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Halal Supply Chain Traceability and Food Safety Model Based on Blockchain Technology and the Internet of Things Using a System Dynamics Approach

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Abstract

This study aims to develop a system dynamics model for halal supply chain traceability and food safety based on Blockchain and Internet of Things (IoT) technology. This approach addresses the lack of transparency, efficiency, and trust in the food supply chain. The model is constructed using primary and secondary data (primarily from Indonesia to facilitate the simulation process), simulated using Vensim PLE, and validated through behavioral, structural, extreme, and parameter tests. This study developed three scenarios: increased growth efficiency, increased investment, and increased farmer storage capacity. During the simulation period, blockchain and IoT implementation increased food availability for consumption by 5% and reduced fresh food inventory losses by 3%. The scenario of increasing farmer storage capacity showed a 10% increase in food availability and reduced fresh food inventory losses by 4% compared to the initial model. Thus, the proposed approach helps maximize food availability and reduce fresh food inventory losses more optimally.

Keywords: Traceability; Halal Supply Chain;Food Safety; Blockchain;Internet of Things;System dynamics.

1. Introduction

The growth of the Muslim population worldwide has driven a significant increase in demand for halal products and food safety assurance. Meanwhile, the traceability system in the overall food supply chain remains a major challenge due to its complexity, the involvement of multiple stakeholders, and the existence of loopholes that allow for cross-contamination or product counterfeiting. Cases of counterfeiting halal and food safety assurance are real problems that affect consumer confidence [1].

The combination of Blockchain and Internet of Things (IoT) technology offers great potential to overcome these challenges. Blockchain enables secure, immutable, and transparent recording of transactions at every stage of the supply chain. This can ensure the integrity of data related to the halal status and food safety of a product [2]. On the other hand, IoT enables real-time data collection through sensors that can monitor critical parameters, such as temperature and humidity, during transportation and storage, thereby ensuring product quality is maintained [3]. The combination of these two technologies offers a comprehensive solution to improve the traceability and accountability of the halal and food safety supply chain.

A system dynamics approach can be used to model the complex interactions between components in the halal and food safety supply chain. This approach allows for the analysis of the impact of technology policies on key parameters, such as operational efficiency, transparency levels, and consumer trust, and provides insights for continuous improvement [4-5].

Many previous studies have not addressed traceability models using a system dynamics approach in halal supply chain traceability and food safety, especially those that utilize a combination of blockchain and IoT technologies. Some studies have addressed them separately [2-3].

This study aims to develop a traceability model of the halal supply chain and food safety based on Blockchain and IoT technology with a system dynamics approach. This model is expected to provide significant contributions to increasing transparency, efficiency, and trust along the halal supply chain.

2. Methodology

This study uses system dynamics methods to model halal supply chain traceability and food safety. The methodology details are as follows:

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2.1. Data Collection

The system dynamics model testing uses primary data from BPS-Statistics Indonesia [6]. This data includes the annual population (used for the 'population' parameter), food crops and livestock products (used for the 'desired fresh food harvested' parameter), production index (used for the 'safety stock' parameter), agricultural production value (used for the 'fresh food harvest' parameter), and trade index (used for the 'food purchase' parameter). Secondary data includes literature review, halal standards, and food safety.

2.2. Model Development

Model development is carried out based on the results of data collection that has been carried out previously. The model that is designed will later be simulated using the help of Vensim PLE software.

2.3. Model Validation

The model validity test is carried out to see whether the designed system dynamics is in accordance with the actual system description. This study uses four validity tests, namely Behavior validity test, Extreme Condition Test, Extreme Condition Test, Model Structure Test, and Model Parameter Test.

2.4. Scenario Design

The scenario design stage can be carried out after the model validity test process has been carried out. In this study, three scenarios will be developed: increasing growth efficiency, increasing investment rate, and increasing farmer storage capacity.

3. Results and discussion

The research results describe the relationship between each variable that makes up the halal supply chain traceability model and food safety.

3.1. Conceptual Framework

This conceptual framework aims to provide a comprehensive picture of the interaction of various elements in the food product supply chain, from farmers, suppliers, food processing, retailers to consumers. The conceptual framework is shown in Figure 1.

Based on Figure 1, farmers play a key role in producing and supplying fresh food products. These products are then sold to suppliers, who serve as links in the supply chain. Suppliers can distribute fresh food products directly to food processors, retailers, or consumers, depending on market demand. Food processors then transform fresh food products into processed food products and distribute them to retailers. Finally, retailers provide products (fresh food or processed products) to consumers as the end users.

