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Understanding The Dynamics of Marine Fish Supply Chain Using a Causal Loop Diagram: A Case Study in Lamongan, Indonesia

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Abstract

The marine fisheries sector is essential in supporting food security and the national economy of Indonesia, especially in coastal regions such as Lamongan Regency, East Java. Despite high levels of marine fish production, price volatility in the market remains a significant issue, directly impacting fishers' welfare. This problem arises from various interrelated factors within the supply chain, from fishing to distribution to end consumers. This study aims to analyze the marine fish supply chain system comprehensively using a system dynamics approach, which captures the complex interactions among variables. The primary tool used is the Causal Loop Diagram (CLD), which maps cause-effect relationships and identifies reinforcing and balancing loops within the system structure. The study was conducted at the Lamongan Fish Auction Center through the collection of both primary and secondary data, including interviews with stakeholders such as fishers, middlemen, and retailers. The results identified five main feedback loops—three reinforcing and two balancing—that provide a holistic understanding of the factors influencing the dynamics of supply, distribution, and pricing of marine fish. The developed CLD serves as a strategic decision-making tool and a foundation for more effective policy formulation to enhance distribution efficiency, maintain price stability, and improve the livelihoods of fishers. This research is expected to contribute significantly to the sustainable management of marine fisheries supply chains.

Keywords
Supply Chain, Dynimic System, Causal Loop Diagram, Fish Auction Center.

1. Introduction
The fisheries sector is one of the key contributors to Indonesia's national economy. As the world's largest archipelagic country, with a marine area of 5.8 million km², Indonesia possesses rich marine biodiversity (BPS, 2024). A large portion of the coastal population depends on fisheries activities, either as fishers or business actors involved in the processing and distribution of marine products. East Java, particularly Lamongan Regency, significantly contributes to national fisheries production. The capture fisheries potential in Lamongan reaches 75,000 tons per year, supplying around 41.51% of the fish demand in the province (BPS, 2024).

Skipjack tuna (ikan tongkol) is the main commodity commonly caught in Lamongan waters, especially during the west monsoon (October–March), when ocean conditions support plankton growth, a natural food source for skipjack (BKIPM, 2023). Ocean currents, water temperature, and nutrient availability from the Indian Ocean make Lamongan waters highly promising for capture fisheries. The total fishery production has increased significantly over the years, with East Java's capture fisheries production rising by 27.85% from 2018 to 2024 (BPS, 2024). However, this increase has not been matched with an effective and structured distribution system, leading to income instability among fishers. Many fishers in Lamongan still sell their catch directly to middlemen at low prices due to a lack of information regarding distribution systems and market demand. This results in uncertain incomes and declining fisher welfare. As Christopher (2016) explained, good supply chain management provides visibility over product and information flows, enabling better decision-making by business actors. By implementing an integrated supply chain management (SCM), fishers can access pricing, market demand, and efficient distribution channels—ultimately increasing their income and reducing post-harvest losses (Mentzer et al., 2001).

The application of a system dynamics approach offers an appropriate solution as it captures cause-effect relationships between actors and variables within the fisheries supply chain. System dynamics is effective in simulating various policy scenarios and their impacts on pricing and business actor welfare (Sterman, 2000). It remains a relevant approach for analyzing fisheries supply chains, especially in capturing nonlinear relationships and enabling long-term policy experimentation (Arvitrida et al., 2022; Bagheri & Gholami, 2020). A study by Mulyaningtyas & Arvitrida (2020) demonstrates that applying system dynamics modeling in cold chain management significantly reduces fish price fluctuations. Thus, this model is highly relevant for analyzing and optimizing the marine fish supply chain in Lamongan, from capture to end consumers.

