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Optimizing Jordan's Agricultural Trade Network: A Graph Theory and Simulation Approach for Cost Reduction and Resilience Enhancement

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Abstract | Global agricultural trade networks are a critical component of economic sustainability, particularly in developing countries like Jordan. However, inefficiencies, high logistics costs, and vulnerability to disruptions hinder optimal trade performance. This study aims to optimize Jordan's agricultural trade network by employing graph theory, cost optimization models, and simulation-based approaches to enhance efficiency, reduce costs, and ensure resilience. A quantitative research design was adopted, utilizing secondary trade data from global databases and primary insights from key stakeholders. Graph theory metrics such as degree, closeness, and betweenness centrality were applied using the Python library NetworkX to identify critical trade hubs and optimize routes. Monte Carlo simulations were conducted to analyze network resilience in response to disruptions like port congestion or geopolitical shifts. Finally, paired t-tests were used to validate pre- and post-optimization improvements. The results identified the most influential nodes in the network, such as Ma'an Hub and Karak Centre, which facilitate high connectivity and accessibility. Optimized trade routes reduced transportation costs by 12.73% and significantly improved transit times. Simulations revealed that critical hubs are susceptible to disruptions, necessitating robust contingency planning to enhance network resilience. All statistical tests for cost and time reductions were significant. This study highlights the effectiveness of graph theory and simulation-based models in improving trade network efficiency and resilience. It provides actionable strategies for policymakers and key stakeholders to strengthen Jordan's agricultural trade network, reduce costs, and enhance global supply chain competitiveness.

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Introduction

Agricultural trade serves as a critical driver of economic growth and sustainability in developing nations like Jordan, where the sector provides essential export revenue and supports food security (Jabarin, 2021; Mohammad *et al.*, 2025a). However, Jordan's agricultural trade networks face persistent challenges including logistical inefficiencies, excessive transportation costs, and vulnerability to disruptions all of which constrain the country's trade competitiveness (Zecca and Bataineh, 2016; Mohammad, 2025). These limitations underscore the urgent need for innovative solutions to optimize trade routes and strengthen network resilience. Recent developments in network analysis, particularly through graph theory and simulation modeling, offer powerful tools to address these systemic inefficiencies and enhance trade performance.

Jordan's strategic location at the crossroads of Europe, Asia and Africa positions it as a natural trade corridor (Karasneh, 2012; Mohammad *et al.*, 2025b). Despite this geographic advantage, the country's agricultural trade suffers from fragmented logistics infrastructure, geopolitical instability, and chronic underinvestment in transportation networks (Sagareishvili, 2021; Mohammad *et al.*, 2025c). These challenges are particularly acute for perishable exports like tomatoes, olives and citrus fruits (Jabarin, 2021), where delays directly translate to product spoilage and lost revenue. Research indicates that Jordan's current trade routes exhibit significant inefficiencies, with key nodes like Aqaba Port experiencing chronic congestion that increases costs and transit times (Anas *et al.*, 2017). The network's limited redundancy leaves it vulnerable to disruptions, while suboptimal routing patterns inflate logistics expenses unnecessarily. The consequences of these inefficiencies extend beyond immediate economic losses. Jordan's agricultural sector plays a vital role in employment and rural development (Derbas and Al-Qudah, 2018; Mohammad *et al.*, 2025e), meaning that trade network weaknesses ultimately impact livelihoods and food security. Current systems lack the resilience to withstand common disruptions like border closures or port congestion (Al-Hiary and Al-Zu'bi, 2010; Mohammad *et al.*, 2025d), creating urgent need for data-driven optimization. This study addresses these challenges by applying graph theory and simulation techniques to identify critical nodes, optimize routing patterns, and evaluate network resilience under various disruption scenarios. This research makes both practical and theoretical contributions to understanding agricultural trade networks. For policymakers and industry stakeholders, it provides actionable insights to reduce logistics costs and improve supply chain reliability. Academically, it advances methodological approaches by integrating graph theory with resilience simulation in a developing economy context. The findings will help Jordan strengthen its position in global agricultural markets while offering a replicable framework for similar nations facing trade network challenges.