3.2. Causal Loop Diagram

The Causal Loop Diagram (CLD) model illustrates how the halal supply chain traceability and food safety models widely used by companies today identify key causal relationships and reveal potential feedback that affects the overall performance of the system. The results of data collection are used to compile a causal loop diagram. The variables that make up the model can be seen in Table 1, while the CLD image can be seen in Figure 2

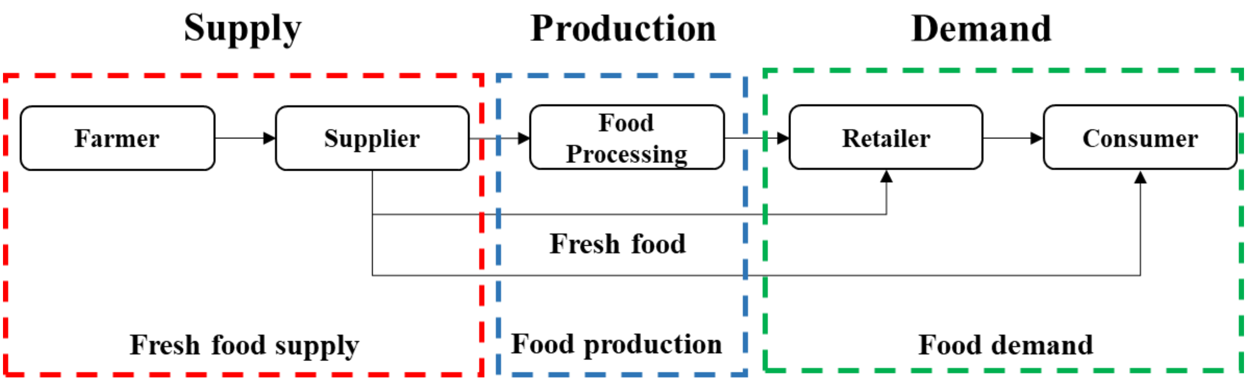

Figure 1. Conceptual framework for the food supply chain

Table 1. Model variables

No	Parameter	Formula	Unit
1	Capacity acquisition	IF THEN ELSE (Traceability system under implementation<=0, capacity initiation, 0.7*capacity initiation*(1+0.7*traceability system under implementation)	kg/year
2	Capacity Initiation	Investment Rate*Efficiency Factor	kg/year
3	Capacity loss	Capacity Initiation-0.7*Traceability system adopted	kg/year
4	Desired Fresh Food Harvested	MIN(Fresh Food demand, Fresh Food Harvested)	kg/year
5	Desired Inventory Level	Fresh Food demand+Safety Stock in Farmer inventory	kg/year
6	Desired Shipment Rate	(Current Inventory Level+Food at Post-production-Safety Stock in Farmer inventory)/Lead time in Farmer inventory	kg/year
7	Farmer Inventory	INTEG(Fresh Food to Farmer Inventory-Inventory Fresh Food Loss-Fresh Food Shipment from Farmer Inventory to Post-production)	kg/year
8	Food at Post-production	INTEG(Fresh Food Shipment from Farm to Post-production+Fresh Food Shipment from Farmer Inventory to Post-production+Food from Other Source-Food Purchase-Food Waste at Post-production,0)	kg/year
9	Food Available for Consumption	INTEG(Food Purchase-Food Consumption-Food Waste at Consumer Level)	kg/year
10	Food Consumption	Population*Food Consumption Required per Kapita	kg/year
11	Food Purchase	MIN(Transport Capacity, (Food demand -(Current Inventory+Safety Stock)))	kg/year
12	Food Waste at Consumer Level	Non-halal Product+unsafe food products	kg/year
13	Food Waste at Post-production	Non-halal Product+unsafe food products	kg/year
14	Fresh Food Available for Harvest	INTEG(Fresh Food Growth-Fresh Food Harvest-Pre-harvest Fresh Food Loss,0)	kg/year
15	Fresh Food Growth	(Desired Fresh Food Harvested – pre_harvest fresh food loss)/growth efficiency	kg/year
16	Fresh Food Harvested	INTEG(Fresh Food Harvest-Fresh Food Shipment from Farm to Post-production-Fresh Food to Farmer Inventory-Post-harvest Fresh Food Loss,0)	kg/year
17	Fresh Food to Farmer Inventory	MIN(Desired Inventory Level, Farmer's Storage Capacity)	kg/year
18	Fresh Food Shipment from Farmer Inventory to Post-production	MIN(Desired Shipment Rate, Transport Capacity)	kg/year
19	Fresh Food Shipment from Farm to Post-production	MIN(Desired Shipment Rate, Transport Capacity)	kg/year
20	Inventory Fresh Food Loss	Farmer Inventory-Farmer's Storage Capacity	kg/year
21	Post-harvest Fresh Food Loss	Non-halal Product+unsafe food products	kg/year
22	Traceability system adopted	INTEG(Capacity loss-Capacity acquisition,0)	kg/year
23	Traceability system under implementation	INTEG(Capacity acquisition-Capacity Initiation,0)	kg/year