1.1 Objectives

This study aims to identify and analyze the current marine fish supply chain management using a system dynamics approach. This method enables an in-depth understanding of the various factors and interactions that influence the overall marine fish distribution flow. Furthermore, the research seeks to design a system dynamics model and perform simulations to improve the performance of the marine fish supply chain management system. Through these simulations, the supply chain can be visualized under different policy scenarios or changes, aiding more effective and efficient decision-making to support sustainability and improved outcomes in the fisheries sector

2. Literature Review

System dynamics has proven to be effective in analyzing and optimizing complex agricultural and fisheries systems. Granita Hajar (2020) demonstrated that system dynamics simulations can increase egg and chicken meat production in East Java through scenarios such as land optimization and reduced corn imports. This shows the approach's ability to provide measurable solutions for production planning and supply resilience. In the context of fisheries, a study by Agustina Eunike et al. (2021) emphasized the importance of partnerships between farmers and suppliers to improve milkfish farmers' profits through partnership simulations supported by government intervention. Additionally, a study by Atika Dwi Febriana et al. (2022) showed that in the seed and aquaculture supply chain, the interaction between biological and economic factors significantly impacts profitability. This reinforces the importance of comprehensively understanding the system structure for strategic decision-making. In addition, the integration of information technology such as digital tracking systems can increase supply chain transparency and reduce logistical inefficiencies (Wijayanti & Ramadhani, 2021).

Meanwhile, research by Dian Mulyaningtyas and Niniet Indah Arvitrida (2020) on cold chain systems in Lamongan showed that applying decentralized cold storage technology helped stabilize the price of mackerel while improving fishery actors' profits. Overall, these studies affirm that system dynamics is a relevant and applicable approach in managing agricultural and fisheries supply chains. It allows for the simulation of various policies and scenarios and reveals the long-term impact of managerial decisions. By considering biological, economic, and distributional aspects integratively, this approach supports the development of a resilient and sustainable marine fisheries sector.

3. Methods

This research employs a case study method with a qualitative research approach, collecting data through observation and direct interviews. The research aims to describe the challenges in the marine fish supply chain (Figure 1)

