Professional paper

IMPROVING THE SUSTAINABILITY OF AGRI-FOOD SUPPLY CHAIN IN CROATIA WITH A FOCUS ON FOOD PROCESSING AND STORAGE

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Abstract: The agri-food supply chain in Croatia has received increasing attention due to its essential role in ensuring food security, public health, and sustainability. Given rising climate variability, disruptions in global markets, and the need for sustainable development, strengthening the efficiency and resilience of the domestic food supply system is becoming a national priority. This paper examines ways to improve the organisation of agricultural processing and storage in Croatia, with particular emphasis on identifying optimal locations for new food storage facilities. It considers key factors such as the geographic distribution of agricultural production, seasonality, transport networks, and logistical efficiency. The analysis addresses important challenges related to supplier coordination, transport, and the distribution of goods across regions. It also accounts for uncertainties in supply and demand, reflecting real-world variability and risk. The results indicate that significant operational improvements are possible, including potential cost savings of up to 4.1%. These improvements could lead to more stable, sustainable, and efficient food distribution systems, particularly in rural and underdeveloped areas. By offering a strategic approach to planning investments in storage infrastructure and food logistics, this research supports national goals related to rural development, food independence, and environmental sustainability. The insights provided can assist policymakers and stakeholders in making informed decisions that enhance the long-term resilience and effectiveness of the Croatian agri-food sector.

Keywords: sustainability, distribution, food security, regional development, food supply independence

1. INTRODUCTION

Agricultural supply chains are essential for ensuring food security, economic stability, and sustainable development. In Croatia, key commodities such as fruit, vegetables, and cereals are important not only for domestic consumption but also for export, contributing significantly to the country's economic growth. As international and regional standards increasingly emphasize sustainability, health regulations, and climate resilience, optimizing supply chain operations, particularly in storage and processing, has become a strategic priority (Mikulić et al., 2023; Wang et al., 2024). This study proposes an integrated planning model for the development of storage infrastructure in the Croatian agri-food sector. The model aims to increase operational efficiency, minimize post-harvest losses, and improve cost efficiency throughout the value chain. Climate change has exacerbated fluctuations in agricultural production, increasing risks to food availability, quality, and pricing. Modern storage solutions serve as critical buffers that mitigate seasonal supply fluctuations and disruptions while supporting food security and economic stability (FAO, 2015). This research promotes the integration of spatial optimisation models, predictive analytics, and decision support systems with smart technologies such as IoT-enabled sensors and real-time inventory tracking. These innovations facilitate evidence-based policymaking and unlock investment opportunities in agricultural and food logistics and infrastructure (FAO, 2015). The development and optimisation of food storage infrastructure are essential to ensure food safety. In many emerging countries, including Croatia, post-harvest losses remain a major obstacle (Gill & Sharma, 2021; Matin et al., 2024). The establishment of modern, strategically located storage facilities can significantly increase supply security, stabilise market prices, and improve farmer profitability. Such advances not only strengthen economic resilience but also contribute to a more stable and affordable food supply. Furthermore, these initiatives align with national climate adaptation strategies and promote sustainable agricultural practices that balance economic development and environmental protection. Investments in storage infrastructure thus represent a highly effective measure with far-reaching social, economic, and environmental benefits that support the long-term sustainable development of the Croatian agri-food sector (Diakosavvas & Frezal, 2019). To effectively improve the resilience and competitiveness of the Croatian food supply chain, a coordinated framework is needed that aligns technological innovation with strategic policy and investment planning. Collaboration between government agencies, industry stakeholders, and research institutions will be critical to ensure that infrastructure development supports national goals of food security, economic growth, climate adaptation, and environmental sustainability (Wang et al., 2021). These considerations are particularly relevant for staple crops such as wheat, which are central to both Croatian agriculture and the global food system. Efficient storage management has a direct impact on product quality, market availability, and price stability, with significant implications for food safety and public health. Given the increasing unpredictability of climate and markets, strategic, data-driven supply chain management is essential (Du et al., 2022; Lisboa et al., 2024). The priorities outlined are closely aligned with global sustainability frameworks, particularly the United Nations Sustainable Development Goals (SDGs), which emphasize the importance of resilient infrastructure and reducing food loss as key strategies for climate action and combating hunger (UNDP, 2015). This analysis is based on Croatian agricultural statistics and focuses on the overall capacity and utilization rates of existing storage facilities. The data includes information from various counties in Croatia, summarized in Table 1.

