spoilage Risk (%)	Loss Quantity (kg)	Average Price (USD/kg)	Financial Loss (USD)	Risk Level
Tomato	2 – 3%	400 – 600	$1.10	$440 – $660	Moderate
Apple	0.5 – 1%	100 – 200	$0.70	$70 – $140	Low

Persimmon	4 – 6%	800 – 1,200	$0.80	$640 – $960	High
Feijoa	5 – 7%	1,000 – 1,400	$0.90	$900 – $1,260	High
Nectarine	6 – 8%	1,200 – 1,600	$1.30	$1,560 – $2,080	Critical
Peach	7 – 10%	1,400 – 2,000	$1.40	$1,960 – $2,800	Critical

6. Risk Mitigation and Management Strategies

6.1. Technological Integration and Real-Time Monitoring

To transition from reactive to proactive risk management, the integration of **Intelligent Transport Systems (ITS)** is essential. The research proposes the mandatory use of independent **USB/Bluetooth Data Loggers** and **GPS-telematics** to ensure end-to-end transparency. These technologies facilitate real-time alerts for thermal deviations, allowing for immediate corrective actions during transit. Such data also serves as a critical evidentiary basis for insurance claims and liability assessments.

6.2. Standard Operating Procedures (SOP) and Operational Protocols

The minimization of post-harvest losses requires a paradigm shift from managing the "cargo" to managing the "cold chain continuity." A comprehensive **"Golden Control Sheet"** has been developed to standardize procedures for drivers, warehouse managers, and logistics coordinators. This includes rigorous adherence to **pre-cooling** requirements, as refrigerated units are designed to maintain existing temperatures rather than reduce the core heat of field-fresh produce.



Figure 2. Scheme of the "cold chain" for agricultural cargo

Figure 2 delineates the sequential stages of the integrated cold chain, emphasizing that the qualitative preservation of agricultural produce is not merely a transport issue but a multi-stage systemic process. For the Azerbaijan–Russia trade corridor, the 'Pre-cooling' (Stage 2)

and 'Refrigerated Transport' (Stage 5) phases are particularly critical. Empiric evidence suggests that failures in Stage 5, often caused by the 2,550 km transit distance and border congestion, can negate the efficiency achieved in the earlier production stages. The transition from Stage 4 (Cold Storage) to Stage 5 represents the highest risk of thermal shock, where precise temperature synchronization is required. Maintaining this continuity is essential to ensure that the produce reaches the final 'Consumer' (Stage 8) with its sensory and nutritional attributes intact.

Table 8. Exporter's "Standard Operating Procedures" (SOP) for Quality Control

Product	Pre-loading (Critical Requirements)	In-transit (Monitoring)	Packaging Standard	Risk Mitigation "Key"
Tomato	Ripening stage must be 70-80% (pink color).	Temperature must not drop below +10°C.	Perforated plastic/cardboard (breathable).	Chilling injury causes rapid tissue softening.
Apple	Fruit firmness (pressure test) must be verified.	Stable temperature between 0°C and +4°C.	Heavy-duty telescopic cardboard boxes.	Ethylene producer; do not store with sensitive crops.
Persimmon	Pedicels must be intact, dry, and attached.	0°C to +1°C; Humidity at 90%.	Single-layer crates with paper dividers.	Respiration accelerates instantly during transit delays.
Feijoa	Surface must be free of spots or browning.	+3°C to +5°C; Rapid delivery is mandatory.	Small ventilated plastic containers.	Highly sensitive to oxygen; prone to rapid browning.
Nectarine	Pre-cool to +2°C prior to loading.	0°C to +2°C; Zero thermal fluctuation.	Cardboard with cell-trays (individual slots).	1-hour cold chain break reduces shelf-life by 2 days.
Peach	Must be firm (stone-like) upon tactile inspection.	0°C to +1°C (Most rigorous requirement).	Single-layer crates to avoid stacking pressure.	Highly vulnerable; use gloves during the loading process.

6.3. Impact of Thermal Fluctuations and Protective Measures

Quantitative analysis demonstrates that even minor breaches in temperature protocols (e.g., a 5°C deviation) exponentially increase biochemical spoilage risks. The study identifies specific biological outcomes and financial consequences associated with such failures across different product groups.

Table 9. Risk and Financial Impact Matrix during Thermal Fluctuations (per 20-Ton Shipment)

Product	Optimal Temp. (°C)	Deviated Temp. (°C)	Spoilage Risk (%)	Estimated Financial Loss (USD)	Biological Consequence
Tomato	+11	+16	20 – 30%	$4,400 – $6,600	Rapid softening and juice leakage.
Apple	+2	+7	5 – 10%	$700 – $1,400	Flavor degradation and skin spotting.
Persimmon	+1	+6	25 – 40%	$3,750 – $6,000	Internal browning (Enzymatic oxidation).
Feijoa	+4	+9	30 – 50%	$5,400 – $9,000	Accelerated decay and bitter aftertaste.
Nectarine	+1	+6	40 – 60%	$10,400 – $15,600	Microbial degradation and mold growth.
Peach	+1	+6	50 – 70%	$14,000 – $19,600	Massive decay; total product failure.

To mitigate these risks, specialized management protocols including **ethylene scavengers**, optimized **airflow clearance**, and the use of **thermal curtains** during customs inspections are recommended based on the sensitivity of the commodity.