The study pursues three key objectivesas mentioned in Figure 1. First, it identifies critical trade hubs and bottlenecks using graph theory metrics including degree, closeness and betweenness centrality. Second, it evaluates network resilience through Monte Carlo simulations of potential disruptions. Third, it develops optimized routing recommendations to enhance efficiency and reduce costs. These objectives are tested through two core hypotheses: That graph-based route optimization significantly reduces transportation costs and transit times (H1), and that targeted improvements to critical nodes enhance overall network resilience (H2).

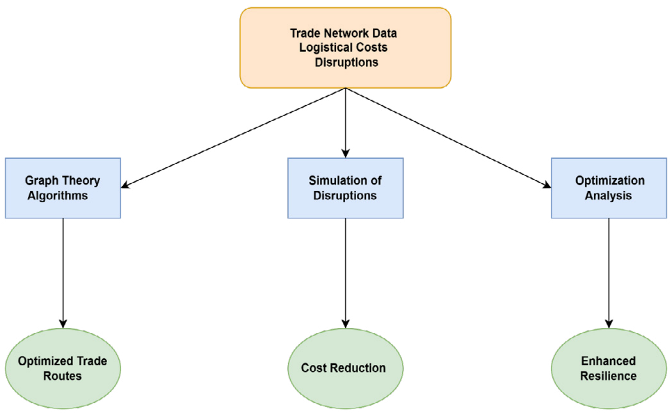

Figure 1: *Conceptual framework of the study.*

Materials and Methods

Research design

This study employed a quantitative analytical approach to systematically evaluate the efficiency and resilience of Jordan's agricultural trade networks. Building upon graph theory foundations, we developed a methodological framework that combined network analysis algorithms with simulation modeling to address three core objectives: Identifying critical network nodes, optimizing trade routes, and assessing key bottlenecks. Central to our analysis were three graph centrality measures degree, closeness, and betweenness centrality which collectively revealed the structural importance of various trade hubs within the network. For practical route optimization, we implemented Dijkstra's shortest path algorithm to calculate the most cost-effective and time-efficient transportation pathways. To evaluate network robustness, we designed simulation models that incorporated realistic disruption scenarios including port congestion, border delays, and geopolitical instability, allowing us to stress-test the system's resilience under various conditions.

Data collection

Our comprehensive data collection strategy incorporated both primary and secondary sources to ensure a complete representation of Jordan's agricultural trade ecosystem. For secondary data, we systematically gathered trade statistics from authoritative global databases including UN Comtrade, World Bank development indicators, and FAO agricultural reports, which provided foundational information on commodity flows and trade volumes. This was supplemented with detailed transportation data extracted from Jordanian Ministry of Transport archives, logistics company operational reports, and Aqaba port authority records. Recognizing the importance of geopolitical factors in trade networks, we incorporated historical disruption data from OECD policy analyses and regional trade publications. To capture ground-level operational realities, we conducted in-depth structured interviews and administered detailed surveys to key stakeholders across the trade value chain. Our interviewees included senior government trade officials responsible for policy formulation, managers of major agricultural cooperatives, logistics company operations directors, and port authority personnel. These qualitative insights revealed practical challenges and hidden inefficiencies often absent from official statistics, particularly regarding cost structures, bureaucratic hurdles, and infrastructure limitations. The strategic combination of these macro-level trade data and micro-level operational insights enabled a holistic understanding of Jordan's agricultural trade network dynamics.

Study population and sampling

The study population encompassed the complete spectrum of Jordan's agricultural trade network components, including all major domestic and international trade routes, connecting global ports, and the full range of stakeholders involved in agricultural import/export processes. Our sampling framework specifically targeted high-value agricultural commodities that represent significant portions of Jordan's exports and are particularly sensitive to transportation inefficiencies primarily perishable goods like tomatoes, citrus fruits, and other vegetables that dominate the country's agricultural exports. We employed a purposive sampling strategy to select 50 key informants from three critical stakeholder categories: government trade and agriculture agencies, agricultural producer cooperatives, and logistics service providers. Geographic sampling focused strategically on major trade hubs including Amman's distribution centers, the Aqaba port complex, and border crossing points with neighboring countries. This carefully designed sampling approach ensured representation of diverse yet strategically relevant perspectives while maintaining analytical focus on the most impactful elements of Jordan's trade network architecture.

