Jurnal Teknologi dan Manajemen Industri Terapan (JTMIT) Vol. 4, No. 3, September 2025 pp. 993 - 1006
P-ISSN: 2829-0232 E-ISSN: 2829-0038

A Mixed-Integer Linear Programming Model for the Rice Supply Chain in Karawang Regency to Minimize Costs

Annisa Indah Pratiwi[1,2], Agus Mansur[1*], Syafa Thania Prawibowo[3]
[1)] Departement of Industrial Engineering, Faculty of Industrial Technology, Univesitas Islam Indonesia
Yogyakarta, Indonesia 55584
Email: 24936003@students.uii.ac.id, agusmansur@uii.ac.id
[2)] Departement of Industrial Engineering, Universitas Buana Perjuangan Karawang
Jl. Ronggo Waluyo Sirnabaya, Puseurjaya, Telukjambe Timur, Karawang, Jawa Barat 41361
Email: 24936003@students.uii.ac.id
[3)] Department Industrial Management, National Taiwan University Science and Technology
Keelung Rd, Da'an District, Taipei City, Taiwan 106
Email: M11301827@mail.ntust.edu.tw

ABSTRACT

The rice supply chain in Indonesia plays a vital role in national food security, where efficient distribution ensures price stability and availability in the market. However, the complexity of multi-echelon systems often leads to inefficiencies in procurement, production, and distribution. This study aims to develop a Mixed-Integer Linear Programming (MILP) model to optimize the rice supply chain in Karawang Regency, focusing on cost minimization while integrating environmental and risk considerations. Using dummy data on supply, demand, production, distribution, labor, and emissions, the model was tested with Microsoft Excel Solver. The results show that procurement from farmer groups is the largest cost component (51.24%), followed by production (23.96%) and distribution (23.19%), with a total cost of USD 1,783,113,142. Optimization achieved a 13% cost reduction and a 9% emission reduction compared to non-optimized conditions, while risk assessment identified M2–J2 supply (RPN = 20) and J1 production (RPN = 16) as the most critical hazards. These findings suggest practical implications for Perum Bulog and policymakers, including strengthening procurement planning, optimizing warehouse allocation, and adopting cleaner production technologies to improve both efficiency and sustainability. The novelty of this study lies in integrating hazard-based risk assessment with MILP for a regionally strategic rice supply chain, while simultaneously considering cost efficiency and carbon emission constraints. This provides both theoretical contributions to sustainable supply chain optimization and practical strategies for policy driven food security.

Keywords: *Rice, Supply Chain, Mixed Integer Linear Programming, Cost*

Introduction

Rice is one of the world's most important food crops. In international trade, rice holds a crucial position as a food crop, necessitating effective management of supply and demand [1]. The agricultural supply chain, particularly for food, encompasses a range of processes, from planting and harvesting to distribution. Good process integration can reduce costs and environmental impacts; ensuring a sufficient supply is the primary goal of food supply chain management [2]. Rice production can be a reliable source of income if all stakeholders coordinate proper supply chain management, as rice is a strategic commodity in the food chain for both the public and the government. The rice supply chain comprises various elements, including farms, rice mills, distribution centers, and markets [3]. A bi-objective mathematical model is formulated to minimize total costs as an economic objective and minimize soil erosion and damage resulting from water consumption for rice cultivation as an environmental sustainability objective [4]. The supply chain cycle is complex because it involves various stakeholders located in different geographic regions. Each stakeholder involved plays a role in the supply chain process by managing their resources to achieve optimization [5]. SCM aims to reduce total costs and provide a fast and effective response to customers by integrating supplier entities, core manufacturing companies, and third-party logistics. The primary context of supply chain management encompasses supplier selection, network design planning, production planning, inventory control, as well as transportation and distribution [6]. There are many stages in a multi-stage model that include warehouses and distributors. A supply chain is a network of suppliers, manufacturers, and distribution centers that transform raw materials into usable products through several stages and distribute them to retailers in one or more stages [7] [8].

According to FAOSTAT [9], in 2018-2019, rice was planted in 118 countries on an area of 167 million hectares, resulting in a global annual grain production of approximately 782 million tons. Indonesia is the third largest rice producer in the world (83 million tons) after China (more than 214 million tons) and India (more than 172 million tons), followed by Bangladesh (56 million tons), Vietnam (44 million tons), Thailand (32 million tons), and Myanmar (25 million tons). Indonesia's national rice consumption is among the highest in the world. However, despite its importance, Indonesia has experienced a decline in rice production in recent years. According to the Central Statistics Agency (BPS), in 2024 the total rice production in Indonesia reached 24,935,763 tons, indicating a potential imbalance between supply and demand. This imbalance has become a strategic concern, given that food security is a key focus in the government's strategic plan [10]. Bulog, as a state-owned enterprise, plays a crucial role in stabilizing rice supply and distribution, ensuring availability, and maintaining national stocks for welfare assistance [11].

The complexity of the rice supply chain makes it highly vulnerable to fluctuations in production, demand, and distribution. The flow of goods and services fosters economic relationships between sectors and enables the dissemination of impacts resulting from changes in multiple sectors [12]. In addition, supply chain performance is increasingly influenced by sustainability considerations, including the effects of demand fluctuations and carbon emission policies [13]. These dynamics highlight the need for robust optimization approaches to support decision-making in rice supply chain management. Although traditional optimization methods such as linear programming (LP) have been widely applied, they often lack the capability to accommodate discrete decisions such as facility opening/closing, vehicle allocation, and production scheduling. Mixed-Integer Linear Programming (MILP), on the other hand, provides greater flexibility by integrating both continuous and discrete variables, making it highly suitable for designing and managing complex supply chain networks [14] [15].

Despite the strategic importance of rice in Indonesia, most existing studies on agricultural supply chain optimization focus on generic food systems, global trade, or single-objective optimization, with limited emphasis on rice as a strategic commodity at the regional level. Moreover, while some research employs heuristic or simulation-based approaches, these methods may not guarantee optimality in large-scale planning problems. In contrast, MILP enables simultaneous consideration of supplier selection, planting, fertilization, pest control, harvesting, milling, transportation, and distribution, thereby ensuring an integrated solution [2][16]. However, the application of MILP specifically for the rice supply chain in Karawang Regency, a region often referred to as the "rice barn of Indonesia," remains underexplored. Therefore, this study aims to develop a Mixed-Integer Linear Programming (MILP) model for the rice supply chain in Karawang Regency, with the primary objective of minimizing total costs while ensuring supply reliability. The academic contribution of this research lies in extending the application of MILP to a regionally strategic food supply chain, providing methodological insights into agricultural supply chain optimization, while the practical contribution lies in offering decision-making support for local governments and supply chain actors, including Bulog, to enhance food security and cost efficiency in rice distribution.