Table 1: Capacities of Storage Facilities in Croatia

County	Total Capacity (t)	Cold storage (t)
Koprivničko-Križevačka	4.807	3.732
Krapinsko-Zagorska	180	N/A
Međimurska	9.985	6.010
Osječko-Baranjska	12.225	8.980
Sisačko-Moslavačka	6.350	4.823
Varaždinska	2.312	N/A
Virovitičko-Podravska	2.725	1.800
Zagrebačka	20.804	18.824
Grad Zagreb	17.802	8.536
Požeško-Slavonska	3.100	3.000
Karlovačka	420	N/A
Vukovarsko-Srijemska	22.685	N/A
Bjelovar-Bilogorska	0	N/A
Brodsko-Posavska	0	N/A
TOTAL	**103.395**	**55.705**

1.1. Role of fruits, vegetables, and cereals in Croatia's agri-food supply chain

Fruits, vegetables, and cereals form the core of Croatian agricultural production and are fundamental for ensuring national food security, rural employment, and macroeconomic stability. These crop groups represent a significant share of total agricultural output and are deeply integrated into the country's socio-economic structure (Croatian Statistical Office, 2025a; 2025b). Their importance is further reinforced by national agricultural development strategies and supranational policy frameworks, particularly the European Union's Common Agricultural Policy (CAP), which emphasizes sustainable agriculture, investment in infrastructure, and climate-resilient farming systems. Due to seasonality and susceptibility to climate variability, the stability and efficiency of supply chains for these commodities are increasingly vulnerable to production and market disruptions. In this context, improving the performance of post-harvest processes – especially handling, processing, and storage – is critical to reducing quantitative and qualitative losses, maintaining product quality, and improving supply chain continuity (European Commission, 2025). Strategic investment in modern, commodity-specific storage infrastructure provides a pathway to improved shelf life, price stabilization, and greater supply chain adaptability to environmental stressors and market fluctuations. For Croatia, this requires developing an integrated approach to supply chain management that balances production capacity with warehouse availability, demand forecasting, and distribution logistics. Such improvements are crucial for building a resilient, efficient, and sustainable agri-food system capable of responding to both current challenges and future uncertainties arising from climate change and evolving market dynamics.

1.2. Economic importance of fruits, vegetables and cereals and their implications for the agri-food supply chain

Fruit, vegetables and cereals are fundamental components of the Croatian agricultural sector, contributing significantly to national food security, rural economic development and overall economic resilience. Their production reflects the diversity of Croatia's agro-ecological zones and underscores the urgent need for robust, adaptable supply chain planning to ensure long-term sustainability and performance. A wide variety of fruits and vegetables are grown in Croatia under both Mediterranean and continental climatic conditions, including olives, grapes, apples and peppers. In 2024, vegetable production amounted to approximately 210,000 tonnes, while fruit production reached about 128,000 tonnes. Compared to 2022, vegetable production decreased slightly by 0.5%, while fruit production increased by 1.1% (Ministry of Agriculture and Forestry, 2024). These crops are predominantly produced by smallholder farmers, family farms and agricultural cooperatives, forming an essential part of rural livelihoods and contributing to local market systems. Beyond their economic value, fruit and vegetables also provide significant nutritional benefits. They are rich in fiber, vitamins, minerals and antioxidants, and play an important role in reducing the risk of non-communicable diseases and improving public health outcomes. The World Health Organisation (WHO, 2023) has emphasized the importance of increasing fruit and vegetable consumption to address the rising prevalence of obesity and diet-related diseases. To achieve these goals, supply chain efficiency must be improved through strategic investments in cold storage infrastructure, advanced post-harvest processing technologies and broader market access. Cereals – especially wheat, maize and barley – form the structural backbone of Croatian agriculture. They occupy about a third of the country's arable land and contribute around a fifth of the total agricultural production value. Croatia's high level of self-sufficiency in grain supports both national food security and the export potential of agriculture, with wheat being particularly important as a staple food and strategic raw material (Ministry of Agriculture, 2024). Nevertheless, grain production remains vulnerable to climate fluctuations. In 2023, the production of maize grain increased by 20.2%, silage maize by 24.3%, alfalfa by 9.9%, potatoes by 9.7% and soya beans by 4.1%. In contrast, wheat (-14.2%), oats (-29.2%), rapeseed (-25.9%), sugar beet (-12.6%) and barley (-10.1%) recorded significant declines compared to the previous year (Croatian Statistical Office, 2024). These fluctuations highlight the need for resilient agricultural practices such as crop diversification, crop rotation and conservation agriculture to ensure stable production and maintain soil fertility under increasingly variable environmental conditions (Jat et al., 2025). To support the effective management and distribution of these critical crops, integrating production systems with modern supply chain solutions is essential. This includes investment in climate-resilient storage infrastructure, real-time logistics tracking and advanced planning methods such as mixed-integer linear programming (MILP) models. These tools enable stakeholders to reduce post-harvest losses, stabilise market supply and increase the overall adaptability and efficiency of the agri-food supply chain in response to climatic and economic uncertainties.