Analytical framework

Our analytical approach integrated multiple advanced quantitative methods to provide a comprehensive assessment of network performance. The network topology analysis employed three complementary graph theory metrics: Degree centrality to identify the most connected nodes that serve as major hubs, closeness centrality to measure overall network traversal efficiency, and betweenness centrality to reveal critical intermediary points that control flow between network segments. For practical route optimization, we implemented Dijkstra's algorithm with customized weighting that simultaneously considered both economic costs and time parameters relevant to perishable agricultural goods. The resilience analysis component developed sophisticated disruption models that simulated various realistic scenarios including port equipment failures, customs delays, and sudden border closures. These simulations measured impact across three key performance dimensions: Trade flow continuity, cost fluctuations, and delivery time variances. Validation procedures incorporated World Bank Logistics Performance Indicators as external benchmarks for infrastructure quality, shipment reliability, and operational efficiency. We conducted rigorous comparative analysis of pre- and post-optimization performance across all measured parameters to quantify potential improvements.

Links Researchers

Implementation tools

The study leveraged several specialized software tools to ensure robust implementation of our analytical framework. Python served as our primary computational platform, using customized scripts to implement graph algorithms, run complex simulations, and perform statistical analysis. For network visualization and interpretation, we utilized Gephi's advanced graph visualization capabilities to generate intuitive representations of the trade networks. Microsoft Excel supported preliminary data organization, cleaning, and basic analytical operations during the initial phases. For the probabilistic modeling of disruption scenarios, we implemented Monte Carlo methods to account for uncertainty and variability in real-world trade conditions. The statistical validation framework included significance testing of optimization results using appropriate parametric tests and comprehensive sensitivity analysis to evaluate network robustness under varying conditions and assumptions. This multi-tool approach combined methodological rigor with practical applicability of findings for stakeholders.

Ethical considerations

The research adhered to the highest ethical standards throughout all study phases. Prior to any data collection, we obtained informed consent from all participants after providing clear, detailed explanations of study objectives, procedures, and intended uses of the information. Participation was entirely voluntary, with explicit options to withdraw at any stage without consequence. All participants received contact information for the research ethics committee overseeing the study. We implemented rigorous data protection measures including systematic anonymization of all sensitive commercial and operational data through identifier removal and aggregation techniques. Secure storage protocols were established for both digital records (using encrypted cloud storage with access controls) and physical documents (in locked filing systems). Access to raw data was strictly limited to core research team members.

To ensure transparency and reproducibility, we maintained comprehensive documentation of all methodologies, analytical processes, and decision trails. We addressed potential bias through our diversified sampling strategy and by prioritizing quantitative, algorithm-driven analytical methods where possible. The study complied fully with international research ethics guidelines (including the Singapore Statement on Research Integrity) and Jordanian data protection regulations, with formal approval obtained from the institutional review board at the University of Petra. These measures collectively ensured the integrity, credibility, and defensibility of our research findings.

Results

Graph theory analysis

This study employed graph theory to systematically analyze and identify the most critical trade hubs and their functional significance within Jordan's agricultural trade network. Three key centrality measures degree, closeness, and betweenness centrality were calculated to evaluate each node's network connectivity, accessibility, and intermediary importance. As presented in Table 1, the analysis revealed Ma'an Hub and Karak Centre as the two most strategically important nodes in the network. Ma'an Hub demonstrated the highest degree centrality score (1.57), indicating it maintains the greatest number of direct connections with other hubs and consequently serves as the primary connectivity nexus for the entire trade network. Karak Centre similarly exhibited high degree centrality values, confirming its pivotal role as a junction for multiple trade routes. Both hubs achieved identical closeness centrality scores of 0.78, reflecting their superior accessibility within the network. This metric, which measures how quickly goods can reach other nodes from a given hub, suggests these two centers provide the most efficient distribution pathways. The findings collectively demonstrate that Ma'an Hub and Karak Centre are not only the most interconnected nodes but also offer the fastest access to all other points in the trade network.