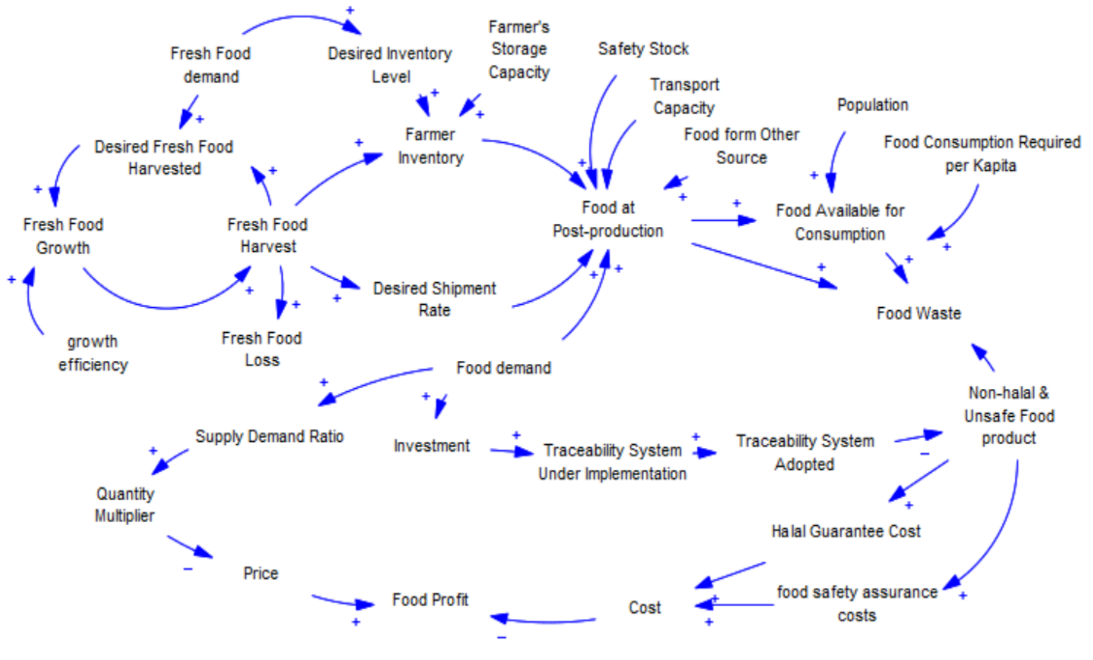

Figure 2. CLD of Traceability Model

The supply chain network starts from fresh food growth, which is influenced by growth efficiency and the desired fresh food harvested [7]. The harvest increases farmer inventory, which is related to the desired shipment rate and affects food at post-production [8-9]. Food waste occurs when deliveries are not on time or there is excess supply [8]. Food demand affects the supply-demand ratio, which requires investment and a quantity multiplier for production balance [10-12]. The implementation of a traceability system requires large investments, and its adoption can reduce halal guarantee costs and food safety assurance costs, which ultimately increase food profits [13-14].

3.3. Stock Flow Diagram

A Stock Flow Diagram (SFD) can be used to incorporate additional information for model formulation, such as variable types and their relationships. Figure 3 presents a halal supply chain traceability and food safety model designed to mimic historical behavior over 21years.

Figure 3 presents seven stock components, namely fresh food available for harvest, fresh food harvest, farmer inventory, food at post-production, food available for consumption, traceability system under implementation, and traceability system adopted. The flow runs dynamically from fresh food growth to food consumption and capacity loss.

For example, the data used for the simulation process is set at an investment rate of 0.05 and an efficiency factor of 0.8, which are standard implementation values in Indonesia according to BPS-Statistics Indonesia [6]. The investment rate and efficiency factor determine the capacity initiation variable. When calculated, the capacity initiation value is 0.04. This value is used to calculate the next variable. Another example, the safety stock value for food companies in Indonesia [6] is on average 0.1 of food demand. This value is used to calculate food purchases.

3.4. Simulation Results

This simulation process produces output in the form of a graph of the quantity of food available for consumption. The simulation is run on 2 conditions, namely the existing condition (current) and the implementation condition of Blockchain and Internet of Things (IoT). The simulation results for each condition are depicted in Table 2.