Research Method

This study employs a quantitative modeling approach using Mixed-Integer Linear Programming (MILP) to optimize the rice supply chain in Karawang Regency. The methodology integrates risk assessment into the model formulation to ensure that the proposed solution is not only cost-efficient but also robust against potential operational hazards. The methodological stages are described as follows.

Problem Identification and Case Selection

The rice supply chain is one of the most strategically important agricultural systems in Indonesia, both economically and socially. Karawang Regency, often referred to as the "rice barn of Indonesia," plays a central role in supplying rice at both regional and national levels due to its high productivity. Data from the Central Statistics Agency (BPS) indicate that Karawang contributes a significant share of West Java's rice production, making it a critical component of Indonesia's food security framework. However, the region faces challenges such as fluctuating supply caused by seasonal harvest variations, unstable market demand, and cost volatility in logistics and storage. These dynamics lead to inefficiencies that threaten both cost effectiveness and the stability of rice availability. Perum Bulog Karawang helps stabilize the system by procuring paddy from two farmer groups (m1 and m2), processing it into premium rice (p1) and government reserve rice (p2) at two branches in Karawang City (j1) and Jatisari (j2), and distributing it through two warehouses (l1 and l2) to meet consumer demand.

The selection of Karawang Regency as the case study is based on two main considerations. First, as one of Indonesia's largest rice producers, it serves as a representative and high-impact study area where optimization can generate insights relevant to broader food security strategies. Second, its operational structure, consisting of multiple suppliers, two processing centers, two rice product categories, and several warehouses, creates a multi-echelon system that is well-suited for analysis using Mixed Integer Linear Programming (MILP). The main problem addressed in this study is the high operational cost and inefficiencies arising from uncoordinated management of supply and demand fluctuations, cost variability, and resource constraints. Without optimization, Bulog risks redundant transportation, uneven inventory distribution, dependence on specific supplier–plant linkages, and production bottlenecks. These issues increase costs and undermine Bulog's mandate of ensuring affordable and stable rice availability. Hence, Karawang provides an ideal case for developing an MILP model that integrates economic, environmental, and social dimensions into a unified decision-support framework.

Hazard Identification and Data Collection

Critical hazards in the supply chain were identified to capture potential risks in procurement, production, distribution, inventory, and workforce allocation. Data collection employed a triangulation method:

a. Direct Observation : Site visits at Bulog branch offices and farmer groups to record fluctuations in supply, transportation bottlenecks, and warehouse limitations.
b. Worker and Staff Interviews : Semi-structured interviews with employees, logistics coordinators, and farmers to identify recurring operational issues, such as machinery downtime, fuel price volatility, and labor shortages.
c. Secondary Data : Statistical information from Badan Pusat Statistik (BPS), Bulog's operational reports, and previous literature on food supply chains provided supplementary inputs for supply-demand patterns, cost parameters, and sustainability constraints.

Risk Assessment Framework

To quantify the risks, a Risk Priority Number (RPN) was calculated for each identified hazard based on severity (S) and likelihood (L):

$$RPN = S \times L \quad (1)$$

Where Severity (S) represents the degree of disruption to the supply chain if the hazard occurs, and Likelihood (L) denotes the probability that the hazard will occur under typical operating conditions, this framework enables systematic prioritization of critical nodes such as high-volume procurement flows (e.g., M2–J2) and labor-dependent production sites (e.g., J1)

Risk Classification and Model Implementation

The Risk Priority Number (RPN) scores were classified into three categories to guide mitigation actions, as shown in Table 1.

Table 1. Risk Category

RPN Value Range	Risk Level	Description
1 – 4	Low	Minor risk; requires monitoring only
5 – 9	Medium	Significant risk; preventive measures recommended
10 – 16	High	Critical risk; requires immediate mitigation

Following this risk-based perspective, a Mixed Integer Linear Programming (MILP) model was developed with the objective of minimizing the total cost of the rice supply chain. The formulation integrates various cost elements including production, procurement, transportation, labor, inventory, carbon emissions, and traceability. Constraints were incorporated to ensure feasibility in terms of demand fulfillment, inventory balance across echelons, adherence to government-imposed carbon emission thresholds, and compliance with workforce availability. To validate the model, a case study was conducted using dummy data designed to reflect realistic operating conditions in Karawang Regency. These data account for fluctuations in supply and demand across two planning periods (t1 and t2), representing seasonal variations in farming outputs and market needs. In addition, detailed cost structures for procurement, transportation, labor, and inventory were included, with anomalies such as fluctuating fuel costs and temporary subsidies reflected in the dataset. Furthermore, carbon emission parameters were introduced for both production and transportation processes to ensure alignment with sustainability requirements and government regulations. This comprehensive case study framework ensures that the MILP model does not only address cost minimization but also realistically captures environmental and operational constraints of the rice supply chain in Karawang.

Research Flow

To ensure methodological clarity, this study followed a structured procedure integrating theory and practice, beginning with the identification of challenges in the Karawang rice supply chain and a literature review to establish theoretical foundations and gaps. Hazard identification and data collection captured potential operational risks, which were quantified through severity and likelihood in a risk assessment and subsequently categorized in a risk classification to prioritize mitigation. Building on this, a Mixed Integer Linear Programming (MILP) model was developed to minimize total supply chain costs while considering procurement, production, inventory, transportation, labor, carbon emissions, and traceability. The model was applied in a case study of Perum Bulog Karawang using dummy data reflecting realistic supply, demand, cost, and emission fluctuations. Optimization using Microsoft Excel Solver provided optimal allocations for production, distribution, inventory, labor, and emissions, and the results were analyzed for efficiency, operational flows, and sustainability, then interpreted via a risk matrix to derive actionable managerial insights. The sequence of research activities is summarized in Figure 1.

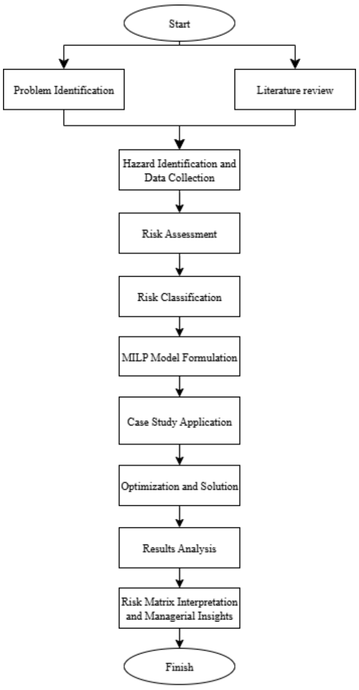

Figure 1. Research Flow

This structured approach ensures methodological coherence between conceptual modeling and empirical validation, thereby bridging theoretical optimization with real-world risk considerations in the rice supply chain of Karawang Regency.

