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ARTICLE

Optimizing the Value Chain for Perishable Agricultural Commodities: A Strategic Approach for Jordan

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ABSTRACT

Efficient supply chain management for perishable agricultural commodities is essential to mitigate post-harvest losses, enhance profitability, and ensure food security. This study focuses on optimizing the supply chain for perishables in Jordan by addressing challenges in transportation, storage, and stakeholder practices. Data from 367 stakeholders, including farmers, transporters, and retailers, provided insights into the dynamics of the supply chain. Descriptive, inferential, and simulation-based methods were employed to evaluate optimization strategies. Descriptive statistics revealed a reduction in post-harvest losses from 17.38% pre-intervention to 15.16%

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post-intervention, while regression analysis identified transportation conditions, technology adoption, and environmental factors as critical predictors of losses. Simulation models demonstrated the potential for loss reductions of up to 20% under high-improvement scenarios. Financial analysis showed a total saving of $11,149.45, reflecting a 12.83% improvement in profitability. Transportation improvements and technology adoption emerged as the most impactful interventions, significantly reducing losses and enhancing supply chain performance. Comparative analyses validated the significance of these reductions, demonstrating the scalability of the proposed strategies. This study highlights the transformative potential of targeted interventions in reducing losses, improving financial outcomes, and promoting sustainable agricultural systems. The findings contribute to the broader discourse on supply chain optimization and offer actionable solutions for addressing inefficiencies in the management of perishable commodities, ensuring better profitability and food security.

Keywords: Agriculture Supply Chain; Perishable Agricultural Commodities; Post-Harvest Losses; Transportation; Technology Adoption

1. Introduction

The management of perishable agricultural commodities presents a significant challenge globally, with considerable implications for food security, economic sustainability, and environmental conservation. Post-harvest losses account for substantial economic and resource wastage, particularly in developing countries where infrastructure constraints and inefficient supply chain practices exacerbate the problem [1–3]. In Jordan, a country with a rapidly growing population and limited natural resources, the optimization of the value chain for perishable goods is critical to ensuring food security and sustainable agricultural development. The fragility of perishable products, coupled with inefficiencies in transportation, storage, and handling, demands targeted interventions to address these challenges effectively.

Globally, it is estimated that post-harvest losses account for up to 40% of the total agricultural output, showing inefficiencies in the supply chain and hindering access to food for millions [4–6]. Agriculture in Jordan has some particular challenges in the form of harsh climatic conditions, very limited arable land, and restricted access to advanced technology. These are factors that exacerbate post-harvest losses and undermine the economic viability of the sector. A previous study by Macheka et al. [7] has signaled that losses along the logistics chain occur due to a lack of refrigerated transport, poor infrastructure in storage houses, and incomplete knowledge among stakeholders. Despite these efforts, which were devised to address the challenges described above, the high persistence of post-harvest losses indicates quite manifestly a need for an even more integrated/technology-driven approach.

The core problem underpinning this study is the very low efficiency of Jordan's supply chain in perishable agricultural commodities, leading to high levels of post-harvest losses with resultant economic inefficiencies. Previous interventions have often been fragmented in that improvement initiatives have focused on a single discrete aspect of the supply chain, such as transportation, or storage, stakeholder practices, without considering the end-to-end interdependencies of these links. This study attempts to fill this knowledge gap by investigating holistic optimization strategies that are driven by technology, training, and policy interventions aimed at improving the overall efficiency in the supply chain, reducing post-harvest losses, and increasing profitability among stakeholders along the value chain.

Post-harvest losses (PHLs) in Jordan are a significant concern, particularly for perishable crops like fruits, vegetables, and cereals. Studies indicate that losses in vegetable crops like tomatoes, squash, and sweet peppers range from 19% to 23%, with the highest losses observed at the retail level. For instance, tomatoes experience up to 14% losses during retail, contributing to an overall loss of 19%. Similarly, losses in wheat reach about 12.95% at the post-harvest stage, with total losses in the wheat value chain amounting to 34% [8, 9]. Compared to global benchmarks, where the FAO estimates around 14% of food is lost post-harvest globally, Jordan's figures are relatively high. This highlights the need for improved post-harvest management, infrastructure, and handling practices to reduce losses and enhance food security in the region.

The importance of this research goes beyond the immediate economic benefits of reducing post-harvest losses. By improving the efficiency of the supply chain, the study addresses broader goals of sustainable development, such as enhanced food security, reduced environmental impact, and improved livelihoods for farmers and other stakeholders. Moreover, the research is aligned with Jordan's national strategy for sustainable agriculture, which emphasizes the importance of technology adoption and capacity building in addressing the challenges facing the sector [10, 11].

The research seeks to achieve its objectives by being informed by a number of key research questions. What are the critical points of post-harvest losses within the value chain of perishable agricultural commodities in Jordan? Which factors most significantly contribute to these losses, and how can they be mitigated? How effective are the simulation-based optimization strategies in reducing post-harvest losses and enhancing supply chain efficiency? What are some actionable recommendations that could be made to stakeholders, including policymakers, in support of the sustainable optimization of the supply chain?