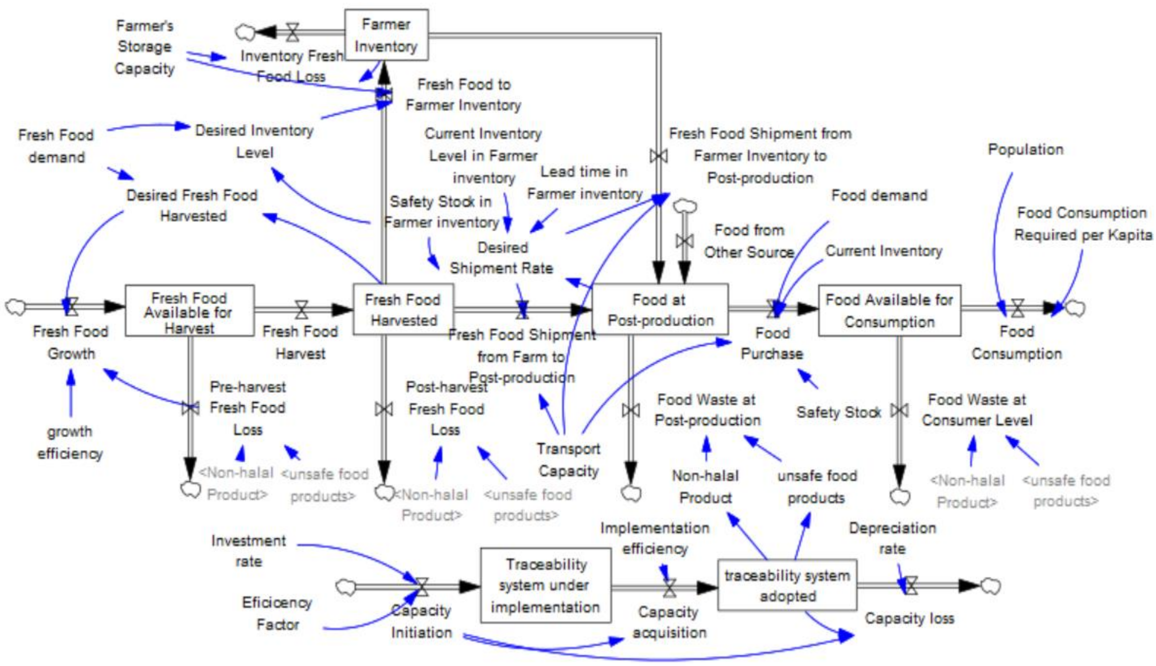

Figure 3. SFD of the traceability model

Table 2. Simulation results of food available for consumption

Year	Food Available for Consumption		Year	Food Available for Consumption	
	Current	Blockchain & IoT		Current	Blockchain & IoT
2014	168,641,023	0	2025	178,741,122	179,836,822
2015	168,740,424	0	2026	178,842,118	179,910,641
2016	168,641,987	0	2027	178,942,221	180,068,116
2017	168,740,512	0	2028	178,841,976	179,958,806
2018	168,941,992	168,848,953	2029	178,842,985	179,970,949
2019	168,673,098	168,550,360	2030	178,791,989	179,865,469
2020	164,157,883	164,000,652	2031	178,662,118	179,722,708
2021	165,809,234	166,600,351	2032	178,541,997	179,621,234
2022	173,247,091	175,383,820	2033	178,545,921	179,608,165
2023	179,103,672	180,289,073	2034	178,484,826	179,533,941
2024	178,641,992	179,710,651			

Table 3. Mean Absolute Percentage Error (MAPE) results

Variables	Year	2019	2020	2021	2022	2023	Average	MAPE
Food waste at consumer level	**AD**	11,268,273	11,045,319	11,090,574	15,291,221	15,297,222	12,798,522	0.2
	SD	11,289,564	11,105,768	11,128,903	15,310,324	15,302,346	12,827,381	
	PEM	0.002	0.005	0.003	0.001	0.000	0.002	
Food Consumption	**AD**	169,038,245	163,777,761	166,200,652	173,819,308	178,749,249	170,317,043	0.1
	SD	168,673,098	164,157,883	165,809,234	173,247,091	179,103,672	170,198,196	
	PEM	0.002	0.002	0.002	0.003	0.002	0.001	
Fresh Food Harvest	**AD**	112,114,486	113,597,483	115,517,923	117,687,022	117,573,115	115,298,006	0.1
	SD	113,023,786	113,329,043	114,897,549	116,987,632	117,478,922	115,143,386	
	PEM	0.008	0.002	0.005	0.006	0.001	0.001	
Food consumption required per kapita	**AD**	210,787	208,854	211,960	214,848	214,188	212,127	0.2
	SD	210,363	210,314	210,312	213,975	213,973	211,787	
	PEM	0.002	0.007	0.008	0.004	0.001	0.002	