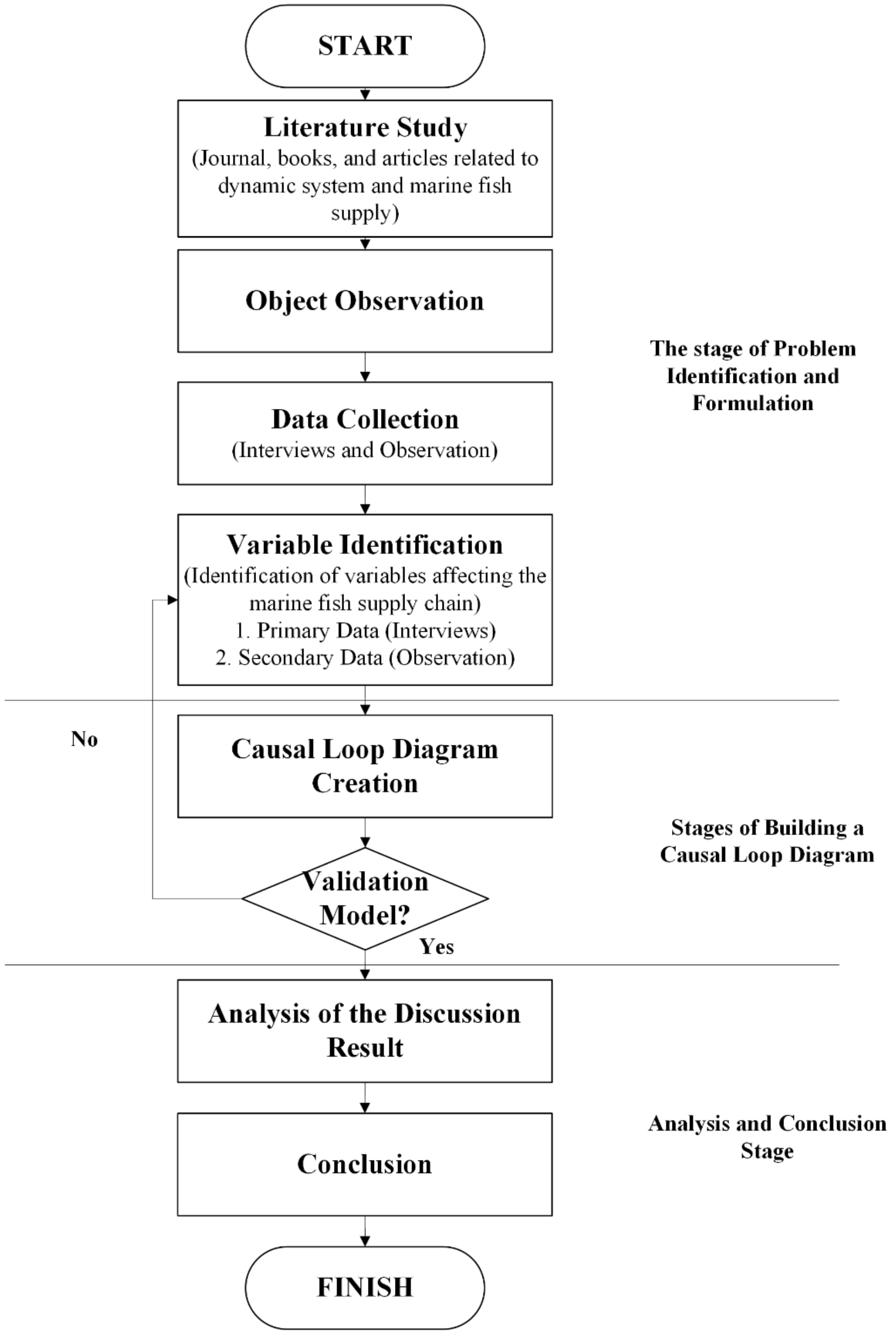

Figure 1. Presents a flowchart illustrating the current research methodology.

The methodology begins with a literature review to obtain a comprehensive understanding of relevant theories, particularly those concerning marine fish supply chains and system dynamics. Literature was gathered from credible sources such as books, journals, and scientific articles, as well as by reviewing previous research to identify research gaps and position this study appropriately.

Next, direct observation was conducted on the research object to understand and analyze real-world challenges in the marine fish supply chain. This observation included identifying entities involved in the system—such as fishers, middlemen, and end consumers—and the relationships among them to provide a comprehensive and detailed picture of the studied system.

Data collection was carried out using both primary and secondary sources. Primary data were obtained through in-depth interviews with various stakeholders in Lamongan Regency, such as fishers, collectors, retailers, and consumers, to gather direct insights into the challenges and dynamics of the marine fish supply chain. Secondary data were obtained from official institutions such as the East Java Department of Marine and Fisheries and Statistics Indonesia (BPS) to support the analysis.

Based on the observations and interviews, variables influencing the supply chain system were identified and formed the basis for building the system dynamics model. The next step was constructing a Causal Loop Diagram (CLD) to depict the cause-effect relationships among system variables. The CLD illustrates dynamic interactions using arrows indicating the direction of influence: a positive (+) sign means one variable increases another, while a negative (−) sign indicates an inverse relationship (Anderson & Johnson, 1997).

The diagram includes two types of feedback loops: reinforcing loops, which amplify system changes, and balancing loops, which stabilize the system (Sterman, 2000). In the context of the marine fish supply chain, the CLD maps elements such as fish production, distribution, market demand, prices, and stock availability. This approach assists identify complex interaction patterns and provides a comprehensive overview useful for both business actors and policymakers in designing strategies to improve the efficiency and sustainability of the marine fish supply chain. Dynamic modeling for policy-making in fisheries has been emphasized to identify leverage points and simulate intervention outcomes (Putri & Handayani, 2022). Furthermore, it allows stakeholders to evaluate scenarios that can improve small-scale fishers' welfare (Setiawan et al., 2023).

4. Results and Discussion

Following a comprehensive literature review from various relevant journals and reference sources, the findings support the analysis of the marine fish supply chain system explored in this study. These findings were then analyzed and discussed in depth to understand the relationships among variables within the system—both reinforcing and balancing—through the application of the causal loop diagram (CLD) approach. This section aims to explain the dynamics of the system and provide practical insights into how these dynamics affect sustainable supply chain management.