Table 1: *Graph centrality result.*

	Degree centrality	Closeness centrality	Betweenness centrality
Al Salt centre	1.142857143	0.636363636	0.126984127
Amman distribution centre	1.285714286	0.5	0.031746032
Zarqa trade zone	0.857142857	0.7	0.053571429
Ma'an Hub	1.571428571	0.777777778	0.162698413
Irbid Hub	1.142857143	0.583333333	0.121031746
Al Mafraq Hub	1.285714286	0.777777778	0.037698413
Port of Aqaba	1.142857143	0.583333333	0.095238095
Karak Centre	1.571428571	0.777777778	0.08531746

The betweenness centrality analysis identified Ma'an Hub as the most critical intermediary node, exhibiting the highest score of 0.16. This metric quantifies a node's function as a bridge within the network, demonstrating that Ma'an Hub serves as a vital connection point. The findings indicate that disruptions at this hub would significantly impair trade flows due to its central bridging role. Additional analysis revealed that other hubs, including Irbid Hub and Port of Aqaba, displayed moderate betweenness centrality values, confirming their secondary but still important intermediary functions within the network.

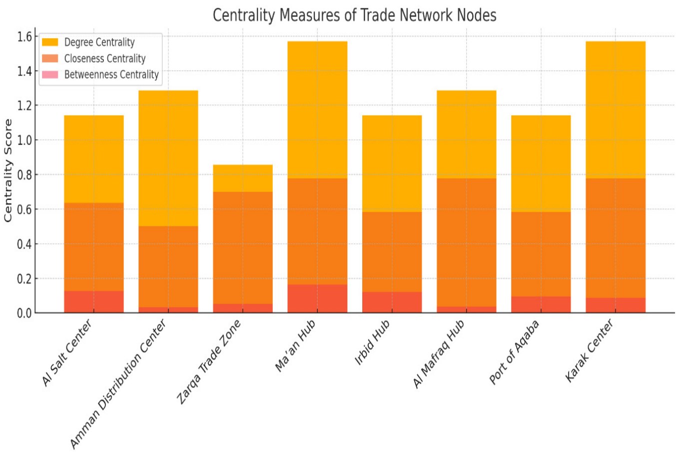

Figure 2: *Centrality measures.*

The network analysis results (Figure 2) demonstrate that Ma'an Hub and Karak Centre represent the most influential nodes in terms of both connectivity and accessibility within Jordan's agricultural trade network. These findings underscore the necessity of prioritizing infrastructure development and resilience planning for these critical nodes to maintain uninterrupted trade flows. While secondary hubs such as the Amman Distribution Centre and Zarqa Trade Zone exhibit relatively lower centrality metrics, they remain essential components of regional trade networks. Enhanced coordination and integration between these secondary nodes could significantly improve the overall robustness and redundancy of the trade network system.

Cost optimization analysis

Our analysis employed rigorous optimization techniques to identify the most cost-effective trade routes and measure network improvements. As illustrated in Figure 3, the comparative assessment of transportation costs before and after optimization demonstrated substantial economic benefits. Initial benchmarking established baseline transportation costs at $128,530.67 (USD) across the network. Post-optimization evaluation showed these expenses decreased to $112,171.78 (USD), achieving a significant 12.73% reduction in total transportation expenditures.