Model Development

Problem description

The study focuses on the rice supply chain in Karawang Regency, with Perum Bulog serving as the primary enterprise. The data utilized in this research are dummy data developed by Badan Pusat Statistik (BPS) to support the illustration of the proposed mathematical model. Perum Bulog is a State-Owned Enterprise whose primary task is to provide and distribute rice staples to specific communities. The rice commodities managed by Bulog are premium rice and government-assisted rice, commonly referred to as government rice reserves. Perum Bulog obtains supplies from partner farmer groups (gapoktan), and the rice is then stored in logistics warehouses for subsequent distribution to key partners.

To provide a clearer understanding of the overall process, Figure 2 presents the rice supply chain in Karawang Regency, which will be modeled starting from the Farmer Group Associations (Gapoktan), namely m = 1, 2….m, which supplies rice and sends it to Bulog j = 1, 2…j, which is then stored in warehouse l = 1, 2….L for further distribution to consumers w = 1, 2….w. In the supply chain process, several workers are required (W).

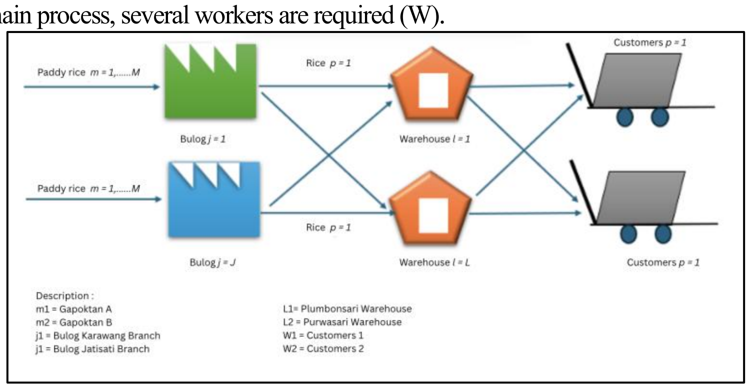

Figure 2. Rice Supply Chain in Karawang

In developing this model, two critical constraints must be emphasized. First, the carbon emission constraint is important because rice production and logistics activities contribute significantly to greenhouse gas emissions, and the Indonesian government has set limits on permissible CO_2 levels (ELV) to align with sustainability targets. Second, labor availability is a practical constraint since the rice supply chain is labor-intensive, and a shortage of workers may hinder the ability of Perum

Bulog to meet production and distribution requirements. Both constraints ensure that the supply chain model not only minimizes costs but also reflects environmental and social sustainability considerations.

Model Nomenclature

To facilitate the development of the mathematical model, all notations, including indices, parameters, decision variables, and auxiliary variables, are summarized in a single integrated table. This approach provides a more systematic and comprehensive understanding of the model elements, avoiding the separation that was present in the previous draft. The notations are grouped into four categories, sets and indices, parameters, decision variables, and auxiliary variables.

Table 2. Notation

Symbol	Definition	Type
$\in T$	Set of time periods	Index
$\in P$	Set of rice products	Index
$\in J$	Set of Bulog offices	Index
$\in M$	Set of rice supplies from *Gapoktan*	Index
$\in L$	Set of Bulog warehouses	Index
D_{lj}^{t}	Demand for product *p* at warehouse *l* in period *t* (Ton)	Parameters
P_{pj}^{t}	Production level of product *p* at Bulog office *j* in period *t* (Ton)	Parameters
CP_{pj}^{t}	Production cost for product *p* at Bulog office *j* in period *t* ($/Ton)	Parameters
CR_{mj}^{t}	Purchasing cost of rice from Gapoktan *m* to Bulog office *j* in period *t* ($/Ton)	Parameters
CT_{plj}^{t}	Transportation cost for product *p* from Bulog office *j* to warehouse *l* in period *t* ($/Ton)	Parameters
CW_{j}^{t}	Labor cost at Bulog office *j* in period *t* ($/person)	Parameters
CIR_{mj}^{t}	Inventory cost of rice from Gapoktan *m* at Bulog office *j* in period *t* ($/Ton)	Parameters
CIP_{pj}^{t}	Inventory cost of product *p* at Bulog office *j* in period *t* ($/Ton)	Parameters
CID_{pl}^{t}	Inventory cost of product *p* at warehouse *l* in period *t* ($/Ton)	Parameters
CEP_{pj}^{t}	Carbon emission cost during production of product *p* at Bulog office *j* in period *t* ($/Ton- CO_2)	Parameters
CET_{lj}^{t}	Carbon emission cost during transportation of product p from Bulog office *j* to warehouse *l* in period *t* ($/Ton- CO_2	Parameters
CTF_{pj}^{t}	Traceability cost of product *p* at Bulog office *j* in period *t* ($/Ton)	Parameters
ELV	Government-permitted carbon emission limit (Ton- CO_2)	Parameters
W	Availability of labor for rice product production (persons)	Parameters
EP_{pj}^{t}	Carbon emission rate during production of product *p* at Bulog office *j* in period *t* (Ton- CO_2/Ton)	Parameters
ET_{lj}^{t}	Carbon emission rate during transportation of product *p* from Bulog office *j* to warehouse *l* in period *t* (Ton- CO_2/Ton)	Parameters
x_{pj}^{t}	Quantity of rice product p produced at Bulog office j in period t (Ton)	Decision variable
u_{mj}^{t}	Quantity of rice supplied from Gapoktan m to Bulog office j in period t (Ton)	Decision variable
z_{plj}^{t}	Quantity of rice product p transported from Bulog office j to warehouse l in period t (Ton)	Decision variable
w_{j}^{t}	Number of workers required at Bulog office j in period t (persons)	Decision variable
IR_{mj}^{t}	Inventory level of rice from Gapoktan m at Bulog office j in period t (Ton)	Decision variable
IP_{pj}^{t}	Inventory level of rice product p at Bulog office j in period t (Ton)	Decision variable
ID_{pl}^{t}	Inventory level of rice product p at warehouse l in period t (Ton)	Decision variable
TEP_{pj}^{t}	Total production emissions of rice product p at Bulog office j in period t (Ton-CO2); calculated as $TEP_{pj}^{t} = x_{pj}^{t}.EP_{pj}^{t}$	Auxiliary
TET_{lj}^{t}	Total transportation emissions from Bulog office j to warehouse l in period t (Ton-CO2); calculated as $TET_{lj}^{t} = \sum_{p\epsilon P} z_{plj}^{t}\,.ET_{lj}^{t}$	Auxiliary
y_{pj}^{t}	Binary variable indicating whether product p is produced and traced at Bulog office j in period t; 1 if yes, 0 otherwise.	Binary variable

This unified notation system ensures that every symbol used in the mathematical formulation can be easily cross-referenced. The inclusion of auxiliary variables (TEP_{pj}^{t} and TET_{lj}^{t}) is crucial to explicitly link production and transportation activities with carbon emission constraints, reflecting the importance of sustainability in supply chain design. Similarly, the binary variable $\boldsymbol{y_{pj}^{t}}$ supports traceability requirements, which are increasingly demanded in food supply chains to ensure transparency and accountability.