4.1. Marine Fish Supply Chain

The marine fish supply chain describes the journey of fish from their natural habitat in the ocean to the hands of end consumers. Each stage of the chain involves multiple actors with interrelated roles and functions. Understanding the structure and mechanisms of this chain is essential for improving distribution efficiency, maintaining product quality, and enhancing the well-being of key stakeholders, particularly fishers. The flow of the marine fish supply chain is detailed in Figure 2.

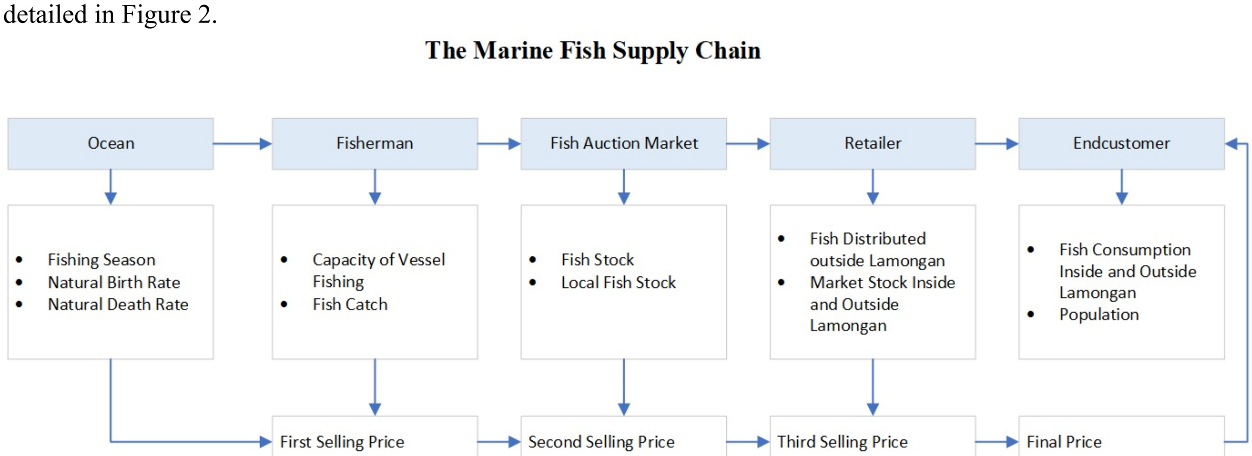

Figure 2. Flow of the marine fish supply chain.

The marine fish supply chain illustrates the distribution flow of fish from the ocean, as the primary source, to the end consumer. This process involves several key actors: fishermen, fish auction markets (collectors), retailers, and final consumers. The initial stage begins in the ocean, where fish stock is influenced by three main factors: the fishing season, the natural birth rate, and the natural death rate. These factors determine the quantity of fish available for harvest.

Fishermen then catch fish using boats, with the boat capacity determining the volume of the catch. The amount of fish caught is referred to as the *fish catch*. At this stage, the fish are sold for the first time, establishing the *first selling price*. Subsequently, the fish enter the fish auction market, where the auction process takes place. Two key aspects at this stage—the overall fish stock and the local fish stock—affect the *second selling price*.

The fish are then purchased by retailers for further distribution. Retailers play a crucial role in distributing fish to areas outside Lamongan as well as supplying local markets within the region. This distribution process influences the availability of fish across different locations and determines the *third selling price*. Ultimately, the fish reach the *end consumer*—the public who purchase and consume the fish. The level of fish consumption, both within and beyond Lamongan, along with the population size, influences demand and determines the *final price* paid by consumers.

A comprehensive understanding of this supply chain reveals how each actor and factor interacts to maintain the sustainability of marine fish availability and the stability of market prices. Efficiency in this supply chain is essential for economic balance and food security, particularly in coastal regions such as Lamongan.