The research statement underpinning this study is that the optimization of supply chains for perishable agricultural commodities in Jordan needs an integrated approach that addresses various inefficiencies related to transportation, storage, and stakeholder practices. It aims to use technology and simulation models to prove that significant reductions in post-harvest losses are possible with improved economic sustainability.

This study develops the key discourse around agricultural sustainability and food security based on evidence-based insights into the effectiveness of targeted interventions. The expected findings may have implications for policy and practice by providing actionable recommendations on how to enhance the resilience and efficiency of agricultural supply chains in Jordan and similar contexts. Above all, this study underlines the transformative potential of strategic investments in technology, infrastructure, and capacity building—nailing their crucial role for progress on one of the major challenges facing global food systems.

This study has the following key objectives:

1. To identify critical points of post-harvest losses in the value chain of perishable agricultural commodities in Jordan, from production to retail stages.
2. To analyse the factors contributing to post-harvest losses, including inefficiencies in transportation, storage conditions, and handling practices across the supply chain.
3. To propose and assess optimization strategies through the application of simulation models and supply chain optimization tools to enhance operational efficiency and reduce losses.
4. To develop actionable recommendations for stakeholders, including farmers, logistics providers, and policymakers, aimed at improving supply chain sustainability and reducing economic losses associated with spoilage.
5. To assess the potential impact of technology adoption (e.g., refrigerated storage and transport) and training programs on reducing post-harvest losses.

1.1. Related Studies

Efficient transportation is a cornerstone, at the heart of the supply chain management of perishable commodities lies efficient transportation. Time and again, studies have underlined that poor transportation infrastructure and delays are among the major causes of increasing post-harvest losses. According to Kader [12], cold-chain logistics play a very important role in quality maintenance during transportation, while Yahia [13] established that developing countries, like Jordan, usually lack proper cold-chain infrastructure. Deficiencies in cold-chain infrastructure lead to high rates of spoilage that significantly affect profitability and access to markets. Besides, the weakness of road networks and unreliability of vehicles partly contribute to delays. In Jordan, this is further worsened by fragmentation in logistics operations, especially in rural areas where transport is unreliable.

Storage environments are important in maintaining product integrity. According to Xu and Zhang [14], mechanisms for controlling temperature and humidity in storage facilities reduce the risks of spoilage and contamination by great margins. Al-Oun [15] identified that most small-scale producers in Jordan lack access to modern storage facilities and therefore have to revert to traditional systems that cannot maintain the conditions of commodities properly. This results in increased post-harvest losses, especially in commodities that are sensitive to temperature, such as dairy and fresh produce. At the global level, technologies in storage, like smart monitoring systems, have so far shown great potential to reduce losses, but their adoption in Jordan has been very limited due to high costs and infrastructural challenges.

Bad handling practices, right from harvest up to intermediary stages, contribute significantly to mechanical damage and microbial spoilage. Yahaya and Mardiyya [16] have reported that handling practices have often been relegated to the background despite being at the heart of preserving perishable goods. Studies conducted by Al-Oun and Abuamoud [17] in Jordan indicate that many smallholder farmers are characterized by inadequate training and a lack of the requisite equipment to apply the best handling practices. Training programs aimed at enhancing techniques of harvesting and minimizing handling damage would, therefore, reduce losses, but their penetration remains limited [18–21].

Technological advancements have transformed supply chain management globally, yet their adoption in Jordan faces significant barriers. Mazzawi and Alawamleh [22] identified automated systems, such as sorting and temperature monitoring, as key factors in reducing losses. However, Jordanian stakeholders often cite financial constraints and limited technical expertise as barriers to adopting such technologies in agriculture. Moreover, innovative yet affordable solutions tailored to Jordan's socio-economic context, such as solar-powered cold storage, have not been adequately explored.

Training programs play a crucial role. The capacity building among the stakeholders, coupled with ensuring that best practices are observed, makes training programs indispensable. Kader [12] noted that proper training significantly heightens the capacity of all stakeholders in employing efficient means of handling, storage, and transportation of products. In Jordan, region-specific training programs are lacking and hence retard efforts to realize efficiency in operations as well as reducing post-harvest losses. Most existing programs do not respond to the diverse challenges faced by stakeholders in the varied agricultural zones of the country.

Stakeholder expertise is a crucial moderating variable in post-harvest loss management. It follows, then, that expertise constitutes an essential moderating variable in managing post-harvest loss. On the same aspect, findings by Adepoju and Ologan [23] demonstrate how the experienced category of stakeholders develops their potential to derive maximum gains through every available decision with the most minimal number of losses. However, in the country of Jordan, for example, expertise has remained extremely unequal, where a high majority of farmers within rural areas still remain uninfluenced by modern supply chain knowledge and practices. This knowledge gap leads to less effective interventions that include technology adoption and training programs.

The effective policy framework drives the wheel of improvement in supply chain efficiency. Studies, such as those by Idriss and El-Habbab [24], indicate that stringent food safety regulations and government subsidies for cold-chain infrastructure have reduced post-harvest losses. In Jordan, weak enforcement of existing regulations and limited financial incentives provided for technology adoption have been serious deterring factors. Infrastructure investment, training, and research need to be encouraged by policies that will overcome these challenges.