1.3. Post-harvest losses and storage solutions

Despite the crucial role that fruit and vegetables play in national food systems, post-harvest losses remain a major challenge, mainly due to inadequate storage infrastructure and inefficient supply chain management. In both developing and emerging economies, a significant proportion of agricultural produce is lost before reaching consumers, disproportionately affecting smallholder farmers and rural communities. The Food and Agriculture Organisation of the United Nations (FAO, 2025) estimates that between 30% and 40% of global agricultural production is lost after harvest, primarily due to improper use of inputs, insufficient storage capacity, limited processing infrastructure, and inadequate transport systems. Losses are particularly pronounced for perishable crops, with estimated losses of 40–50% for fruit, vegetables, and root crops, 30% for cereals and fish, and 20% for oilseeds. These inefficiencies contribute to food insecurity, lower agricultural incomes, and environmental pollution throughout the value chain. In the Croatian context, improving the efficiency, capacity, and technical sophistication of storage infrastructure represents a strategic opportunity to reduce food spoilage and waste. By modernizing existing facilities and developing new, strategically located storage centers, post-harvest losses can be significantly reduced, directly contributing to national food security and sustainability goals. The adoption of advanced storage technologies, including controlled atmosphere storage, vacuum cooling systems, and robust cold chain logistics, is essential for extending shelf life and maintaining the quality of perishable produce (Wills & Golding, 2016). Such innovations not only preserve product integrity for domestic markets but also improve the competitiveness of Croatian agricultural and food exports.

1.4. Innovations in processing and storage of cereal crops

The sustainability of Croatian agricultural and food supply chains increasingly depends on effective cooperation between farmers, policymakers, researchers, and private sector actors. Climate change poses significant risks to agricultural productivity and supply chain stability, particularly in Mediterranean regions, which are vulnerable to changing precipitation patterns, temperature extremes, and water scarcity (Tchonkouang et al., 2024). Therefore, the development and deployment of climate-resilient crop varieties bred to tolerate abiotic stresses such as drought, salinity, and heat are crucial. Strategic investment in agricultural research and development (R&D) remains essential to promote innovations in plant genetics, resource-efficient farming methods, and adaptive technologies (FAO, 2018). Building resilient agricultural systems capable of producing stable yields under unfavourable conditions is fundamental to ensuring a consistent and diverse supply of fruits, vegetables, and cereals. These advances contribute directly to national food security and strengthen the economic resilience of rural communities. However, technological innovation must be complemented by effective management of biological threats, including the increasing incidence of pests and diseases due to climate variability. Integrated pest management (IPM) provides a science-based framework to reduce reliance on synthetic agrochemicals while improving environmental sustainability. IPM integrates biological control agents, crop rotation, habitat management, and judicious use of pesticides to maintain plant health and promote biodiversity. The widespread adoption of IPM aligns with the environmental objectives of the European Union, including the European Green Deal and the Farm to Fork Strategy (Yarahmadi & Rajabpour, 2024). Cross-sectoral collaboration between academic institutions, extension services, agricultural cooperatives, and policy institutions is crucial to facilitate knowledge transfer and build local capacity. Educational programmes and participatory research empower farmers to implement sustainable practices tailored to their regional agroecological conditions. In addition, the integration of digital agricultural tools and decision support systems improves monitoring, early warning, and adaptive capacity, thus strengthening the resilience of the agricultural and food system (Prajapati et al., 2025). Ensuring the long-term sustainability of the Croatian food supply chain requires a holistic and multidisciplinary approach. By integrating technological innovation, evidence-based policymaking, and active stakeholder engagement, Croatia can build a more adaptable, productive, and environmentally sustainable agricultural sector capable of meeting future challenges.