3.5. Model validation

The model validation process uses the following methods:

3.5.1. Behavior validity test

This method is carried out by comparing the results of the model simulation with historical data or real system behavior patterns. This method uses statistical tests by measuring the suitability between the model output and real data using the Mean Absolute Percentage Error (MAPE) method according to equation (2). The model is declared valid if the Percent Error Mean (PEM) value is less than 5% [15]. The results of the MAPE calculation are shown in Table3.

Based on the MAPE calculation above, it shows that the Percent Error Mean (PEM) value is less than 5%. So based on the calculation above, the model can be declared valid.

3.5.2. Extreme Condition Test

Extreme Condition Test is a validation method used in system dynamics to test the reliability and consistency of the model. In this study, a test was conducted by entering the smallest extreme condition values (value = 1) and the largest (value = 1,000,000,000) against the population value to see the behavior of the food consumption variable in the production and inventory sub-models. The model is declared valid when the food consumption and desired production values are not negative in the lowest extreme conditions and the highest extreme conditions. The validation results are shown in Figure 4.

In Figure 4, the blue color indicates the highest extreme value condition, the red color indicates the lowest extreme value, and the green color indicates the current condition. The simulation results show that in the lowest extreme condition, namely population with a value of 1, the value of food available for consumption is not negative. The highest extreme conditions, namely population with a value of 1,000,000, the value of food available for consumption is also not negative. This shows that the model can still function well in extreme conditions, both the lowest and highest conditions, so the model is declared valid.

3.5.3. Model Structure Test

The model structure test ensures that the relationships between elements, variables, and loops in the model truly reflect the relevant supply chain process. The model structure test in this study uses two methods, namely verification with competent experts and verification with the help of software.

Based on the results of interviews with competent experts and supported by several studies, it is evident that there is a relationship between variables as described in the causal loop diagram. Some variables that affect this model, for example, are population, food harvest, and food available for consumption. An increasing population can increase the value of food available for consumption. Likewise, when the value of food harvest decreases, it can decrease food available for consumption.

The validation process with the help of Vensim PLE software shows that the model has been verified, so it can be concluded that the model structure is valid.

3.5.4. Model Parameter Test

The variable used in this model parameter test is the population to test the food available for consumption variable. The population variable value will be increased 2 times and decreased 2 times to determine its effect on the output produced. Based on the simulation results, when the population variable is increased by 2 times, the value of the food available for consumption variable also increases linearly. Likewise, when the value of the population variable is decreased, the value of the food available for consumption variable also decreases. The population variable positively affects the food available for consumption variable, meaning that if the population increases, the food available for consumption also increases, and vice versa [16-17]. The results of the model parameter test of the food available for consumption variable can be seen in Figure 5.