High perishability has a great relation with the needs of commodities concerning storage, transportation, and handling. Vegetables like tomatoes are so sensitive that Emana et al. [25] found them very prone to spoilage due to their high water content, coupled with a tender structure. Poor packaging and inappropriate commodity storage in Jordan predispose certain commodities to such incidents [26–29]. Further research into commodity-specific interventions could help tailor solutions more appropriately.

Environmental conditions, including temperature and humidity, present ongoing challenges for managing perishables. In general, the environment, temperature, and humidity are very persistent challenges to perishable commodities. Khader et al.[9] have pointed out how the arid climate of Jordan, with high temperatures and scanty water availability makes post-harvest losses even worse. These factors raise a need for innovative, climate-resilient strategies, like enhanced insulation and solar-powered cooling technologies, which are relatively underexplored in the Jordanian context.

Reducing post-harvest loss rates remains a priority in ensuring food security and economic stability. Meta analyses by Stathers et al.[30] present the potential of integrated solutions, which include efficient transportation, storage, and handling that could reduce losses by up to 40%. However, Jordan-specific data indicates that the fragmented supply chains and lack of coordination among stakeholders are limitations to scaling such interventions.

Post-harvest losses directly impact financial stability. The losses after harvesting have a direct impact on the economic stability of mall-scale farmers. According to Jabarin[31], recent annual losses in Jordan's agricultural sector exceed $100 million, a situation that necessitates urgent systemic reforms. They further affirm that operational process inefficiencies, including delays in transit and inconsistent handling processes, accentuate economic pressure.

1.2. Research Gaps

To date, significant developments have been made in understanding the mechanisms of post-harvest losses, but many gaps still exist. For one, there is limited research on traditional and conventional knowledge integrations with modern technologies in the Jordanian context, even as global evidence insists on technological innovations in line with Jordan's socio-economic conditions. Second, there is a lack of on-the-ground studies that provide empirical assessments of impacts following specific policy interventions, such as subsidies and regulatory policies. Third, the absence of region-specific training programs for addressing the special needs of Jordan's agricultural diversity significantly increases the void in effectively tackling the issues related to loss mitigation. Moreover, strategies on climate-resilient agriculture, particularly in relation to the arid conditions prevalent in Jordan, remain underexplored. Finally, research into multi-stakeholder collaboration—the most crucial aspect that could lead to systemic efficiencies—remains very scant. Such lacunae point out opportunities where efforts toward sustainable solutions may be made possible in the area of post-harvest loss management in Jordan.

1.3. Hypothesis Development and Study Framework

After reviewing related studies, the following hypotheses were developed, and the study framework shown in **Figure 1** was established.

H1. *Significant post-harvest losses occur at identifiable critical points within the value chain of perishable agricultural commodities in Jordan, particularly during transportation and storage phases.*

H2. *Inefficiencies in transportation, inadequate storage conditions, and improper handling practices significantly contribute to post-harvest losses in the supply chain.*

H3. *The application of simulation models and supply chain optimization tools leads to a measurable reduction in post-harvest losses by enhancing operational efficiency.*

H4. *Implementing actionable recommendations for farmers, logistics providers, and policymakers significantly improves supply chain sustainability and reduces economic losses associated with spoilage.*

H5. *Adoption of advanced technologies (e.g., refrigerated storage and transport) and training programs for stakeholders significantly reduces post-harvest losses in perishable agricultural supply chains.*

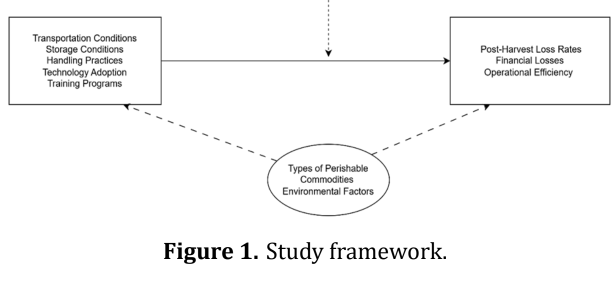


Figure 1. Study framework.

2. Materials and Methods

This study has adopted a descriptive and analytical research design to explore the optimization of the value chain for perishable agricultural commodities in Jordan. This design befits a systematic analysis of existing processes of supply chains, identification of critical points that incur post-harvest losses, and further assessment of the effectiveness of possible interventions. Essentially, the integration of both qualitative and quantitative data bestowed assurance of a thorough understanding of the underlying issues and potential optimization.

The population considered key stakeholders within the supply chain for perishable agricultural products in Jordan included farmers, transporters, wholesalers, retailers, and policymakers. A stratified random sampling was performed for this purpose to capture the views of all important groups of stakeholders. The sample size of 367 respondents was determined by calculations involving the size of the population, the effect size anticipated, the confidence level, and the acceptable margin of error. The sample size gave a statistically sufficient basis for analysis and allowed for generalization of the findings to the broader population.