4.2 Variable Identification

Before constructing the causal loop diagram, variable identification is essential to gain a deeper understanding of the observed system. These variables influence the cause-effect relationships within the marine fish supply chain and help determine why market fish prices are often significantly higher than those at the Fish Auction Center (TPI). The variables identified through interviews and real-world observations are grouped into five categories, as shown in Table 1.

Tabel 1. Variabel Identification of The Marine Fish Supply Chain

Ocean	Fisherman	Fish Auction Market	Retailer	Endcustomer
Natural Birth Rate	Number of Fisherman	Fish Stock at Fish Auction Market	Market Stock Lamongan	Fish Consumption Outside Lamongan
Natural Death Rate	Fish Catch	Second Selling Price	Market Stock Outside Lamongan	Fish Consumption Within Lamongan
Fish Aviability	Fishing Intensity	Overstock	Overstock Market Lamongan	Population of Lamongan
	Material Cost	Distribution Fee	Overstock Market Outside Lamongan	Population Outside Lamongan
	Capasity of Vassel Fishing	Fish Storage Cost	Demand for Lamongan	
	First Selling Price		Demand Outside Lamongan	
			Third Selling Price	
			Distribution Fee	

4.3 *Causal Loop Diagram*

A causal loop diagram represents cause-and-effect relationships used to illustrate the interconnections among variables within an observed system, as well as the influences these variables exert on one another. The diagram is depicted using arrows. A positive arrow (+) indicates a direct relationship: when variable A increases, variable B also increases (or when A decreases, B also decreases). This reflects a reinforcing or same-direction influence. For example, the number of fishermen going to sea affects the volume of fish caught.In contrast, a negative arrow (−) indicates an inverse relationship: when variable A increases, variable B decreases (or when A decreases, B increases). This represents an opposing or balancing influence. For instance, continuous fish harvesting will reduce the availability of fish in the ocean. The variables influencing both fish supply and market prices are illustrated in Figure 3 below.