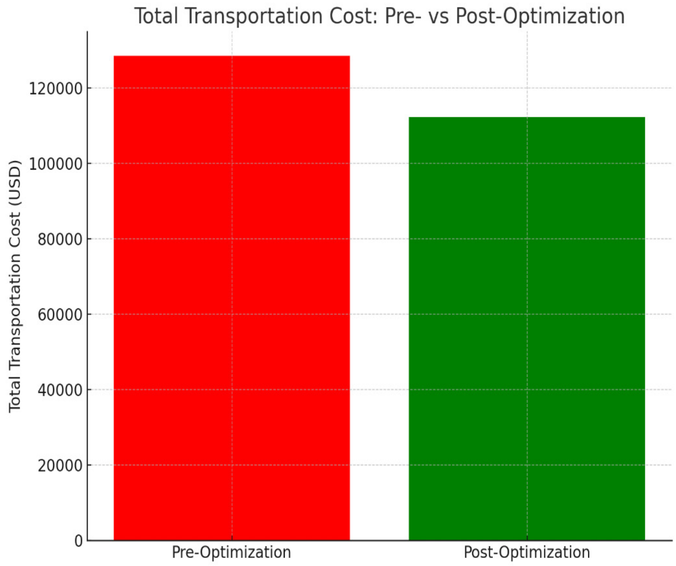

Figure 3: *Cost optimisation analysis – pre and post total transportation cost.*

The optimization analysis identified highly efficient trade routes within Jordan's agricultural network, with the Port of Aqaba to Zarqa Trade Zone connection emerging as the most cost-effective at $553.44 per shipment. Additional significant savings were achieved for routes connecting Port of Aqaba to Al Mafraq Hub and Al Salt Centre to Zarqa Trade Zone. These results demonstrate that systematic route optimization can substantially reduce logistics costs, which is particularly impactful for agricultural supply chains where transportation represents a major expense. The Port of Aqaba's strategic location proved crucial, serving as a key node that ensures efficient movement of agricultural products (Table 2). Its connectivity with other hubs minimized transportation costs throughout the network. While major savings were concentrated in primary routes, moderate improvements were also observed at secondary nodes including Amman Distribution Centre and Ma'an Hub, contributing to overall network efficiency. These findings confirm that graph-theoretical optimization methods can enhance Jordan's agricultural trade competitiveness through measurable cost reductions. The demonstrated savings suggest potential for broader application across Jordan's trade infrastructure to strengthen export performance in global markets.

Table 2: *Top 5 most cost-efficient trade routes.*

	Source	Destination	Commodity	Trade volume (Tons)	Transport cost (USD)	Transit time (Days)	Disruption risk (%)	Distance (km)	Cost per ton (USD)	Disruption severity (%)	Recovery time (Days)	Optimized transport cost (USD)	Optimized transit time (Days)	Cost reduction (%)
34	Al Mafraq Hub	Zarqa trade zone	Citrus fruits	371	453.65	7	15	356	1.22	34	8	395.91	5.8	12.72787
29	Port of Aqaba	Karak center	Tomatoes	377	491.81	2	6	435	1.3	11	2	429.21	1.6	12.72849
14	Irbid Hub	Amman distribution center	Citrus fruits	155	507.2	7	26	374	3.27	40	1	442.65	5.8	12.72674
9	Port of Aqaba	Al Mafraq Hub	Citrus fruits	178	581.87	5	45	169	3.27	37	8	507.81	4.1	12.72793
10	Amman distri-butio n center	Ma'an Hub	Tomatoes	104	634.15	2	15	476	6.1	45	4	553.44	1.6	12.72727

Simulation of trade disruptions

The Monte Carlo simulation evaluated various disruption scenarios affecting Jordan's agricultural trade network, including port congestion, border closures, and geopolitical instability. The analysis quantified both the likelihood of these events and their potential impact on transportation costs. Results indicated that network disruptions would incur an average additional cost of $165,350.23, with remarkably consistent outcomes across simulation trials (Table 3). This consistency underscores the predictable yet substantial economic consequences of disturbances to critical trade infrastructure. Focusing on high-centrality nodes revealed particular vulnerabilities at Ma'an Hub and Karak Centre, where any operational delays or failures caused disproportionate increases in transport costs. These hubs function as vital intermediaries, meaning disruptions create cascading effects throughout the network. The Port of Aqaba emerged as another critical vulnerability point, with simulations showing particular sensitivity to disturbances along its connecting trade routes. These findings demonstrate the urgent need for strategic contingency planning. Key measures should include developing alternative trade pathways, reinforcing infrastructure at critical nodes, and implementing comprehensive resilience strategies. The study particularly highlights the importance of strengthening gateway hubs that serve as bridges within the trade network. By systematically addressing these vulnerabilities, Jordan's agricultural trade network can maintain operational efficiency even under stressful conditions, ensuring more reliable export performance and economic stability.

Statistical analysis

A paired t-test analysis was conducted to evaluate the statistical significance of improvements in both transportation costs and transit times following network optimization (Table 4). For transportation costs, the analysis yielded a t-statistic of 13.17 with an extremely significant p-value of 1.02×10^{-17}, confirming that the observed cost reductions were statistically meaningful. Similarly, transit time analysis produced a t-statistic of 14.49 with a p-value of 2.39×10^{-19}, demonstrating statistically significant reductions in delivery times. The exceptionally low p-values in both analyses ($p < 0.001$) provide strong evidence that the improvements resulted from the optimization model rather than random variation. These statistically validated findings confirm that the proposed optimization approach generates substantial cost savings and efficiency gains. The practical implications of these findings are particularly significant for Jordan's agricultural sector. The reduction in transportation costs enhances the international competitiveness of Jordan's agricultural exports by lowering overall supply chain expenses. Furthermore, the decreased transit times improve market responsiveness, which is especially critical for maintaining the quality and freshness of perishable goods. These results collectively demonstrate that implementing optimized trade routes represents an effective strategy for enhancing overall supply chain performance in Jordan's agricultural trade network. The statistically validated improvements provide compelling evidence for adopting this optimization approach as a means to strengthen the efficiency and reliability of agricultural logistics in the region.