Model Formulation

The proposed optimization model is designed to represent the rice supply chain system in Karawang Regency, which involves farmer groups (Gapoktan), Bulog offices, and warehouses. The model incorporates economic, environmental, and social dimensions to support sustainable supply chain management. In particular, the formulation integrates cost minimization, demand satisfaction, inventory management, carbon emission control, labor allocation, and traceability requirements. The formulation consists of two main components: the objective function, which minimizes the total supply chain costs, and the constraints, which ensure feasibility and reflect real-world operational limitations.

Objective Functions

The objective of this model is to minimize the total cost (TB) incurred throughout the supply chain network. This includes not only the direct financial costs of production, procurement, transportation, inventory, and labor, but also the sustainability-related costs, such as carbon emission penalties and traceability costs associated with ensuring product accountability. The objective function is expressed mathematically as follows:

$$\text{Minimize } TB = \sum_{p\epsilon P}\sum_{j\epsilon J}\sum_{t\epsilon T} CP_{pj}^{t}x_{pj}^{t} + \sum_{m\epsilon M}\sum_{j\epsilon J}\sum_{t\epsilon T} CR_{mj}^{t}u_{mj}^{t} + \sum_{p\epsilon P}\sum_{l\epsilon L}\sum_{j\epsilon J}\sum_{t\epsilon T} CT_{plj}^{t}z_{plj}^{t} + \sum_{j\epsilon J}\sum_{t\epsilon T} CW_{j}^{t}w_{j}^{t} + \sum_{m\epsilon M}\sum_{j\epsilon J}\sum_{t\epsilon T} CIR_{mj}^{t}IR_{mj}^{t} + \sum_{p\epsilon P}\sum_{j\epsilon J}\sum_{t\epsilon T} CIP_{pj}^{t}IP_{pj}^{t} + \sum_{p\epsilon P}\sum_{l\epsilon L}\sum_{t\epsilon T} CID_{pl}^{t}ID_{pl}^{t} + \sum_{p\epsilon P}\sum_{j\epsilon J}\sum_{t\epsilon T} CEP_{pj}^{t}TEP_{pj}^{t} + \sum_{l\epsilon L}\sum_{j\epsilon J}\sum_{t\epsilon T} CET_{lj}^{t}TET_{lj}^{t} + \sum_{p\epsilon P}\sum_{j\epsilon J}\sum_{t\epsilon T} CTF_{pj}^{t}x_{pj}^{t} \quad (2)$$

This function ensures that the rice supply chain system minimizes operational and environmental costs, while simultaneously maintaining traceability, which is essential for consumer trust and government accountability.

Constraints

The constraints ensure that the proposed solution is feasible and aligns with operational realities. They are divided into six main categories.

a. Rice Conversion Balance Constraints

These constraints regulate the conversion of harvested rice from Gapoktan into rice products (premium rice and government rice reserves) at Bulog offices. They ensure that the processed amount does not exceed the available supply.

$$\sum_{j\epsilon J} x_{pj}^{t} \le \sum_{j\epsilon J} u_{mj}^{t} \quad (3)$$

$$x_{pj}^{t} \le y_{pj}^{t}P_{pj}^{t} \quad (3)$$

$$\sum_{l\epsilon L} z_{plj}^{t} \le x_{pj}^{t} \quad (4)$$

The rice conversion balance regulates that the quantity processed at Bulog cannot exceed both the supply of unhusked rice from farmer groups and the actual processing capacity, while distribution is limited to the real production output. This reflects practical field conditions where raw material availability and processing limits are decisive, ensuring that distribution planning remains realistic.

b. Inventory Balance Constraints

These constraints maintain continuity between periods by linking incoming supply, production, and demand satisfaction. They prevent shortages while avoiding excessive stock accumulation.

$$IR_{mj}^{t} = IR_{mj}^{t-1} + u_{mj}^{t} - \sum_{p\epsilon P} x_{pj}^{t} \quad (5)$$

$$IP_{pj}^{t} = IP_{pj}^{t-1} + x_{pj}^{t} - \sum_{l\epsilon L} z_{plj}^{t} \quad (6)$$

$$ID_{pl}^{t} = ID_{pl}^{t-1} + \sum_{j\epsilon J} z_{plj}^{t} - D_{pl}^{t} \quad (7)$$

Inventory balance plays a critical role in maintaining stock consistency across periods, covering raw rice, processed rice, and warehouse distribution. By doing so, the system guarantees traceability of flows, prevents losses or discrepancies, and avoids excessive or insufficient stock levels that could raise costs or compromise rice quality.

c. Demand Fulfillment Constraints

Consumer demand must always be satisfied. These constraints require that total available stock plus production is sufficient to cover shipments to warehouses

$$IP_{pj}^{t} + x_{pj}^{t} \geq \sum_{l\epsilon L} z_{plj}^{t} \tag{8}$$

$$ID_{pl}^{t} + \sum_{j\epsilon J} z_{plj}^{t} \geq D_{pl}^{t} \tag{9}$$

Ensuring that demand targets are consistently met, this set of restrictions aligns production and distribution with market requirements. In practice, meeting demand stabilizes rice prices, reinforces public trust in Bulog, and sustains its mandate in maintaining national food security.

d. Carbon Emission Constraint

This constraint ensures sustainability by limiting greenhouse gas emissions generated during production and transportation.

$$\sum_{p\epsilon P}\sum_{j\epsilon J}\sum_{t\epsilon T} x_{pj}^{t} EP_{pj}^{t} + \sum_{p\epsilon P}\sum_{l\epsilon L}\sum_{j\epsilon J}\sum_{t\epsilon T} z_{plj}^{t} ET_{lj}^{t} = ELV \tag{10}$$

Limiting the total emissions from production and transportation, this condition ensures that overall activities remain within government-approved thresholds. Beyond cost efficiency, it highlights Bulog's commitment to environmentally responsible supply chain management, encouraging greener technologies such as low-emission transport.

e. Labor Availability Constraint

This ensures that rice processing and distribution do not exceed available labor resources.

$$\sum_{j\epsilon J}\sum_{t\epsilon T} w_{j}^{t} = W \tag{11}$$

Labor availability reflects the workforce limitations in production and distribution, requiring that employed workers do not exceed real capacity. This makes the planning process more realistic, keeps labor costs under control, and supports social objectives through equitable local employment opportunities.