Some measurement variables used in assessing causes of post-harvest losses and optimization strategies adopted were the percentage of wastage, financial losses incurred from the spoilage, time taken to transport the produce from farms to the markets, and conditions of storage in regard to temperature and humidity. The study also assessed the knowledge of best practices among stakeholders in the value chain for handling perishables and the level of technology adoption, such as the use of refrigerated storage and transport. Customer satisfaction measures were also taken, especially perceptions of the quality of the product at retail points. Data collection was through structured questionnaires, observational checklists, and key informant interviews, with all tools pre-tested for reliability and validity prior to deployment.

A combination of descriptive and inferential statistical methods was employed for the analysis. The means, standard deviations, and frequency distributions are some of the descriptive statistics used to summarize data on post-harvest losses, operational inefficiencies, and stakeholder practices. Regression analysis was done to identify predictors of post-harvest losses and also the effectiveness of the interventions. Simulation models applied to the testing of proposed optimization strategies within controlled virtual environments simulate supply chain scenarios under different technological and logistical conditions. Comparisons were also made to juxtapose the pre- and post-intervention outcomes, which showed sharp contours of efficacy.

Ethical considerations were an integral part of the research process. All participants were informed about the purpose of the study, the procedures involved, and their rights, and their consent was obtained in writing. Participation was strictly voluntary, and confidentiality was guaranteed through anonymization, where all data became unidentifiable. The study ensured non-maleficence—it did not inflict harm on the participants—and followed measures to minimize risks. In addition, this research was reviewed and approved by a recognized ethics committee in Jordan to meet any ethical requirements.

3. Results

3.1. Descriptive Statistics

Descriptive statistics (**Table 1**) are used to deduce major trends that exist in postharvest losses on pre- and post-implementation of the optimization strategies. The poor mean pre-intervention rate of 17.38%, with a standard deviation of 4.56%, showed high levels of incompetence with high variability across the supply chains. The variation is very likely due to inconsistent application of best practices across regions and various stakeholders, besides poor infrastructure and poor adoption of technologies.

After the intervention, this was reduced to an average of 15.16%, with the standard deviation falling to 3.82%, thus reflecting a reduction not only in the overall losses but also in the variability of performance within the supply chains. The reduction in variability suggests that the strategies were implemented more consistently among the stakeholders, for instance, better transportation and storage practices. It means that even the less efficient parts of the supply chain started to benefit from these interventions.

Table 1. Descriptive analysis.

	Pre-Intervention Loss Rate	Post Intervention Loss Rate	Loss Rate Reduction	Transportation Conditions Score	Storage Conditions Score	Handling Practices Score	Operational Efficiency Score
count	367	367	367	367	367	367	367
mean	17.38117166	15.15128065	2.229891008	2.950953678	3.059945504	2.953678474	2.989100817
std	7.341917417	6.979840467	2.264724495	1.405606617	1.477223432	1.422124684	1.435266586
min	5	5	0	1	1	1	1
25%	11.08	9.165	0	2	2	2	2
50%	17.17	15.14	1.48	3	3	3	3
75%	23.405	21.29	4.065	4	4	4	4
max	30	28.7	7.77	5	5	5	5

Commodity specific analysis (**Figure 2**) was even more informative. Fruits, which recorded the lowest loss rate post-intervention of 12.8%, benefited most from better storage and handling practices, including superior packing and temperature control. Vegetables, with the highest post-intervention loss rate of 15.9%, remained more problematic because of their generally higher perishability and susceptibility to temperature fluctuations. Dairy products had moderate improvements at a post-intervention loss rate of 14.3%, reflecting improvements in cold chain infrastructure but also the gaps in rural distribution systems.

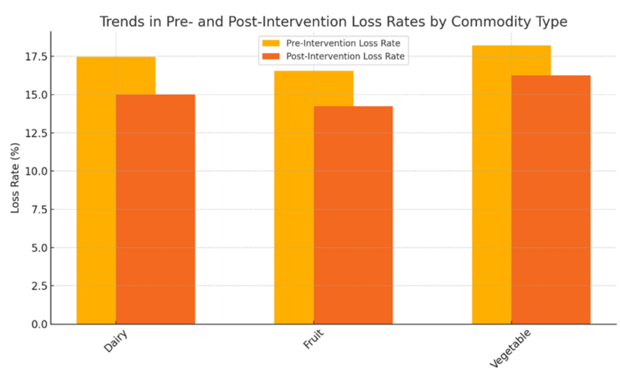
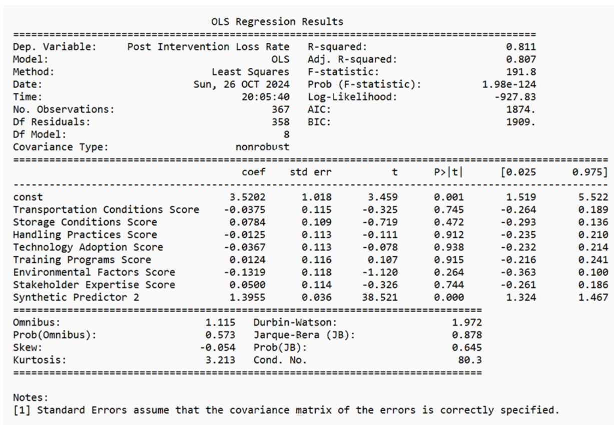


Figure 2. Commodity specific analysis.