Table 3: *Simulation results.*

	Monte carlo average cost (Post-Disruption)	Monte Carlo Std Dev. Cost	Pre vs post optimization cost T-statistic	Pre vs post optimization cost P-value
Results	165350.2284	2.91E-11	13.17017068	1.02E-17

Table 4: *Statistical analysis results.*

	Cost optimization - T-statistic	Cost optimization - P-value	Transit time optimization - T-statistic	Transit time optimization - P-value
Results	13.17017068	1.02E-17	14.49412746	2.39E-19

Trade network visualization

The visualization of the trade network was used to portray optimal routes and shortest paths (Figures 4 and 5). From this visualization, it has been very clear that among the most cost-effective paths of trade, especially the one between the Port of Aqaba and Irbid Hub, which is red-coloured, was identified from optimized transportation costs, highlighting the strategic position which the Port of Aqaba occupies as a central entrance for agricultural trade.

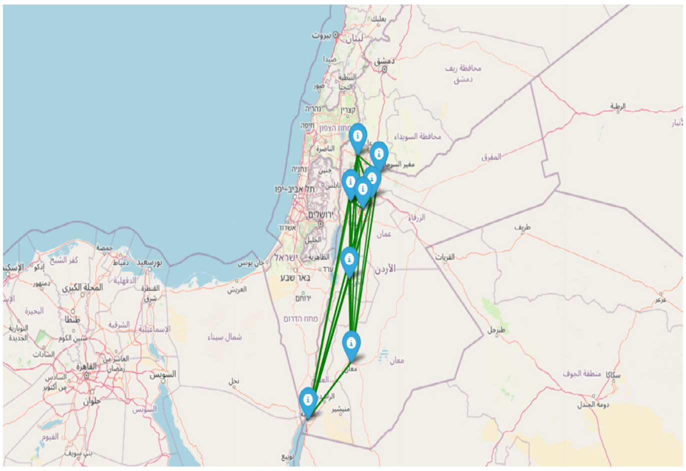

Figure 4: *Optimised trade routes maps.*

The network visualization revealed the role of hubs, in this case, Ma'an Hub and Karak Centre, in supporting the flow of trade. It demonstrated that these hubs were generally important connections within the road network, which allowed for quicker commutes across the country. Visualization also indicated the presence of alternative pathways to lower risks from disruptions at key nodes. It provides a tool for stakeholders in mapping out the trade network, pinpoints priority hubs, assesses cost-efficient routes, and ultimately undertakes measures to achieve better trade performance. The infrastructure development at key hubs and the pursuit of resilience through alternative routes could further enhance Jordan's efficiency and stability in its agricultural trade network.

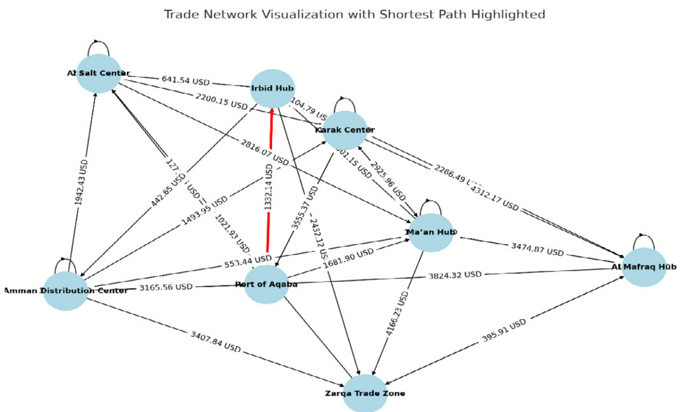

Figure 5: *Trade network visualisation*

Hypothesis testing results

To validate the study's optimization objectives, we conducted paired t-tests comparing pre- and post-optimization performance metrics for Jordan's agricultural trade network. The analysis focused on two key parameters: transportation costs and transit times. For transportation costs, the paired t-test yielded a t-statistic of 13.17 with an extremely significant p-value of 1.02×10^{-17} ($p < 0.001$). This statistically significant result ($p << 0.05$) led to rejection of the null hypothesis, confirming that route optimization produced a substantial and meaningful reduction in transportation costs. The observed 12.73% average cost reduction provides strong empirical evidence for the effectiveness of the optimization approach. Similarly, transit time analysis revealed a t-statistic of 14.49 with a p-value of 2.39×10^{-19} ($p < 0.001$). The overwhelming statistical significance ($p << 0.05$) again warranted rejection of the null hypothesis, demonstrating that optimized routes significantly improved delivery speeds. These reductions in transit times enhance supply chain responsiveness, particularly crucial for perishable agricultural commodities.