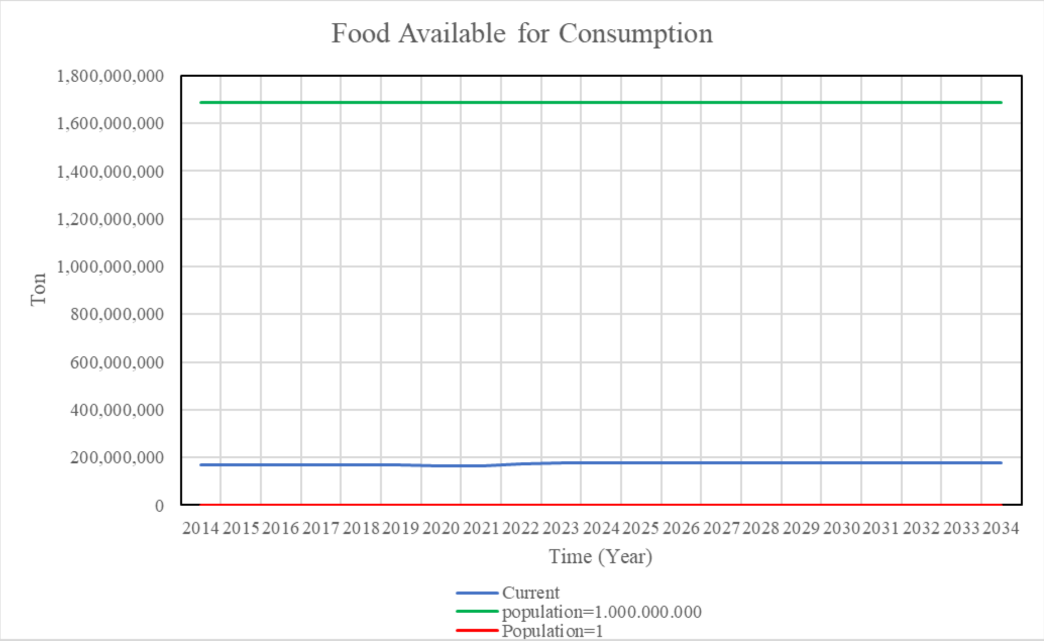

Figure 4. Extreme Condition Test simulation results

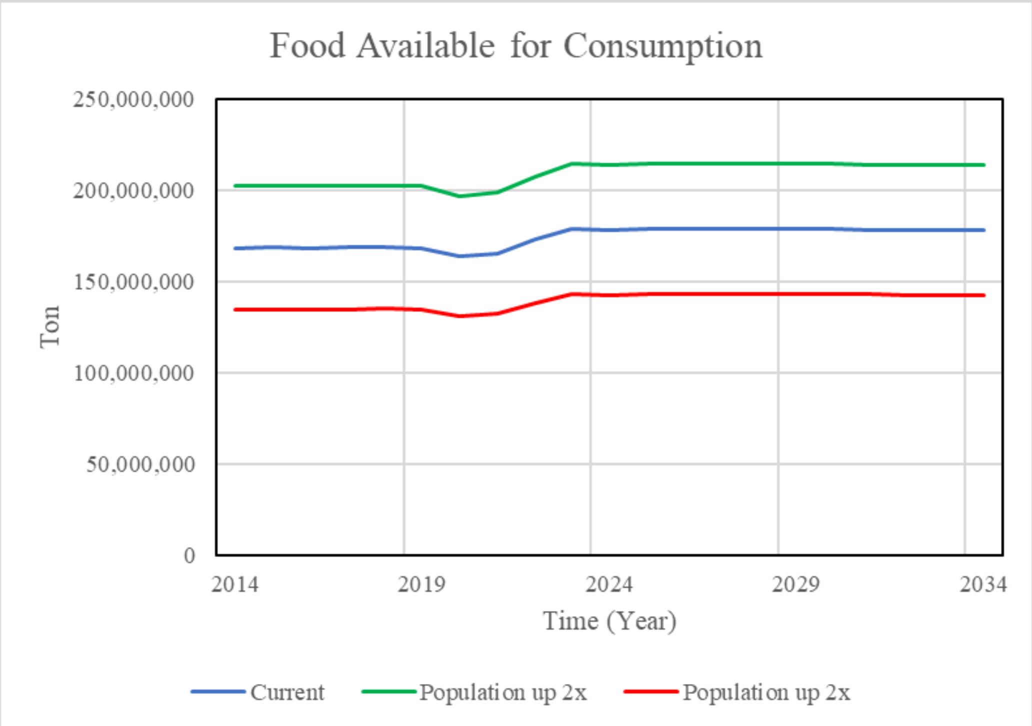

Figure 5. Model Parameter Test

3.6. Scenario design

This scenario was created to provide recommendations for improvements to existing models. The scenarios developed in this study include:

3.6.1. Increasing Growth Efficiency

Growth efficiency is the ability of a production system to produce large amounts of fresh harvest with minimal input [18]. The growth efficiency value is influenced by seed quality, use of agricultural technology (e.g., precision farming, smart irrigation), effectiveness of fertilizer and pesticide use, and sustainable cultivation practices. The growth efficiency value will be increased by 15% from the initial value. The results of the scenario change simulation can be seen in Figure 6 and Figure 7.

Based on the simulation results, it is known that scenario 1 can increase the amount of food available for consumption by 4%. However, the implementation of scenario 1 is also able to increase the value of fresh food loss inventory by 31%.

3.6.2. Increased Investment rate

Investment rate refers to the increase in the level of investment per unit of time (per month or per year). The increase in investment rate is usually in the form of financial capital, technological resources, physical infrastructure, human resources, and information systems.

The increase in Investment Rate in this case means that more funds are invested each period to accelerate system development, procurement of technological devices, implementation of halal standards and food safety digitally. In addition, increasing the investment rate also means accelerating the implementation phase and expanding the reach of the traceability system. Existing conditions show that the percentage of investment rate is still 8%. The scenario tries to simulate an increase in the investment rate to 35%. The results are shown in Figures8 and Figure9.