1.5. Sustainability and climate resilience

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1.6. Scenario analysis

To account for fluctuations in domestic supply and demand for fruit, vegetables, and cereals, several scenarios were developed, including optimistic, pessimistic, and realistic market conditions. This scenario-based modelling approach provides a systematic and robust framework for examining a range of possible future outcomes and allows policymakers and stakeholders to evaluate strategic options under different plausible market conditions. By simulating various conditions, these scenarios help identify vulnerabilities and opportunities in the Croatian agri-food sector. Such analyses support informed decision-making and increase the resilience of supply chains in the face of uncertainty, thus contributing to the development of adaptation strategies that ensure food security and economic stability (Moallemi et al., 2025).

1.7. Mathematical models used in scenario based agricultural market analysis

One of the most frequently used approaches in agricultural market research is the partial equilibrium model, which focuses on supply, demand, and price formation within a single sector. These models enable the simulation of market reactions to changes in yields, import patterns, or policy interventions, providing clear insights into market adjustments under different scenarios. Their relevance in agri-food analysis is well documented in the works of Britz and Witzke (2014), who developed comprehensive partial equilibrium frameworks for European agricultural markets. Complementing this perspective, computable general equilibrium (CGE) models analyse interactions across the entire economy. In the context of the agri-food sector, CGE models make it possible to assess how changes in agricultural production or prices influence other economic sectors, household incomes, and trade flows. Their methodological foundations are extensively presented in Dixon and Jorgenson's Handbook of Computable General Equilibrium Modeling (2013) and Hertel's Global Trade Analysis (1997), both of which demonstrate the utility of CGE modelling in agricultural policy evaluation. In situations where forecasting is required, econometric time-series models, such as ARIMA, VAR, or error-correction models, play a crucial role. These models rely on historical data to estimate future values of production, consumption, or prices, making them essential tools in scenario construction. The classical works of Pindyck and Rubinfeld (2018) provide a solid theoretical and practical foundation for the use of econometric forecasting tools in agricultural market research. Another approach that has proven valuable in analysing complex systemic interactions is system dynamics modelling. By representing production, consumption, storage, and distribution as interconnected stocks and flows, system dynamics models allow researchers to simulate the long-term behaviour of agricultural systems under uncertainty. This methodology is particularly useful for identifying structural bottlenecks and feedback loops that may amplify market disruptions. While system dynamics captures aggregate behaviour, agent-based modelling (ABM) focuses on interactions among individual actors such as farmers, processors, or consumers, whose decisions collectively shape market outcomes. ABMs are particularly effective in scenarios involving behavioural changes, market imperfections, or heterogeneous adaptation strategies. Foundational works by Wilensky and Rand (2015) demonstrate the applicability of this approach in agricultural contexts. In addition to simulation-based approaches, many studies rely on optimisation and linear programming models, which identify optimal resource allocation strategies given constraints related to land, labour, capital, or policy requirements. These models are widely used to determine efficient production plans, supply chain configurations, or input use (Williams, 2013). Given the inherent uncertainty in agricultural production, stochastic models and Monte Carlo simulations are often employed to incorporate variability in yields, prices, or demand. By generating a distribution of outcomes, these models facilitate risk assessment and help identify critical points of vulnerability within the supply chain. The works of Hardaker et al. (2015) highlight the importance of probabilistic approaches in agricultural risk analysis. Alongside partial and general equilibrium models, econometric forecasting techniques, system dynamics, agent-based models, and stochastic simulations, mixed-integer linear programming (MILP) serves as a complementary optimisation tool that translates these analytical insights into cost-efficient, resource-constrained decisions for agricultural supply chains, particularly under conditions of uncertainty.