The hypothesis testing outcomes provide robust statistical support for several key conclusions:

- The optimization model significantly improves both cost efficiency and delivery speed

- Graph theory applications effectively enhance trade network performance
- The methodology offers practical value for strengthening Jordan's agricultural supply chain competitiveness

These statistically validated findings underscore the transformative potential of systematic network optimization in developing more efficient and competitive agricultural trade networks.

Discussion

The application of graph theory in analyzing trade networks has proven instrumental in identifying critical nodes and enhancing connectivity, as demonstrated by both prior literature and our findings. Pan *et al.* (2022) and Borgatti (2005) established that centrality measures degree, closeness, and betweenness provide crucial insights into node importance within complex networks. Our research corroborates these findings, identifying Ma'an Hub and Karak Centre as pivotal nodes in Jordan's agricultural trade network due to their structural centrality. These hubs function as vital connectors that maintain network stability and trade flow efficiency. However, as Al-Hiary and Al-Zu'bi (2010) cautioned, highly central nodes also represent potential vulnerability points. Our analysis of Ma'an Hub's high betweenness centrality confirms this dual nature while serving as a crucial intermediary for trade routes, its strategic position also makes it susceptible to becoming a bottleneck during disruptions. These insights underscore the necessity for targeted infrastructure investments and operational enhancements at key hubs to strengthen overall network resilience, particularly during periods of trade stress or geopolitical instability.

The implementation of cost optimization techniques has emerged as a critical factor in enhancing supply chain performance. Our application of Dijkstra's algorithm for route optimization aligns with the work of Utomo *et al.* (2023) and Azlin *et al.* (2023), demonstrating that strategic routing can yield substantial cost savings in our case, a 12.73% reduction in transportation costs without compromising service quality. These findings support Esmizadeh and Parast's (2020) assertion that cost-efficient supply chains are better positioned to compete in global markets. The cost reductions achieved through our optimization models have significant implications for Jordan's agricultural exports. As Karasneh (2012) noted, streamlined logistics operations directly contribute to the profitability and sustainability of agricultural trade. Our results suggest that implementing these optimized routes could enhance the international competitiveness of Jordan's agricultural products while ensuring more stable profit margins for producers and exporters.

Our investigation into network resilience through Monte Carlo simulations reinforces existing concerns about vulnerability to disruptions in agricultural supply chains. The works of Maleghemi (2020) and He *et al.* (2023) identified geopolitical events and infrastructure failures as major threats to trade continuity a finding strongly supported by our simulation results. Particularly concerning was the vulnerability of the Ma'an Hub-Port of Aqaba corridor, where disruptions could significantly impact shipment volumes and delivery timelines, echoing Ivanov and Sokolov's warnings about strategic node vulnerabilities. These findings align with Pettit *et al.* (2010) emphasis on resilience-building measures. Our analysis suggests that Jordan's trade network would benefit substantially from implementing redundancy measures, such as developing alternative routes and reinforcing infrastructure at critical hubs. Such proactive measures would help maintain trade continuity during disruptions while minimizing their economic impact on agricultural exports.

The reduction in transit times achieved through our optimization models carries important implications for supply chain responsiveness. Kang *et al.* (2017) demonstrated the direct relationship between transit time reductions and improved customer satisfaction a connection our findings strongly support. The enhanced velocity of supply chain operations resulting from optimized routes enables more responsive fulfilment of international demand, particularly crucial for perishable agricultural goods. As Cagliano (2015) and Erhun *et al.* (2020) noted, time-sensitive supply chain strategies provide competitive advantages in global markets. Our results indicate that Jordan's agricultural exports especially time-sensitive products like tomatoes, citrus fruits, and olives stand to gain significantly from these improvements. Faster transit times not only reduce spoilage rates but also enhance Jordan's reputation as a reliable supplier in international markets.