Different results are shown from the simulation of scenario 2. Based on the simulation results, it is known that scenario 2 can increase the amount of food available for consumption by 8%. However, the implementation of scenario 2 is also able to increase the value of fresh food loss inventory by 3%. This shows better results compared to scenario 1.

3.6.3. Increasing Farmer storage capacity

Increasing Farmer Storage Capacity is an effort to increase or improve the storage capacity of harvested products owned by farmers. Improvement efforts include storage volume, storage quality (temperature, humidity, ventilation), storage technology, and storage duration (extending the shelf life of fresh food).

The positive impacts of this scenario include more stable food stocks, longer storage times, and more flexible distribution. Food loss decreases drastically because products are not immediately damaged or rejected due to sudden overstock. The results of the scenario 3 simulation can be seen in Figure 10 and Figure 11.

The results of the simulation comparison of each scenario can be seen in Table 4. Based on the simulation, it is known that scenario 3 is the best scenario that can be run because it produces the highest increase in food availability for consumption compared to other scenarios. In addition, the value of fresh food inventory loss is the lowest compared to other scenarios. This can also be used by decision makers in determining optimal decisions. Increasing farmer storage capacity can be used as a consideration.

Increasing farmer storage capacity has been shown to increase food availability for consumption. This aligns with Kader [19] findings that adequate storage capacity at the farmer level can extend shelf life and reduce losses in quantity and quality. Furthermore, the integration of blockchain and IoT can minimize damage through temperature, humidity, and logistics tracking systems [20].

This research allows for simulations in other countries. This depends on the availability of the required data. This simulation is only to test the designed model to see whether it is in accordance with real conditions.