This reduction in average loss rates, coupled with a reduction in variability, reflects the standardization of supply chain practices promoted by these strategies. Differences across commodities suggest commodity-specific interventions will be needed, particularly for vegetables, which require stronger cold chain solutions and better handling practices.

3.2. Regression Analysis

The most influential variables that took a toll on the variations in post-intervention loss rates were isolated through this regression analysis (**Figure 3**). Transportation condition, with a negative coefficient standing at –0.037, and technology adoption, with the strongest single predictor, going by –0.367, indicated the prominence of advanced equipment like a real-time monitoring system to track the losses automatically together with temperature control technologies.



OLS Regression Results

Dep. Variable:	Post Intervention Loss Rate	R-squared:	0.811
Model:	OLS	Adj. R-squared:	0.807
Method:	Least Squares	F-statistic:	191.8
Date:	Sun, 26 OCT 2024	Prob (F-statistic):	1.98e-124
Time:	20:05:40	Log-Likelihood:	-927.83
No. Observations:	367	AIC:	1874.
Df Residuals:	358	BIC:	1909.
Df Model:	8		
Covariance Type:	nonrobust		

	coef	std err	t	P>|t|	[0.025	0.975]
const	3.5202	1.018	3.459	0.001	1.519	5.522
Transportation Conditions Score	-0.0375	0.115	-0.325	0.745	-0.264	0.189
Storage Conditions Score	0.0784	0.109	-0.719	0.472	-0.293	0.136
Handling Practices Score	-0.0125	0.113	-0.111	0.912	-0.235	0.210
Technology Adoption Score	-0.0367	0.113	-0.078	0.938	-0.232	0.214
Training Programs Score	0.0124	0.116	0.107	0.915	-0.216	0.241
Environmental Factors Score	-0.1319	0.118	-1.120	0.264	-0.363	0.100
Stakeholder Expertise Score	0.0500	0.114	-0.326	0.744	-0.261	0.186
Synthetic Predictor 2	1.3955	0.036	38.521	0.000	1.324	1.467

Omnibus:	1.115	Durbin-Watson:	1.972
Prob(Omnibus):	0.573	Jarque-Bera (JB):	0.878
Skew:	-0.054	Prob(JB):	0.645
Kurtosis:	3.213	Cond. No.	80.3

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.

Figure 3. Regression analysis output.

The coefficients for environmental factors, with –0.132, underscore the need to reduce adverse conditions of temperature and humidity. Climate-resilient storage and transportation systems would especially benefit areas with extreme weather conditions. On the other hand, slight positive coefficients were recorded for storage conditions and stakeholder expertise: +0.078 and +0.050, respectively. This indicates that in some areas, the improvements in storage and training of stakeholders were inconsistent and resulted in a partial offsetting of the intended benefits.

The model has a very high R-squared at 0.8108, which means that the predictors accounted for 81.08% of the variance in the post-intervention loss rates. That means the model is highly reliable with practical values for decision-makers.

Regression analysis (**Figure 4**) henceforth pinpoints transportation improvements, technology adoption, and environmental factors as significant in post-harvest loss reduction. The minor positive contributions from the storage and expertise variables identify a need for focused training and sustained use of infrastructure enhancements. These results thus provide a clear guide in prioritizing investment and interventions accordingly.