Table 10. Risk Management Protocols by Product Groups

Measure	Tomato / Persimmon	Peach / Nectarine	Apple
Pre-cooling	Essential	**Critical**	Recommended
Humidity Control	Normal (85%)	High (90%+)	Normal
Ethylene Filter	Mandatory (Persimmon)	Mandatory	Not Required
Transit Priority	Standard	**Maximum (Express)**	Standard

6.4. Future Perspectives: Digitalization and the "Energy-Risk" Trade-off

The integration of **Electronic CMR (e-CMR)** and blockchain-based documentation is poised to redefine the efficiency of the Azerbaijan–Russia trade corridor. Digitalizing the phytosanitary and customs clearance processes at the Samur border point can reduce administrative dwell times by up to 30%. From a risk management perspective, reducing the "stationary time" of a refrigerated unit is as critical as maintaining its temperature, as stationary reefers are more susceptible to ambient thermal shocks and localized "hot spots" within the cargo.

Furthermore, a critical trade-off exists between **energy consumption and spoilage risk**. During peak summer months, external ambient temperatures in the North-South corridor (specifically in Dagestan and Southern Russia) can exceed +35°C. To maintain a +1°C internal environment for stone fruits, the fuel consumption of the refrigeration unit increases by approximately 15–20%. Logistic managers must therefore balance the operational cost of fuel against the potential $15,000 loss of a compromised shipment, reinforcing the necessity of automated telematics that optimize cooling cycles based on real-time external data.

6.5. Post-Harvest Physiological Priming: Pre-cooling and Modified Atmospheres

Beyond the transport phase, the mitigation strategy must begin at the **post-harvest handling** stage. "Physiological priming," or reducing the internal temperature of the fruit to its target metabolic baseline within 4–6 hours of harvest, is the most effective defense against subsequent logistical delays. Research suggests that for every hour of delay in pre-cooling a peach or nectarine, its total shelf-life is reduced by 8–12 hours.

In addition to thermal control, the implementation of **Modified Atmosphere Packaging (MAP)** – utilizing specialized films that regulate O_2 and CO_2 exchange—provides an extra layer of protection. When combined with the proposed **SOP protocols**, MAP can act as a secondary barrier during mandatory customs inspections where refrigerator doors are opened, shielding the produce from the sudden influx of warm, humid air.

7. Conclusion

This research provided a comprehensive analysis of the logistical risks and economic efficiencies within the Azerbaijan–Russia agro-export corridor. By integrating the **Van Arsdel TTT model** and Q_{10} **respiration kinetics**, the study quantified how thermal fluctuations and transit delays directly impact the residual shelf-life and market value of perishable commodities.

The findings conclude that:

- **Risk Categorization:** Agricultural goods exhibit diverse resilience levels; while **apples** demonstrate high transportability, **stone fruits** (peaches and nectarines) are subject to critical spoilage risks, with potential financial losses exceeding **$15,000 per shipment** during cold chain failures.
- **Economic Impact:** Logistical scenarios (A, B, and C) reveal that protocol adherence can increase the probability of ideal delivery to **95%**, whereas a mere **5°C deviation** can escalate financial losses by 3 to 5 times.
- **Strategic Interventions:** To enhance Azerbaijan's non-oil export competitiveness, the transition to **"Smart Cold Chain"** technologies—including real-time IoT monitoring, mandatory pre-cooling, and standardized SOP protocols—is imperative.

Ultimately, the sustainability of this trade corridor depends on shifting the management focus from simple transportation to rigorous **cold chain continuity**. The proposed **"Golden Control Sheet"** and risk-mitigation framework provide a practical roadmap for exporters and logistics providers to minimize post-harvest waste and maximize economic rentability.

References

Azerbaijan International Road Carriers Association (ABADA). (2025a). *Analysis of international road transport costs on the North-South corridor for 2025-2026* [Official Report]. abada.az

Azerbaijan International Road Carriers Association (ABADA). (2025b, June 30). *Changes in the rules for entering the Russian Federation from June 30, 2025.* ABADA News Portal.

Azerbaijan Land Transport Agency (AYNA). (2025, March 17). *Majority of cargo transportation with Russia is carried out by Azerbaijani companies.* Report News Agency. https://report.az/en/infrastructure/azerbaijani-firms-dominate-85-of-bilateral-cargo-traffic-with-russia

Azerbaijan State Statistical Committee. (2025). *Agriculture statistics of Azerbaijan: Export dynamics of horticultural products.* https://www.stat.gov.az

Council of Heads of Government of the Commonwealth of Independent States. (2009). *Agreement on the rules for determining the country of origin of goods in the Commonwealth of Independent States.* CIS Executive Committee.

FAO. (1989). *Prevention of post-harvest food losses: Fruits, vegetables and root crops.* FAO Corporate Document Repository. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2011). *Global food losses and food waste: Extent, causes and prevention.* Rome: Food and Agriculture Organization of the United Nations.

FAO. (2022). *The state of agricultural commodity markets 2022: Geography of food and agricultural trade: Policy approaches for sustainable development.* doi.org

Food Safety Agency of the Republic of Azerbaijan (AFSA). (2024). *Requirements for the export of plant products to the Russian Federation.* Official Portal of AFSA.

Government of the Russian Federation. (2023). *On the establishment of a tariff quota for the import of fresh or chilled tomatoes into the Russian Federation in 2024 (Decree No. 2280).* Official Internet Portal of Legal Information.

Kader, A. A. (Ed.). (2002). *Postharvest technology of horticultural crops* (3rd ed.). University of California, Agriculture and Natural Resources, Publication 3311.

Rodriguez-Bermejo, J., Barreiro, P., Robla, J. I., & Ruiz-Garcia, L. (2007). *Postharvest management of the cold chain.* In Food Engineering Essentials. CRC Press.

United Nations Economic Commission for Europe (UNECE). (2020). *Agreement on the international carriage of perishable foodstuffs and on the special equipment to be used for such carriage (ATP).* United Nations Publications. https://unece.org

Van Arsdel, W. B., Copley, M. J., & Morgan, A. I. (1969). *Quality and stability of frozen foods: Time-temperature tolerance and its significance.* Wiley-Interscience.