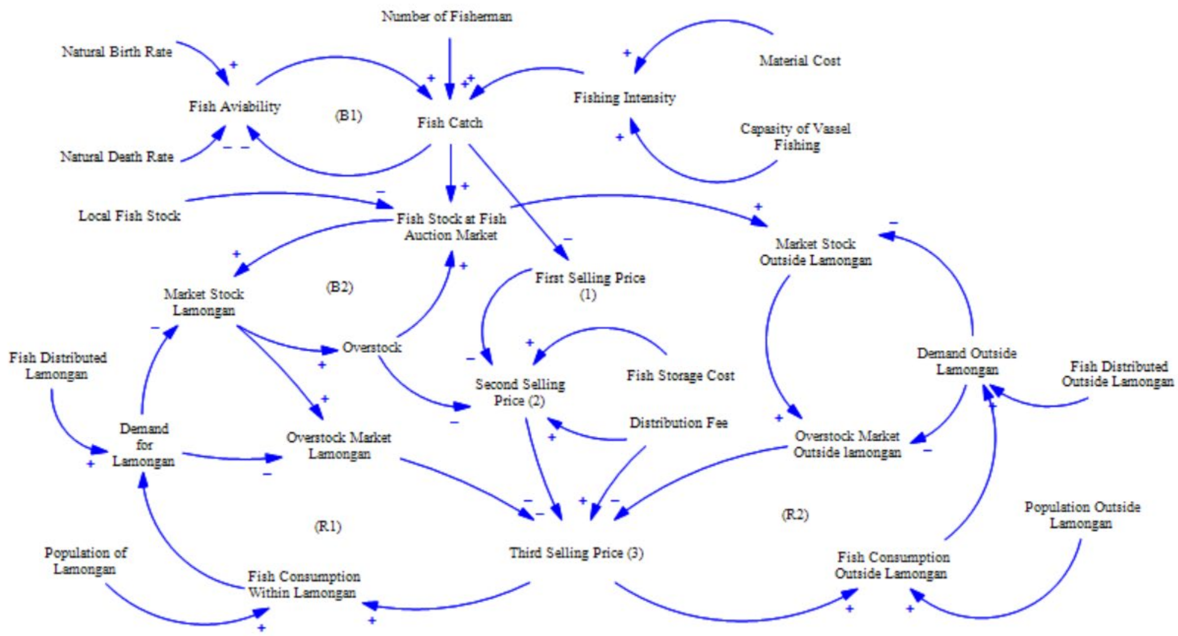

Figure 3. Causal Loop Diagram The Marine Fish Supply Chain

The causal loop diagram (CLD) above illustrates the dynamics of the marine fish supply chain system in Lamongan Regency, which involves various interrelated variables such as the number of fishermen, fish availability, fish catch, selling price, market demand, and distribution. This diagram consists of several reinforcing and balancing loops. One reinforcing loop (R1) shows that an increase in Lamongan's population will drive fish consumption, increasing demand, which in turn increases distribution and market stock. Excess stock can lower the third selling price and trigger a return to increased consumption. Balancing loops such as B1 and B2 illustrate that an increase in the number of fishermen and fishing intensity will increase catch yields, but local fish stocks will decline if fishing exceeds natural regeneration, thereby naturally balancing the system. Additionally, there are distribution and demand dynamics both within and outside Lamongan, which also influence prices and market stocks in each region. This diagram provides an overall comprehensive view of the complex interactions between production, distribution, consumption, and prices within the marine fish supply chain system in the region (Figure 4).

1. *Reinforcing Loop* 1 : Market Stock Lamongan → Overstock Market Lamongan (+) → Third Selling Price (-) → Fish Consumption Within Lamongan (+) → Demand for Lamongan (+) → Market Stock Lamogan (-)

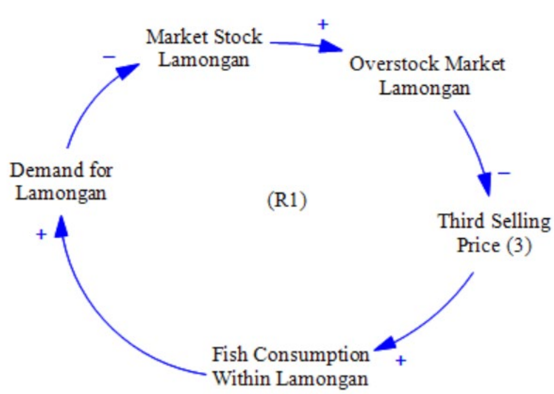

Figure 4. Reinforcing Loop 1

Reinforcing Loop 1 (R1) in the marine fish supply chain system in Lamongan illustrates the mutually reinforcing cause-and-effect relationship between market stock, demand, and fish consumption in the region. This loop begins with the Lamongan Market Stock. When market stock increases, it has the potential to cause an Overstock Market in Lamongan. This excess stock will drive down the Third Selling Price as an effort to reduce the surplus supply. The price decrease provides an incentive for the community to purchase more fish, thereby increasing Fish Consumption Within Lamongan. Higher consumption then triggers an increase in Demand for Lamongan. This increased demand directly reduces market stock as more fish are purchased, which ultimately affects Lamongan Market Stock again. In other words, the higher the fish consumption, the greater the demand, and the faster the market stock decreases, thereby driving the restocking process to meet the demand.

This process creates a reinforcing loop, where an increase in one variable drives a continuous increase in the other variables. This loop structure explains how local-level dynamics of demand and consumption can influence the distribution flow and stock turnover of fish in the Lamongan market. If not managed properly, this system risks driving continuous increases in demand that may not be commensurate with supply from the fisheries sector, potentially leading to pressure on production capacity and the risk of overfishing (Figure 5).

2. *Reinforcing Loop* 2 : Market Stock Outside Lamongan → Overstock Market Outside Lamongan (+) → Third Selling Price (-) → Fish Consumption Outside Lamongan (+) → Demand Outside Lamongan (+) → Market Stock Outside Lamogan (-).