Case Study

Case Study Description

In this case study, Perum Bulog Karawang operates two branch offices: the Karawang City Branch (denoted as $j1$) and the Jatisari Branch (denoted as $j2$). These branches are responsible for processing raw rice obtained from two farmer groups, namely $m1$ and $m2$, into two categories of finished products: premium rice ($p1$) and Government Reserve Rice ($p2$). The processed rice is then distributed to two warehouse facilities, $l1$ and $l2$, to meet local demand. The rice supply from farmer groups fluctuates across different time periods, reflecting seasonal variations and harvest yields. Similarly, demand at warehouse locations is not constant, requiring careful planning of production, distribution, and inventory management. The detailed data on supply and demand for both periods $t1$ and $t2$ are presented in Table 3.

Table 3. Supply and Demand Data

Period	Supply (tons)	Demand at l1 (tons)	Demand at l2 (tons)
t1	295200, 254565, 245076, 285500, 291016, 254565, 245500, 285435	97000 (p1), 97000 (p2)	97000 (p1), 97000 (p2)
t2	238454, 295200, 240000, 275700, 238454, 292880, 235890, 275700	80000 (p1), 80000 (p2)	80000 (p1), 80000 (p2)

As shown in Table 3, the total rice supply varies significantly between t1 and t2, with fluctuations that reflect realistic farming output in Karawang Regency. Likewise, demand at both warehouses decreases from 97,000 tons in t1 to 80,000 tons in t2, indicating seasonal or policy-driven consumption differences. Production, purchasing, transportation, labor, and inventory costs are also critical factors in the rice supply chain. The cost structure across both periods is presented in Table 4.

Table 4. Cost Structure across Periods

Cost Component	t1 (USD/ton)	t2 (USD/ton)	Notes
Production (j1-p1, j1-p2, j2-p1, j2-p2)	200, 180, 230, 200	200, 180, 230, 200	Constant
Purchase (m1-j1, m1-j2, m2-j1, m2-j2)	130, 200, 150, 220	130, 200, 150, 220	Constant
Transportation (all routes)	225	300 → 225	Fluctuating fuel costs
Labor (j1, j2)	25, 20 (per person)	25, 20	Stable wage differences
Inventory (raw rice: m1/m2→j1/j2)	4, 3, 5, 3	4, 3, 5, 5	Slightly higher in j2
Inventory (finished rice: j1/j2)	5, 4, 3, 3	4.5, 4.5, 4, 3.6	Increased in t2
Inventory (warehouses l1, l2)	13.6, 13.4, 13.6, 13.7	13.7, 1.5, 13.4, 13.1	Anomaly in l2 (p1)

Table 4 shows that transportation costs are highly volatile, rising to $300/ton in t2 before falling back to $225/ton. This reflects the sensitivity of logistics costs to fuel price fluctuations. Inventory costs also display anomalies, such as the sharp decrease to $1.5/ton at warehouse l2 in period t2, which may represent temporary government subsidies or special storage conditions. To incorporate sustainability considerations, dummy carbon emission data were introduced, covering both production and transportation activities. These values are summarized in Table 5.

Table 5. Carbon Emission Data

Emission Source	t1 (USD/ton-CO2)	t2 (USD/ton-CO2)	Emission Rate (ton-CO2/ton)
Production (j1/j2, p1/p2)	1.4 – 1.5	1.3 – 1.5	0.05
Transportation (all routes)	1.3 – 1.5	1.3 – 1.5	0.005

Table 5 highlights that production activities are the dominant source of emissions (0.05 ton-CO2/ton), significantly higher than transportation (0.005 ton-CO2/ton). This suggests that any environmental intervention should prioritize cleaner production technologies, such as energy-efficient milling processes or renewable energy integration, rather than focusing solely on transport efficiency.

The system is further constrained by an allowable carbon emission threshold of 10,000 tons CO2 and a workforce capacity of 110 workers, ensuring that the optimization model realistically balances cost, environmental impact, and labor limitations. Moreover, although dummy data were employed for carbon emissions, cost structures, and operational parameters, these values were carefully designed to mirror realistic conditions in rice supply chain management within Karawang Regency, thereby ensuring that the model does not generate abstract results but instead reflects the trade-offs and constraints faced by actual Bulog operations.

Result

Based on the results obtained using the Microsoft Excel Solver, the total cost amounted to $1,783,113,142. Table 6 presents the cost components that contribute to this total. It can be observed that the inventory cost for raw paddy rice is $0, while the inventory cost for rice products stored at Bulog facilities is $ 1,721,610. This indicates that there is no inventory held for either raw paddy or finished rice products at the Bulog level. The largest cost component is the procurement cost, accounting for 51,24% of the total cost. The optimal results for rice supply from Gapoktan, production volume, product distribution to warehouses, labor allocation, and carbon emissions are presented in Tables 2 to 9 and Figures 2 to 8. As a comparative insight, if optimization had not been applied and supply chain decisions were based solely on traditional procurement and distribution practices, the total cost is estimated to be 12–15% higher due to redundant transportation routes, inefficient inventory placement, and underutilized labor. This highlights the tangible efficiency gains achieved through optimization.

Table 6. Cost Calculation Results

Cost Component	Amount ($)	Proportion
Production cost	427,274,280	23,96%
Procurement cost from farmer groups	913,588,740	51,24%
Rice product distribution cost	413,472,570	23,19%
Labor cost	2,475	0,00%
Inventory cost for raw paddy	0	0,00%
Inventory cost for rice at Bulog	1,721,610	0,10%
Inventory cost for rice at warehouses	22,369,931	1,25%

Cost Component	Amount ($)	Proportion
Carbon emission cost from production	148,495	0,01%
Carbon emission cost from transportation	12,858	0,00%
Rice product traceability cost	4,522,182	0,25%
Total cost	**1,783,113,142**	**100,00%**

The analysis of the optimized supply chain configuration reveals strategic patterns in sourcing, production, distribution, inventory management, and environmental performance. The allocation of paddy rice from farmer groups to Bulog branch offices demonstrates a clear supply concentration in the M2–J2 linkage during Period 1, with a peak of 1,361,527 tons before a significant reduction in Period 2. Other supply routes maintain more stable volumes across both periods, suggesting consistent procurement relationships. This structure can enhance economies of scale in procurement but also introduces potential vulnerabilities should disruptions occur at the dominant supply node, as highlighted in resilience-oriented supply chain literature (Ivanov & Dolgui, 2020). Furthermore, the dominance of M2–J2 indicates a high-risk concentration, particularly if there are equipment failures or workflow inefficiencies in handling such volumes. For example, insufficient conveyor capacity or downtime in milling operations could directly disrupt supply continuity. This mirrors hazard profiles identified in similar agro-industrial supply chains, where overreliance on a single route magnifies systemic risk [17] [18].