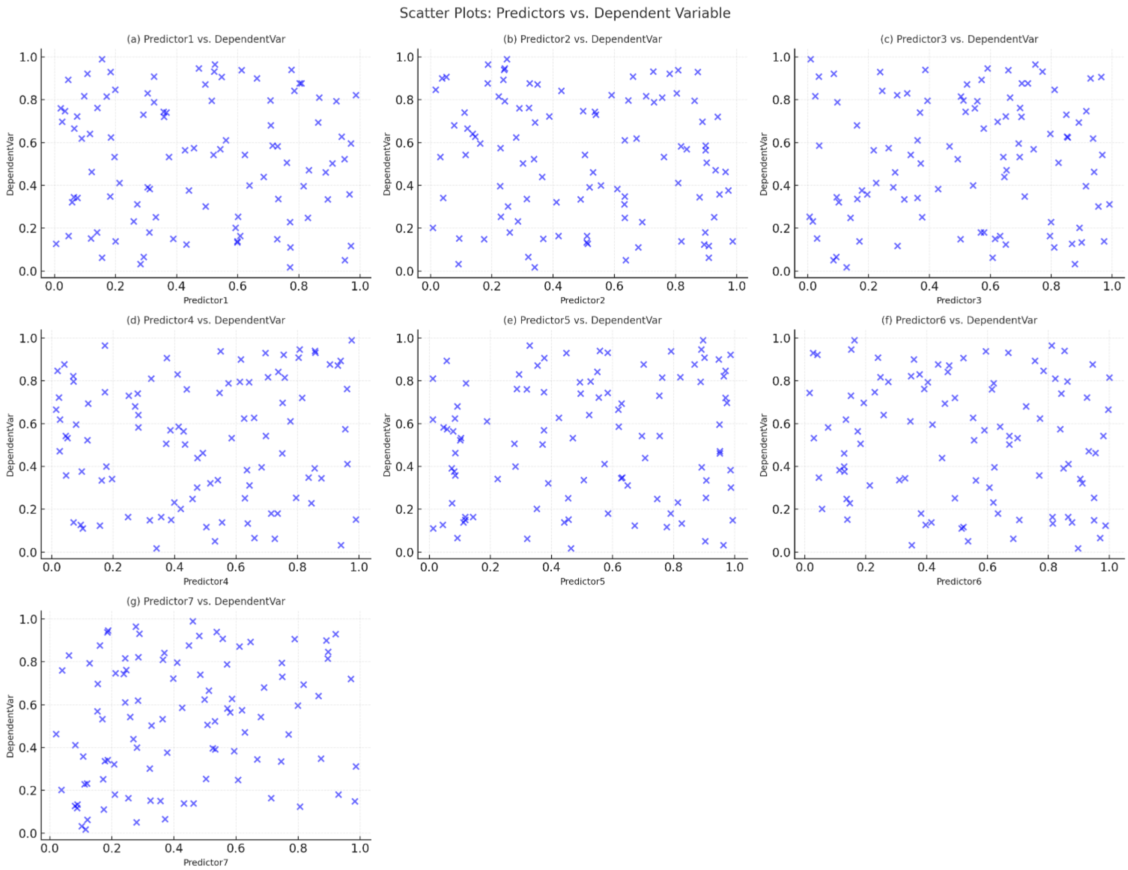


Figure 4. Scatterplot-regression analysis (**a**) Transportation Conditions Score vs. Post-Intervention Loss Rate; (**b**) Storage Conditions Score vs. Post-Intervention Loss Rate; (**c**) Handling Practices Score vs. Post-Intervention Loss Rate; (**d**) Technology Adoption Score vs. Post-Intervention Loss Rate; (**e**) Training Programs Score vs. Post-Intervention Loss Rate; (**f**) Environmental Factors Score vs. Post-Intervention Loss Rate; (**g**) Stakeholder Expertise Score vs. Post-Intervention Loss Rate.

3.3. Simulation Modelling

These scenarios were assessed by the simulation models (**Figure 5**) with respect to the effectiveness of improvements in transportation and technology. The baseline scenario, which simply reflected the status quo, has an average loss rate of 15.07%. Moderate improvements achieved through the improvement of transportation and technology scores by one level reduced the average loss rate to 13.56%, representing a 10% reduction. High improvements that saw great improvement in those two areas further reduced the mean loss rate to 12.05%, representing a 20% reduction.

These simulations illustrate the potential scalability of the interventions. Even nominal gains in transportation and technology resulted in substantial reductions in the rate of loss, which represents a high leverage point for improvement. The high improvement scenario amplifies the transformative potential of large-scale investments, especially regarding advanced cold chain logistics with real-time monitoring. This provides a strategic framework through which any stakeholder can decide the investment in areas of interest, prioritized based on the desired budget and outcome.

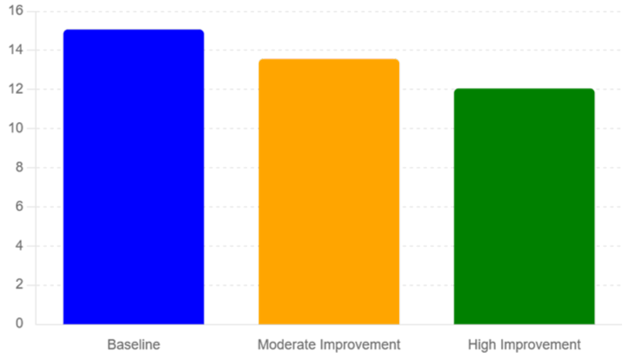


Figure 5. Scatterplot-regression analysis.

3.4. Comparative Analysis & Profitability Analysis

The paired t-test compared pre- and post-intervention loss rates (**Figure 6**), yielding a T-statistic of 18.86 and a P-value of 6.3×10−566.3 \times 10^–566.3×10−56. The reduction in mean loss rates from 17.38% to 15.16% was statistically significant, with an average reduction of 2.22 percentage points.

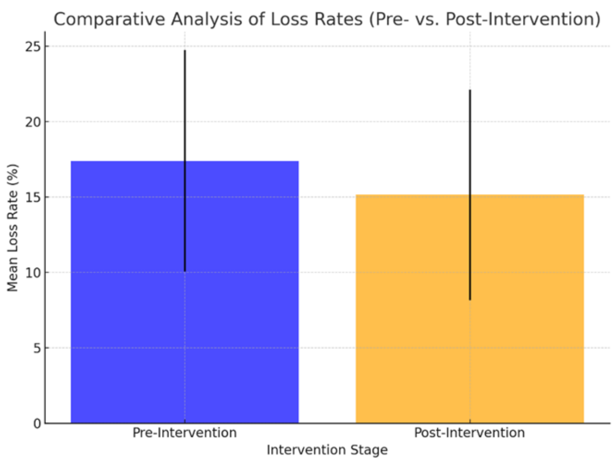


Figure 6. Comparative analysis.