2. MATERIALS AND METHODS

In this study, a mixed-integer linear programming (MILP) model was developed to optimise the agri-food supply chain in Croatia. The objective of the model is to minimise total supply chain costs while ensuring demand fulfilment, efficient inventory utilisation, and informed investment planning. The model comprises the following key components:

1. Supplier selection and order planning – identification of domestic and international suppliers based on cost-efficiency, reliability, and quality criteria (Lee et al., 2024).
2. Transport and storage planning – optimisation of transportation routes and storage strategies to minimise total logistics costs and enhance system-wide operational efficiency (Stopka et al., 2022).

3. Capacity planning – determination of required capacity for existing and newly proposed storage facilities, accounting for infrastructure constraints and projected future demand (Lambiase et al., 2015).

The model operates across multiple time periods and product categories, incorporating seasonality, demand variability, and commodity-specific requirements. Inventory levels are tracked dynamically, while binary decision variables represent the activation of storage facilities, including their associated fixed and operational costs. To enhance resilience and adaptability, the MILP model integrates scenario-based programming, enabling assessment under alternative supply and demand conditions, including disruptions related to climate variability, market volatility, and policy changes. In the context of the Croatian agri-food sector, MILP provides a robust analytical framework for evaluating supply chain strategies under uncertainty and resource constraints. By integrating seasonal production patterns, storage limitations, and market demand, the model supports cost-efficient and strategically targeted infrastructure planning. Scenario-based extensions further allow policymakers to evaluate potential shocks, such as climate-related yield fluctuations or economic disturbances, and design adaptive measures to safeguard food security and rural livelihoods. All decisions within the model are constrained by supply availability, storage capacity, demand fulfilment requirements, and inventory balance equations, ensuring internal consistency and operational feasibility throughout the supply chain. Overall, the proposed MILP framework provides a data-driven basis for evidence-based policy development, infrastructure investment decisions, and long-term planning in the Croatian agri-food logistics sector.

3. CONCLUSION

The Croatian agri-food supply chain is vital for maintaining national food security, public health, and sustainable rural development, especially amid increasing climate variability, market instability, and evolving regulatory requirements. This study shows that mixed-integer linear programming (MILP), when applied to the spatial and logistical characteristics of the Croatian food system, provides a robust analytical foundation for optimising storage infrastructure, reducing operational inefficiencies, and strengthening overall supply chain resilience. By integrating detailed data on existing storage capacities across counties, the MILP model captures significant regional disparities, ranging from counties with no storage infrastructure to those with substantial cold storage capacity. These imbalances are explicitly incorporated into the optimisation framework through capacity constraints, enabling the model to identify the most cost-efficient locations for new storage facilities and the optimal utilisation levels of existing ones. In this way, the model translates static capacity data into dynamic, operationally meaningful decisions. The MILP approach also incorporates seasonality, multi-period planning, variable demand patterns, and product-specific storage requirements – elements crucial for Croatia's fruit, vegetable, and cereal supply chains. Through scenario-based extensions, the model evaluates system performance under optimistic, realistic, and pessimistic conditions, revealing that improved allocation of storage capacity, better routing decisions, and more balanced supplier coordination can collectively yield cost savings of up to

4.1%. This demonstrates that the optimisation logic embedded in the MILP structure is not only theoretically robust but also practically impactful. Furthermore, the model's ability to represent infrastructure activation via binary variables ensures that investment decisions – such as opening new storage sites in counties currently lacking capacity – are based on a rigorous assessment of both fixed and variable costs. This provides policymakers with a transparent, data-driven tool for designing long-term development strategies aligned with rural development goals and food security priorities. Beyond quantifying cost reductions, the MILP framework highlights the strategic value of modern storage technologies, improved logistics, and better coordination across actors in the agri-food system. When combined with innovations such as digital monitoring, advanced post-harvest management, and climate-adaptive practices, the optimised storage network can significantly reduce post-harvest losses and enhance product quality across the supply chain. Overall, the MILP model developed in this study offers a scientifically grounded and operationally actionable pathway for strengthening the Croatian agri-food sector. By linking regional production patterns, storage capacity constraints, climate and market uncertainties, and logistical considerations into a single optimisation framework, the study provides a robust basis for evidence-based decision-making. These insights are essential for building a competitive, resilient, and environmentally sustainable food system capable of meeting Croatia's current and future needs.

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