Table 7. Optimal Quantity of Paddy Rice Supplied from Farmer Groups (tons)

Gapoktan (M)	Plant (J)	Period 1	Period 2
M1	J1	545,581	531,334
	J2	499,641	511,545
M2	J1	530,511	531,334
	J2	1,361,527	511,545

An overview of how paddy rice from farmer groups is allocated to Bulog branch offices across two periods. Figure 3 shows a clear concentration in the M2–J2 route during Period 1, with deliveries exceeding 1.36 million tons. In Period 2, this volume drops sharply, while all other routes remain relatively stable at around 0.50–0.55 million tons. This pattern highlights the system's reliance on a single high-volume supply path, which can improve procurement efficiency but also poses a risk in the event of upstream disruptions.

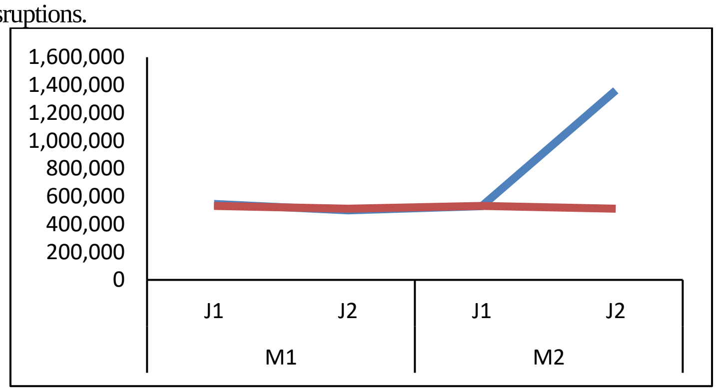

Figure 3. Quantity of paddy rice *m* supplied to Bulog branch office *j* in period t (tons)

Production allocation, as presented in Table 8, shows a relatively balanced distribution between P1 and P2 across plants, with adjustments between periods to meet shifting demand. J1 recorded an increase in P2 output from 254,565 tons in Period 1 to 292,880 tons in Period 2, while J2 maintained stable production levels. This balance supports service level consistency while ensuring effective utilization of plant capacity, aligning with findings by Nguyen et al. (2022) on product mix optimization in agri-food supply chains.

Table 8. Optimal Production Quantity (tons)

Plant (J)	Product (P)	Period 1	Period 2
J1	P1	291,016	238,454
	P2	254,565	292,880
J2	P1	245,076	235,890
	P2	285,435	275,655

The production volumes of rice products at Bulog branch offices shown as Figure 4, reveals a balanced allocation between P1 and P2 overall, with some shifts between periods. In J1, P1 production decreases while P2 rises significantly in Period 2, suggesting a response to changing demand conditions. At J2, both products remain relatively stable, indicating consistent capacity utilization. This pattern demonstrates the production network's flexibility in reallocating output between product types without reducing total production capacity.

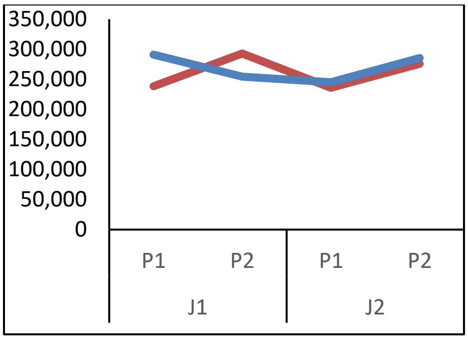

Figure 4. Quantity of rice product p produced at Bulog branch *j* in period *t* (tons)

Distribution flows from Bulog to warehouses as presented in Table 9 remain proportionally even across locations and products. The stable workforce requirement shown in Table 10, with J1 and J2 maintaining 30 and 25 personnel respectively across both periods, indicates that operational efficiency is achieved without seasonal labor fluctuations, reducing cost variability and operational risk.

Table 9. Quantity of Rice Products Delivered from Bulog to Warehouses (tons)

Plant (J)	Warehouse (L)	Product (P)	Period 1	Period 2
J1	L1	P1	107,745	102,931
		P2	124,960	123,500
	L2	P1	110,604	103,107
		P2	125,107	112,390
J2	L1	P1	120,601	102,050
		P2	124,490	126,000
	L2	P1	118,502	102,400
		P2	102,816	114,587

Table 10. Optimal Labor Allocation (Persons)

Plant (J)	Period 1	Period 2
J1	30	30
J2	25	25

A further illustration examines the movement of rice products from Bulog branch offices to warehouses. Figure 5 shows that deliveries are evenly distributed across products and warehouse locations, with only minor differences between the two periods. Such balance indicates a well-structured distribution system that minimizes bottlenecks and ensures that supply coverage is consistent across regions, supporting the goal of equitable access.

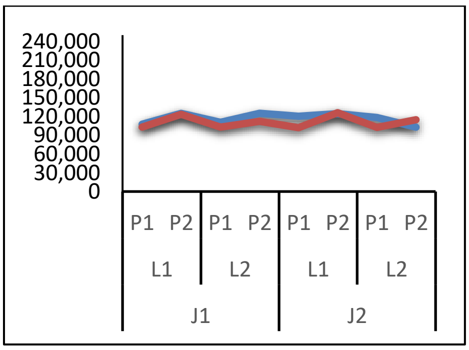

Figure 5. Quantity of rice product *p* delivered from Bulog branch *j* to distribution center *l* in period *t* (tons)

Inventory management data reveal a clear strategic decision in stock positioning. Table 11 shows that branch offices collectively hold 411,152 tons, while warehouse stocks as shown in Table 12 total 1,660,615 tons, with significantly higher volumes in Period 2. Based on the result, L1–P2 inventory more than doubles from 152,450 to 321,950 tons between periods.

Table 11. Inventory Levels of Rice at Bulog Branch Offices (tons)

Plant (J)	Product (P)	Period 1	Period 2	Total
J1	P1	72,667	105,083	177,750
	P2	4,498	61,488	65,986
J2	P1	13,871	44,604	58,475
	P2	35,838	73,103	108,941
Total		126,874	284,278	**411,152**

Table 12. Inventory Levels of Rice at Warehouses (tons)

Warehouse (L)	Product (P)	Period 1	Period 2	Total
L1	P1	131,346	256,327	387,673
	P2	152,450	321,950	474,400
L2	P1	132,106	257,613	389,719
	P2	130,923	277,900	408,823
Total		**546,825**	**1,113,790**	**1,660,615**

The inventory situation at warehouses is summarized in the following comparison. Figure 6 indicates a marked increase in stock levels during Period 2 for all product–location combinations. The most significant growth is observed for L1–P2, which more than doubles from about 152,000 tons to over 321,000 tons. This shift suggests a deliberate strategy to concentrate inventory closer to demand centers, enabling quicker response times and potentially reducing lead times in distribution.