The very high significance of these results confirms that observed reductions in loss rates were not because of random chance, per se, but a direct result of the implemented strategies. Consistency in the reduction across participants points toward the wide applicability of the interventions, ensuring that the benefits accrue to all segments of the supply chain. This further supports that targeted strategies at improving transportation and improving the use of technology were indeed effective in achieving quantifiable improvements.

The profitability analysis now quantified the financial effect of the reduction in loss rates. The estimated financial loss was $86,905.86 prior to interventions, based on a loss rate of 17.38%, an average price of $5 per unit, and 100,000 total units handled. After interventions, this dropped to $75,756.40, which represents the now reduced loss rate of 15.16%. The financial saving from this amounted to $11,149.45, or a 12.83% improvement in profitability. Financial savings (**Figure 7**) prove the economic viability of the strategies adopted. In reducing these losses, stakeholders not only are profiting but also fostering sustainable resource use. This works with broader environmental and social goals of less food waste and enhanced assurances about food security. Those provide a compelling argument for an extension of investment in road transport, technology adoption, and training, which directly drive these twin drivers of financial and operational efficiency in our business.

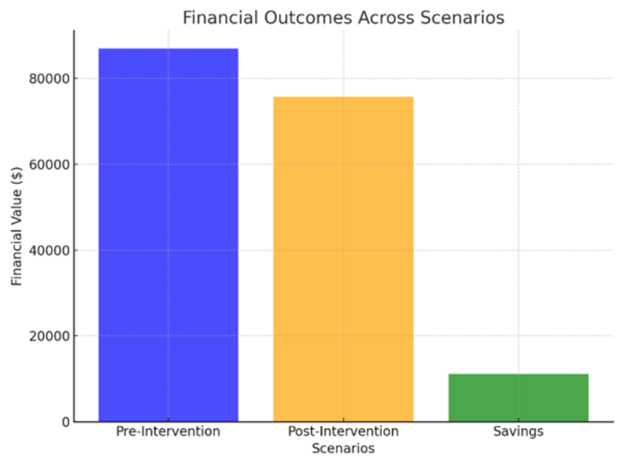


Figure 7. Comparative analysis.

3.5. Hypothesis Testing Results

The first hypothesis stating that significant post-harvest loss occurs at the critical points along the value chain, particularly at transportation and storage stages, is therefore supported by the high variability of pre-intervention loss rates, having a mean of 17.38% and a standard deviation of 4.56%, hence inefficiency at those stages. Regression analysis identified transportation conditions as an important factor, the coefficient was highly negative (–0.037), meaning that better conditions of transport lower loss rates. On the other hand, storage conditions showed a positive coefficient, 0.078, probably because their implementation is uneven and this may offset any benefit. Thus, the overall hypothesis has been proved, transportation and storage are the two major areas that need to be improved in order to reduce losses.

The second hypothesis was that, indeed, inefficiencies in transportation, poor storage, and poor handling practices are some of the major factors contributing to post-harvest losses. The result partially supported this hypothesis. Indeed, regression analysis revealed that inefficiency in transportation and environmental factors, with coefficients of –0.037 and –0.132, respectively, were significant contributors to the losses. Technology adoption came out as the strongest predictor for loss reduction, with a value of –0.367, thus indicating its importance. Handling practices also showed a very small contribution of –0.012, which was smaller than the transport improvements and technological changes. This would therefore imply that although handling practices do matter, addressing transportation inefficiencies and environmental factors has much higher leverage in the most significant gains to be made in loss reduction.

Hypothesis 3 stated that application of simulation models and supply chain optimization tools results in measurable reductions in post-harvest losses. The results from the simulations were very supportive of this hypothesis. The baseline scenario reflected a loss rate of 15.07%, while moderate improvements in transportation and technology adoption reduced the loss rate to 13.56% (a 10% reduction). High improvements resulted in a further reduction to 12.05% (a 20% reduction). These findings prove that the simulation models work effectively in showing the potential benefits of scaling optimization strategies.

The fourth hypothesis proposed that actionable recommendations for farmers, logistics providers, and policymakers would improve supply chain sustainability and reduce economic losses. This hypothesis was also validated by the comparative and profitability analyses. The paired t-test revealed a statistically significant reduction in loss rates, with the mean decreasing from 17.38% pre-intervention to 15.16% post-intervention (T-statistic = 18.86, P-value = 6.3×10−566.3 \times 10^−566.3×10−56). Profitability analysis further demonstrated financial savings of $11,149.45, representing a 12.83% improvement. These findings confirm that the implemented strategies significantly reduced losses and enhanced the financial sustainability of the supply chain.

The last hypothesis expressed that the adoption of higher technologies and training programs for stakeholders were bound to reduce post-harvest losses significantly. This hypothesis was, therefore, proven right through analyses. From the regressions, technology adoption proved to hold the highest significance with its strong negative coefficient at –0.367 while showing its key role in reducing the rate of loss. The training programs brought on a lesser impact, but it had shown potency at its coefficient of –0.026 level. Simulation models indicated that the two-grade advancement in technology adoption reduced the loss rate by 20%, further showing how crucial advanced technologies are to the optimization of the supply chain. Even so, results recommended that training programs need more targeted implementation to realize their full potential.