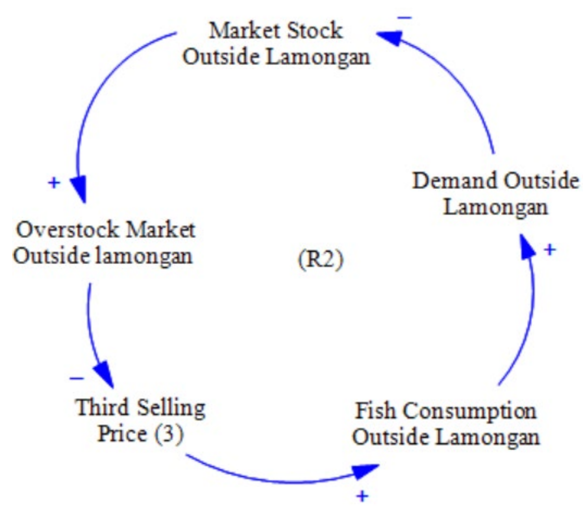

Figure 5. Reinforcing Loop 2

Reinforcing Loop 2 (R2) illustrates the reinforcement cycle in the distribution and consumption of marine fish outside the Lamongan region. This loop shows how external market dynamics can affect the stability of supply and prices of fish distributed from Lamongan to other areas. The process begins with Market Stock Outside Lamongan. If this stock is excessive, it will create an Overstock Market Outside Lamongan. This excess supply drives a decrease in the Third Selling Price to boost purchasing power and reduce accumulated stock. The price decrease further drives an increase in Fish Consumption Outside Lamongan, as lower prices attract more consumers. This increased consumption raises Demand Outside Lamongan, which then accelerates the reduction of external market stock and strengthens the need for restocking.

This cycle forms a reinforcing loop, where increased consumption drives increased demand, which then accelerates stock turnover and supports the sustainability of fish distribution to markets outside Lamongan. Reinforcing Loop 2 (R2) shows that markets outside Lamongan play an important role in absorbing excess stock from local production. However, if this cycle continues without proper management, there is a risk of overdependence on external markets and pressure on fish production capacity in Lamongan (Figure 6).

3. *Reinforcing Loop* 3 : Market Stock Lamongan → Overstock (+) → Fish Stock at Fish Auction Market (+) → Market Stock Lamongan (+)

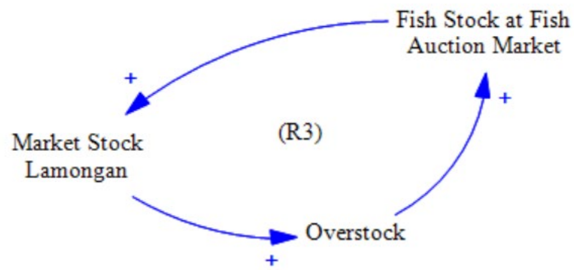

Figure 6. Reinforcing Loop 3

Reinforcing Loop 3 (R3) illustrates the positive feedback loop between fish stocks at Lamongan Market, overstocking, and fish stocks at the Fish Auction Market. This process begins with an increase in fish stock at the Fish Auction Market. The high availability of stock drives increased distribution to Lamongan Market, causing fish stock at Lamongan Market to rise (indicated by a positive relationship (+)). However, when stock at Lamongan Market exceeds market demand, overstock or excess supply occurs. This condition does not halt distribution but reinforces the signal that stocks continue to increase (another positive correlation), driving further increases in fish stock at the Fish Auction Market to ensure distribution continues and market demand can be met at any time. In other words, the higher the overstock, the more it triggers an increase in fish stock at the Fish Auction Market to ensure sufficient supply remains available for the market. This process creates a reinforcing loop, where an increase in one element causes a continuous increase in the other elements.