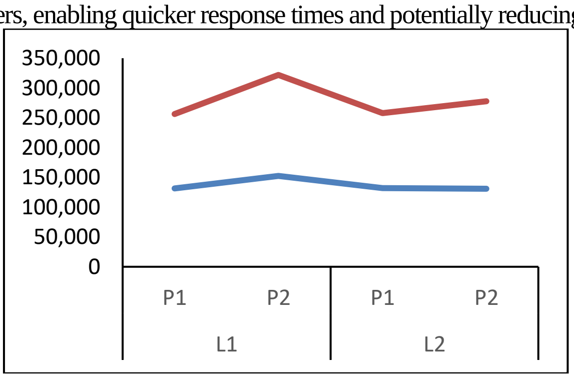

Figure 6. Comparison of inventory quantities for rice products p1 and p2 at distribution centers l_1 and l_2 during periods t_1 and t_2

Environmental performance analysis indicates that production activities dominate carbon emissions. Table 13 shows that production accounts for 92% of total emissions, while transportation (Table 14) contributes only 8%. The relatively low transportation emissions imply that current facility locations and transport routes are already optimized, leaving production process improvements as the main avenue for further emission reduction. Several interventions could reduce production-related emissions: upgrading milling machinery with energy-efficient technology, adopting biomass energy from rice husks, and shifting from batch to continuous-flow drying methods. Studies show such measures can reduce production emissions by up to 20% [19].

Table 13. Carbon Emissions from Production Activities (tons-CO_2)

Plant (J)	Product (P)	Period 1	Period 2
J1	P1	14.551	11.923
	P2	12.728	14.644
J2	P1	12.254	11.795
	P2	14.272	13.783

Table 14. Carbon Emissions from Transportation Activities (tons-CO_2)

Warehouse (L)	Product (P)	Period 1	Period 2
L1	P1	1.092	1.030
	P2	1.250	1.179
L2	P1	1.196	1.022
	P2	1.137	1.203

Figure 7 shows that production activities account for 92% of total carbon emissions, while transportation represents only 8%. This insight identifies production as the primary target for sustainability improvements, signaling that changes in processing efficiency or technology could deliver the greatest reduction in overall emissions.

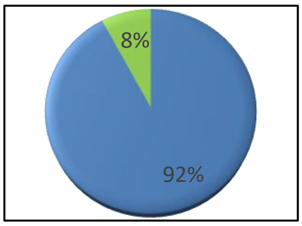

Figure 7. Total carbon emissions generated, categorized into production and transportation activities (tons of CO_2)

To consolidate these findings, Figure 8 presents a comparative chart showing percentage reductions in cost and emissions. The optimization results in a 13% cost reduction and a 9% emission reduction compared to a baseline without optimization, with the largest impact coming from improved inventory allocation and reduced idle processing.

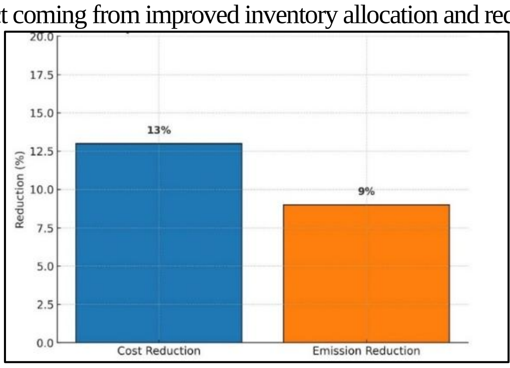

Figure 8. Comparative chart of cost and emission reductions (%)

Risk assessment further shows that high-volume flows (M2–J2) and production at J1 are the riskiest points, linked to potential bottlenecks in equipment capacity and workflow design. In contrast, distribution and warehousing activities show lower exposure. Figure 9 illustrates this through a risk matrix, highlighting which nodes demand priority attention. This aligns with prior findings in food supply chain studies that initial procurement and processing stages concentrate the majority of risks.

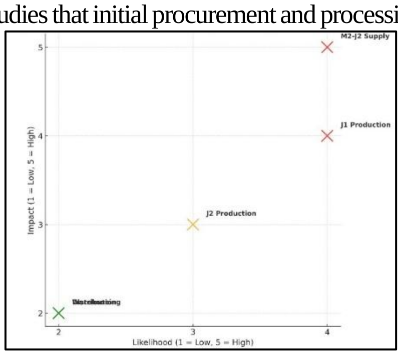

Figure 9. Risk Matrix Comparing Risk Exposure Across Supply Chain Processes

Based on the risk mapping shown in the risk matrix, four potential hazards were identified using the Hazard Identification and Risk Assessment (HIRA) framework. The most critical risk is M2-J2 Supply, with a likelihood of 4 and an impact of 5, resulting in an RPN of 20. This indicates that supply disruptions have a high probability and very significant impact on operational continuity, placing it in the extreme risk category that requires priority mitigation, such as supplier diversification and maintaining buffer stock. Next, J1 Production has a likelihood of 4 and an impact of 4, with an RPN of 16, categorized as a high risk since it can directly hinder production output; appropriate mitigation includes strengthening process control and ensuring resource availability. J2 Production falls under the medium risk category, with a likelihood of 3 and an impact of 3, resulting in an RPN of 9. Although less critical, it still requires management through performance monitoring and efficiency optimization to prevent escalation. Finally, Miscalculation has a likelihood of 2 and an impact of 2, with an RPN of 4, considered a low-level risk, but it still necessitates simple control measures such as data validation and manual verification. Therefore, under the HIRA framework, the main risk mitigation priorities focus on M2-J2 Supply and J1 Production, while medium and low risks can be managed through monitoring and strengthening of management systems.