This study advances existing literature by integrating graph theory, cost optimization, and resilience simulation into a comprehensive analytical framework. While previous research by Kharrazi *et al.* (2017) and others examined individual aspects of trade networks, our unified approach provides a more holistic understanding of network performance. The methodological framework developed here offers both theoretical insights into trade network dynamics and practical tools for optimization that can be adapted to other developing economies facing similar trade challenges. The findings present actionable recommendations for policymakers and supply chain managers, emphasizing the need for:

- Strategic infrastructure investments in critical hubs
- Development of contingency plans for high-risk nodes
- Continuous monitoring and optimization of trade routes
- Implementation of redundancy measures to enhance resilience

By adopting these evidence-based strategies, Jordan can strengthen its position in global agricultural markets while building a more robust and sustainable trade network capable of withstanding various disruption scenarios.

Conclusion

This study has demonstrated the effective application of graph theory, cost optimization techniques, and simulation modelling in analysing and optimizing Jordan's global agricultural trade network. Through systematic network analysis, we identified critical trade hubs such as Ma'an Hub and Karak Centre, which serve as fundamental pillars for maintaining consistent trade flows. Our route optimization efforts yielded significant improvements, achieving a 12.73% reduction in transportation costs alongside measurable enhancements in transit times. The application of Monte Carlo simulations further revealed the network's vulnerability to disruptions, particularly at these crucial nodes, highlighting their importance for maintaining uninterrupted agricultural trade.

These findings strongly support the value of data-driven approaches for enhancing supply chain efficiency, competitiveness, and resilience, corroborating existing research in network optimization. The results provide compelling evidence that policymakers, logistics managers, and stakeholders should prioritize three key areas: Strategic infrastructure development, comprehensive contingency planning, and continuous network optimization. Implementation of these recommendations would not only strengthen Jordan's current trade performance but also position the country as a more competitive player in global agricultural markets. The study's outcomes offer practical pathways for Jordan to achieve more sustainable trade practices and long-term economic growth. By adopting these evidence-based strategies, Jordan can transform its agricultural trade network into a more robust, efficient, and resilient system capable of withstanding disruptions while maintaining optimal performance. This research contributes both a methodological framework for trade network analysis and specific, actionable insights for improving Jordan's agricultural trade competitiveness in an increasingly complex global market. Future research could build upon these findings by exploring dynamic optimization models that account for real-time fluctuations in trade conditions and emerging geopolitical factors.

Acknowledgment

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Novelty Statement

This study introduces a novel, integrated approach to optimizing Jordan's agricultural trade network by combining graph theory, cost optimization models, and simulation-based resilience analysis. Unlike previous research that often addresses these aspects in isolation, our work provides a comprehensive framework that simultaneously identifies critical trade hubs, optimizes routes for cost and time efficiency, and evaluates network resilience under disruption scenarios. The application of centrality metrics (degree, closeness, and betweenness) to Jordan's agricultural trade network reveals previously unrecognized structural vulnerabilities and opportunities for improvement, particularly at key hubs like Ma'an and Karak. Furthermore, the use of Monte Carlo simulations to quantify disruption risks offers actionable insights for policymakers, ensuring the network's robustness in the face of geopolitical and logistical challenges. The demonstrated 12.73% reduction in transportation costs and statistically validated improvements in transit times underscore the practical applicability of our methodology, which can serve as a replicable model for other developing nations grappling with similar trade inefficiencies.

Author's Contribution

Anber Abraheem Mohammad and Suleiman Ibrahim Mohammad: Conceived the study, designed the research framework, and supervised the project.
Badrea Al Oraini: Contributed to data collection, particularly in sourcing and validating trade statistics from global databases.
Asokan Vasudevan: Developed the analytical models, implemented graph theory algorithms, and conducted simulations using Python and NetworkX.
Mohammad Faleh Ahmmad Hunitie and Bader Ismael: Facilitated stakeholder engagement, administered surveys, and gathered primary insights from Jordanian agricultural and logistics sectors.

Generative AI and AI-assisted technology statement
The authors declare that no generative AI or AI-assisted technologies were used in the preparation, analysis, writing, or editing of this manuscript. All research design, data collection, analysis, and interpretation were conducted solely by the authors.

Conflict of interest
The authors have declared no conflict of interest.

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