4. *Balancing Loop* 1 : Fish Catch → Fish Aviability (-) → Fish Catch (+)

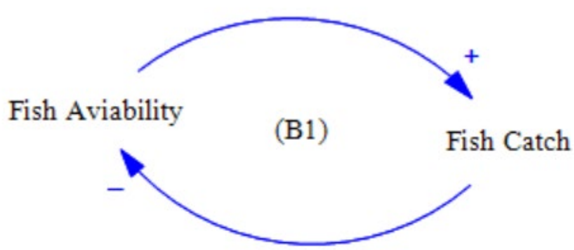

Figure 7. Balancing Loop 1

Balancing Loop 1 (B1) in the marine fish supply chain illustrates the balancing cause-and-effect relationship between fish catch and fish availability in the sea (Figure 7). When the number of fish caught increases, the remaining fish stock in the waters will decrease. This decline causes a decrease in potential catch in the following period, as there are fewer fish available to catch. In other words, the higher the level of fishing, the greater the pressure on fish resources, which ultimately impacts future catch yields. This pattern forms a natural control mechanism, where an increase in one variable (catch volume) gradually reduces or suppresses that variable in subsequent periods through a decline in stock levels.

This structure aims to explain the dynamics of balance in the capture fisheries system, particularly in maintaining the sustainability of marine resources. As shown in the causal loop diagram, Balancing Loop 1 represents how overexploitation of fish can reduce future production capacity. Therefore, understanding this loop is crucial as a foundation for formulating sustainable fisheries management policies, ensuring that fishing activities do not exceed the regenerative capacity of fish resources.

6. Conclusion

Stakeholders involved in the marine fish supply chain must understand the underlying system structure that affects overall distribution performance and customer satisfaction. A thorough understanding of this structure is essential for ensuring the efficient and sustainable operation of fish harvesting, distribution, and marketing processes. Based on the results of a systematic literature review, this study identified and summarized the key factors contributing to the dynamics of the marine fish supply chain, as well as their consequences. These factors were further analyzed using a Causal Loop Diagram (CLD) approach to construct a framework that illustrates the cause and effect relationships among the main variables in the supply chain system.

Several critical variables influence the efficiency and sustainability of the supply chain, including the number of fishermen, volume of fish catch, distribution costs, market demand, and fish prices. The interactions among these variables create a complex feedback structure. Reinforcing loops drive continuous system growth and improvementfor example, an increase in market stock may lead to an overstock condition in the Lamongan market. This excess stock triggers a reduction in the Third Selling Price to alleviate the surplus, which then incentivizes the local community to increase fish consumption, thereby reinforcing demand and accelerating stock turnover.

On the other hand, balancing loops help maintain system stability. For instance, overfishing can reduce fish availability, which in turn lowers future catch volumes, creating a self-regulating mechanism within the system.
The CLD structure developed in this study consists of four key loops: three reinforcing and one balancing. Each loop demonstrates how one variable can directly or indirectly influence others and how the system adapts to changes. Nevertheless, many additional variables remain to be explored in future research to enhance the model and provide a more comprehensive understanding of the dynamic behavior of the marine fish supply chain.

The main contribution of this study lies in identifying and mapping the fundamental structures that influence the efficiency and sustainability of the marine fish supply chain. The resulting model provides a solid foundation for developing dynamic system simulations aimed at capturing feedback relationships and long-term system behavior.
Similar studies also show that active involvement of fishermen in supply chain planning can increase the resilience of the system to price fluctuations and extreme weather (Yuliana et al., 2023). Consequently, organizations and stakeholders in the fisheries sector can formulate more effective, system based policies to enhance operational efficiency, ensure the sustainability of marine resources, and optimally meet market demand.

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Biographies

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Granita Hajar is a researcher and lecturer at the Department of Logistics Engineering, Telkom University Surabaya, Indonesia. Her expertise lies in system dynamics and supply chain management. Her research interests include dynamic modeling of fisheries logistics to support national food security, the development of intelligent supply chains through GIS and technology integration, ERP-based demand planning and sales forecasting, and assessing the environmental and social impacts of battery subsidies in closed-loop supply chains. She actively collaborates with experts in informatics and infrastructure to develop innovative, data-driven solutions for sustainable logistics systems.