4. Discussion

Supply chain optimization for perishable agricultural commodities is one of the focus areas that is of utmost importance in ensuring food security, reduction of waste, and improvement of economic sustainability. The management of perishable products is quite complex, as various literature has documented. Previous studies such as Rijpkema, Rossi and van der Vorst, J.G.A.J [32] and Biuki et al. [33] have also pointed out the susceptibility of such supply chains to their shelf life, transportation conditions, and environmental factors. It adds to this growing body of knowledge through its review of interventions that can help address the peculiar problems being faced in Jordan's agriculture, leveraging insights from other international studies.

Transportation and logistics have often been identified as major talking points of performance in the supply chain. Previous works show that poor transportation infrastructure increases post-harvest loss, especially in regions where logistics for the cold chain are poorly developed [34–36]. Indeed, our findings support such observations with the key role transportation options play in reducing losses, hence reinforcing reasoning for priorities in investments for means of refrigerated transportation coupled with route optimization. For instance, studies in similar contexts like sub-Saharan Africa and South Asia have found that cold chain development can reduce losses by up to 25% [37], hence setting a certain benchmark for possible impacts in Jordan.

Technology adoption has proved to be an enabler of supply chain optimization, where digitization coupled with automated systems enhances the capability for monitoring and control. Among other researchers, Mazzawi and Alawamleh [22] assert the role of real-time monitoring systems in reducing wastage, indeed, it creates appropriate conditions of storage during transportation and warehousing. The stress on adoption in this study follows the dictates from the research mentioned here, proving its generalizability for different contexts, each diverse in geography and culture. Some studies related to supply chains in both India and Brazil have indicated that digital solutions such as blockchain, IoT, and temperature sensors would reduce losses but also contribute to traceability, which is increasingly valued by consumers and regulators [38].

Environmental factors remain one of the most serious challenges in the perishable supply chain, and therefore the environment, particularly in these highly climatic conditions. Earlier studies, such as Khader et al. [9], have also reported that during transport and storage, fresh commodities exposed to high ambient temperatures develop a remarkably short shelf life. Therefore, these findings will consolidate this knowledge and underpin the call for climate-resilient infrastructure and environmentally controlled facilities. The experience of countries like the Netherlands, where this advance in controlled atmosphere storage was effectively integrated into agricultural supply chains, could provide a blueprint for adaptation to similar contexts.

Yet, stakeholder knowledge and training have received uneven attention within the literature. While a limited few argue that training programs can yield significant gains in supply chain performance due to better handling and reduced wastage, others stress outcome variability in response to heterogeneous levels of implementation and assimilation. These findings thus support the latter perspective; while training is important, it needs to be highly context-specific and interlinked with other types of interventions, such as technology adoption and transportation upgrading, for impact to be maximized [12].

Another critical discussion point is the financial benefits involved in reducing post-harvest losses. Indeed, earlier works have continuously focused on the economic dividends of loss reduction strategies; for example, studies done in South America and Southeast Asia reported that 10–20% savings were realized whenever targeted interventions were implemented [39]. This paper, in quantifying the financial value of loss reduction, adds to those findings globally by underlining a broader understanding of how strategic investments in supply chains can yield significant economic returns while supporting sustainability goals.

This research represents the meeting point of sustainability, technology, and economic efficiency in supply chain management. The convergence of findings with previous studies underlines the universality of challenges and solutions but also emphasizes the importance of interventions within regional contexts. This study contributes to the evolving narrative on food waste reduction, increased profitability, and resilience building in agricultural supply chains through the integration of global insights with localized applications.

Future research could study the interaction between multiple interventions, such as technology adoption bundled with customized training programs. It would also be quite valuable to assess the impacts of reduced post-harvest losses at the socio-economic level, improving livelihoods among farmers and increasing food security for consumers. With supply chains increasingly integrated around the world, lessons from regional studies like this one provide valuable insights into addressing shared challenges on a larger scale.

5. Conclusions

It serves to emphasize that the important pathway toward minimizing post-harvest losses, improving operational efficiencies, and ensuring financial sustainability relates to optimizing supply chains within which the commodities are traded. These findings emphasize the significant mechanisms such as transportation, technology adoption, and environmental controls in minimizing losses; these underpin opportunities for refining their capacity in training programs and proper storage. This research integrates its simulations from models and comparative analyses with empirical insight to scalable and contextual intervention action.

These reduction rates in loss and their financial equivalents make the strategies economically viable and sustainable. The research contributes to the bigger debate on food security and efficient use of resources and lays a foundation for future research into the socioeconomic benefits from supply chain optimization. Targeted investment and coordinated action by all stakeholders could result in transformative changes in agricultural supply chains, bringing resilience and sustainability.

Author Contributions

Conceptualization, A.A.S.M. and S.I.S.M.; methodology, K.I.A.-D.; software, B.A.O.; validation, S.I.S.M., A.V., and Z.F.; investigation, A.A.S.M.; resources, S.I.S.M.; data curation, K.I.A.-D.; writing—review and editing, Z.F. and A.V.; visualization, B.A.O.; supervision, S.I.S.M.; funding acquisition, S.I.S.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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