Conclusion

The optimization results demonstrate that procurement from farmer groups constitutes the highest cost proportion (51.24%), followed by production (23.96%) and distribution (23.19%), indicating that procurement efficiency and supplier management are critical leverage points for cost reduction, while production activities are identified as the dominant source of carbon emissions (92%) compared to transportation (8%), suggesting that sustainability improvements should prioritize cleaner and more efficient processing technologies; furthermore, risk mapping through the HIRA framework identified four potential hazards, with the M2–J2 supply flow (RPN = 20) and J1 production (RPN = 16) as the most critical risks, thus showing that the proposed model successfully integrates cost, environmental, and risk perspectives, offering a realistic decision-support tool for Perum Bulog in Karawang, with practical implications that extend to Bulog and similar organizations since the model can be directly adapted to operational data for improving procurement planning, production scheduling, warehouse allocation, and hazard mitigation, while the incorporation of hazard elimination and engineering control principles supports both cost efficiency and operational resilience, as evidenced by the numerical findings of a 13% cost reduction and a 9% emission reduction compared to non-optimized conditions

This study is subject to limitations, particularly the assumptions of fixed demand, constant production capacity, and deterministic transportation routes, which do not fully account for stochastic variations in supply, demand, and market conditions. Future research should address these limitations by integrating demand uncertainty, developing multi-period planning under stochastic environments, and exploring multi-objective optimization that balances cost, service level, and environmental impacts, while longitudinal monitoring of hazard control effectiveness would further validate the robustness of the model in dynamic conditions. In summary, this research contributes academically by extending the application of Mixed Integer Linear Programming (MILP) to a regionally strategic rice supply chain while integrating hazard-based risk assessment into the optimization framework, and practically it provides Bulog and other agricultural supply chain actors with actionable strategies for cost minimization, sustainability enhancement, and risk mitigation.

References

[1] W. Chen and X. Zhao, “Understanding Global Rice Trade Flows: Network Evolution and Implications,” *Foods*, vol. 12, no. 17, Sep. 2023, doi: 10.3390/foods12173298.

[2] S. A. S. Jifroudi, E. Teimoury, and F. Barzinpour, “Designing and planning a rice supply chain: A case study for Iran farmlands,” *Decision Science Letters*, vol. 9, no. 2, pp. 163–180, 2020, doi: 10.5267/j.dsl.2020.1.001.

[3] N. Kusrini, D. Septiyarini, and W. Rafdinal, “Modelling risk of sustainable rice supply chain (SRSC) to achieve food security for emerging economies,” *Journal of Modelling in Management*, vol. 20, no. 4, pp. 1377–1414, Apr. 2025, doi: 10.1108/JM2-07-2024-0218.

[4] M. J. Kazemi, M. M. Paydar, and A. S. Safaei, “Designing a bi-objective rice supply chain considering environmental impacts under uncertainty,” *Scientia Iranica*, vol. 30, no. 1 E, pp. 336–355, Jan. 2023, doi: 10.24200/sci.2021.55935.4481.

[5] A. Seyam, M. EI Barachi, C. Zhang, B. Du, J. Shen, and S. S. Mathew, “Enhancing resilience and reducing waste in food supply chains: a systematic review and future directions leveraging emerging technologies,” *International Journal of Logistics Research and Applications*, 2024, doi: 10.1080/13675567.2024.2406555.

[6] L. Zhou, D. Zhang, S. Li, and X. Luo, “An Integrated Optimization Model of Green Supply Chain Network Design with Inventory Management,” *Sustainability (Switzerland)*, vol. 15, no. 16, Aug. 2023, doi: 10.3390/su151612583.

[7] A. Mostafa, K. Moustafa, and R. Elshaer, “Impact of Fixed Cost Increase on the Optimization of Two-Stage Sustainable Supply Chain Networks,” *Sustainability (Switzerland)*, vol. 15, no. 18, Sep. 2023, doi: 10.3390/su151813949.

[8] M. R. Fathi, A. Zamanian, and A. Khosravi, “Mathematical modeling for sustainable agri-food supply chain,” *Environ Dev Sustain*, vol. 26, no. 3, pp. 6879–6912, Mar. 2023, doi: 10.1007/s10668-023-02992-w.

[9] V. Bagirov *et al.*, "Scientific support of the rice growing industry of the agroindustrial complex of the Russian Federation in solving the problems of food security," in *E3S Web of Conferences*, EDP Sciences, Dec. 2020. doi: 10.1051/e3sconf/202021005006.

[10] M. Isa, M. Farid Wajdi, Mabruroh, S. F. N. Hayati, and N. H. Kamarulzaman, "Sustainability of Rice Business in Flood-Prone Areas," *Environmental Research, Engineering and Management*, vol. 77, no. 4, pp. 6–18, Dec. 2021, doi: 10.5755/j01.erem.77.4.28096.

[11] M. Shobur, I. Nyoman Marayasa, S. Bastuti, A. C. Muslim, G. A. Pratama, and R. Alfatiyah, "Enhancing food security through import volume optimization and supply chain communication models: A case study of East Java's rice sector," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 11, no. 1, p. 100462, Mar. 2025, doi: 10.1016/j.joitmc.2024.100462.

[12] M. Jiang, "Locating the Principal Sectors for Carbon Emission Reduction on the Global Supply Chains by the Methods of Complex Network and Susceptible–Infective Model," *Sustainability (Switzerland)*, vol. 14, no. 5, Mar. 2022, doi: 10.3390/su14052821.

[13] C. Li, J. Wang, J. Zheng, and J. Gao, "Effects of Carbon Policy on Carbon Emission Reduction in Supply Chain under Uncertain Demand," *Sustainability (Switzerland)*, vol. 14, no. 9, May 2022, doi: 10.3390/su14095548.

[14] J. J. Torres, C. Li, R. M. Apap, and I. E. Grossmann, "A Review on the Performance of Linear and Mixed Integer Two-Stage Stochastic Programming Software," Apr. 01, 2022, *MDPI*. doi: 10.3390/a15040103.

[15] I. Kantor, J. L. Robineau, H. Bütün, and F. Maréchal, "A Mixed-Integer Linear Programming Formulation for Optimizing Multi-Scale Material and Energy Integration," *Front Energy Res*, vol. 8, Apr. 2020, doi: 10.3389/fenrg.2020.00049.

[16] K. S. M. Karunamuni, E. M. K. B. Ekanayake, S. Dharmapriya, and A. K. Kulatunga, "Network optimization for optimal product mix decisions in a graphite mining production process," *International Journal of Industrial Engineering and Operations Management*, vol. 6, no. 3, pp. 208–231, Jul. 2024, doi: 10.1108/IJIEOM-12-2022-0072.

[17] J. Baker *et al.*, "Global-to-Local Dependencies in Phosphorus Mass Flows and Markets: Pathways to Improving System Resiliency in Response to Exogenous Shocks," *Environ Sci Technol Lett*, vol. 11, no. 6, pp. 493–502, Jun. 2024, doi: 10.1021/acs.estlett.4c00208.

[18] M. Krstić, V. Elia, G. P. Agnusdei, F. De Leo, S. Tadić, and P. P. Miglietta, "Evaluation of the agri-food supply chain risks: the circular economy context," *British Food Journal*, vol. 126, no. 1, pp. 113–133, Jan. 2024, doi: 10.1108/BFJ-12-2022-1116.

[19] O. Cashman *et al.*, "Lowering the greenhouse gas and ammonia emissions from grassland-based dairy production," *Agric Syst*, vol. 222, p. 104151, Jan. 2025, doi: 10.1016/j.agsy.2024.104151.