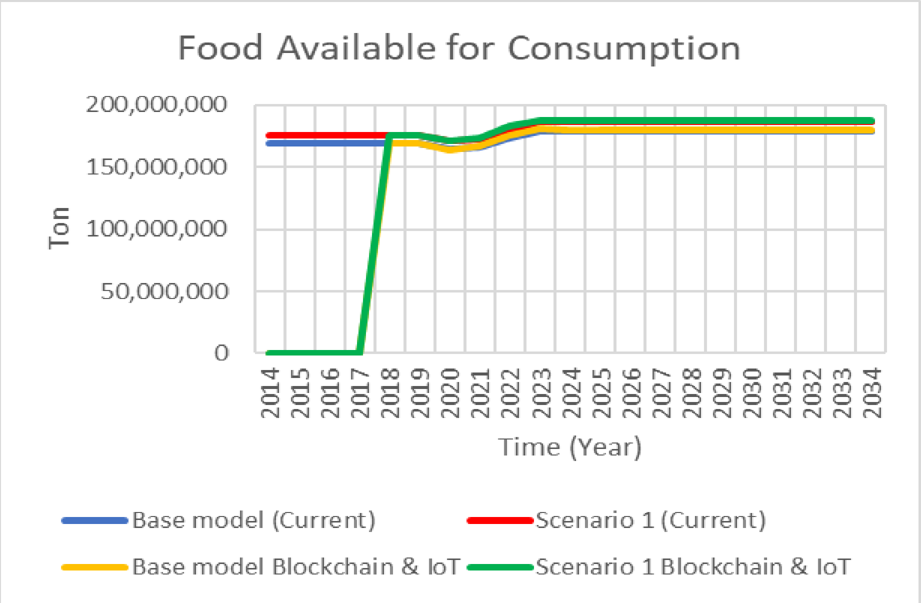

Figure 6. Simulation results of scenario 1 on food available for consumption

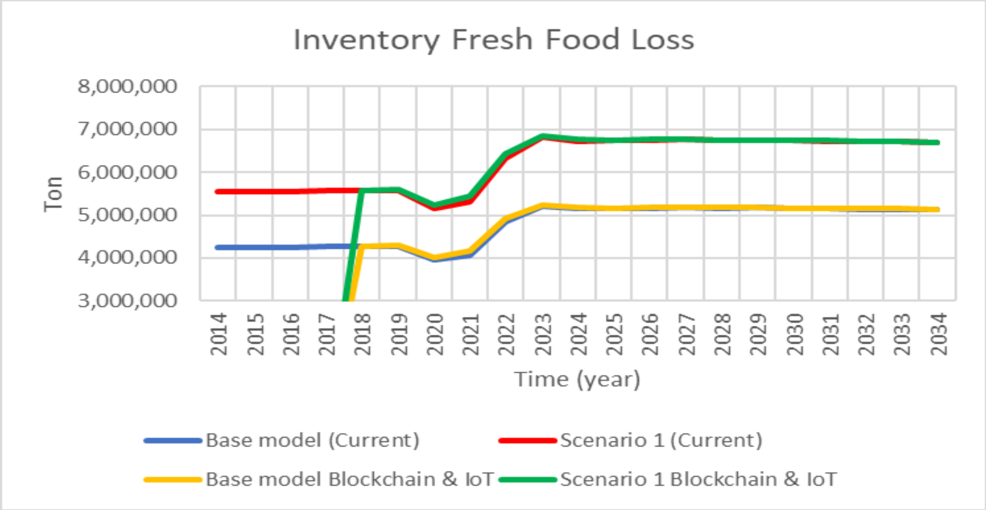

Figure 7. Simulation results of scenario 1 on fresh food inventory loss

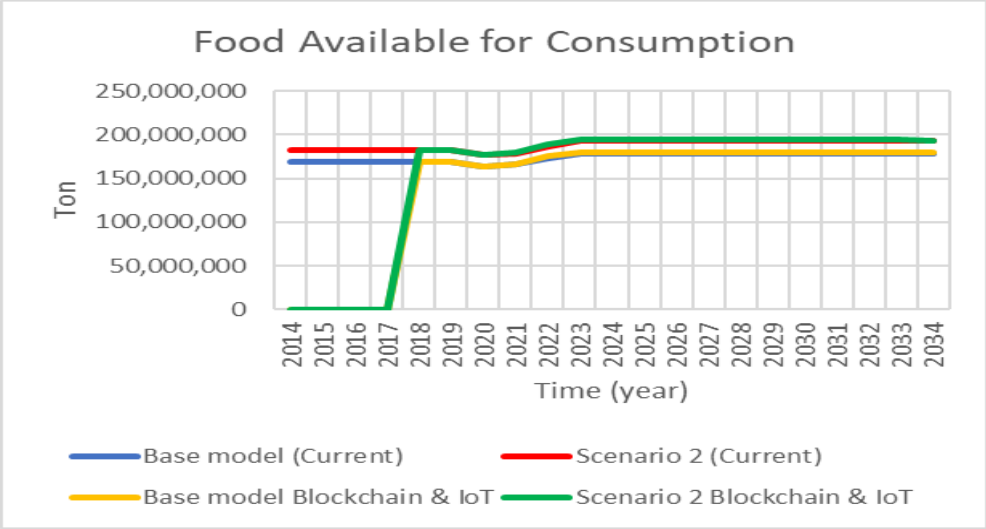

Figure 8. Simulation results of scenario 2 on food available for consumption

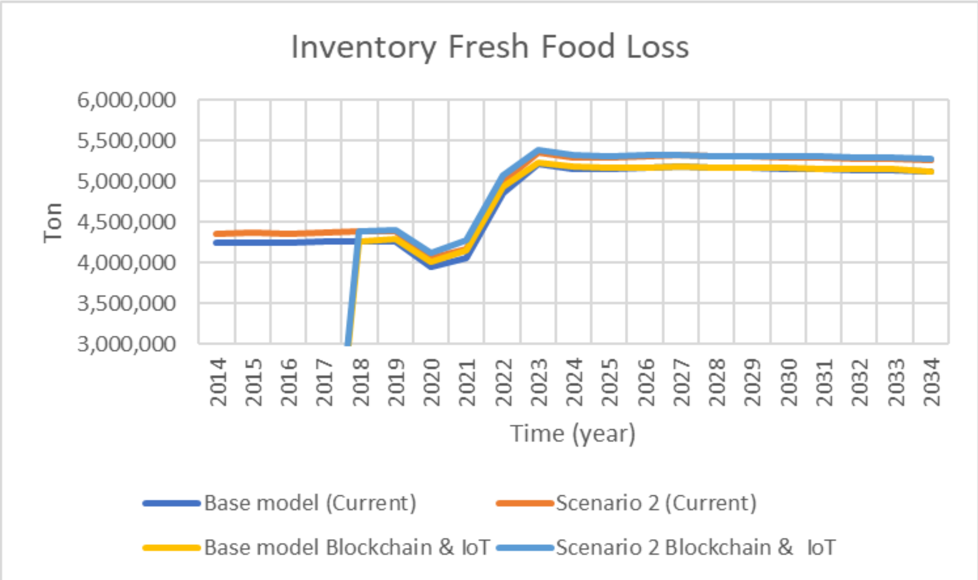

Figure 9. Simulation results of scenario 2 on fresh food inventory loss

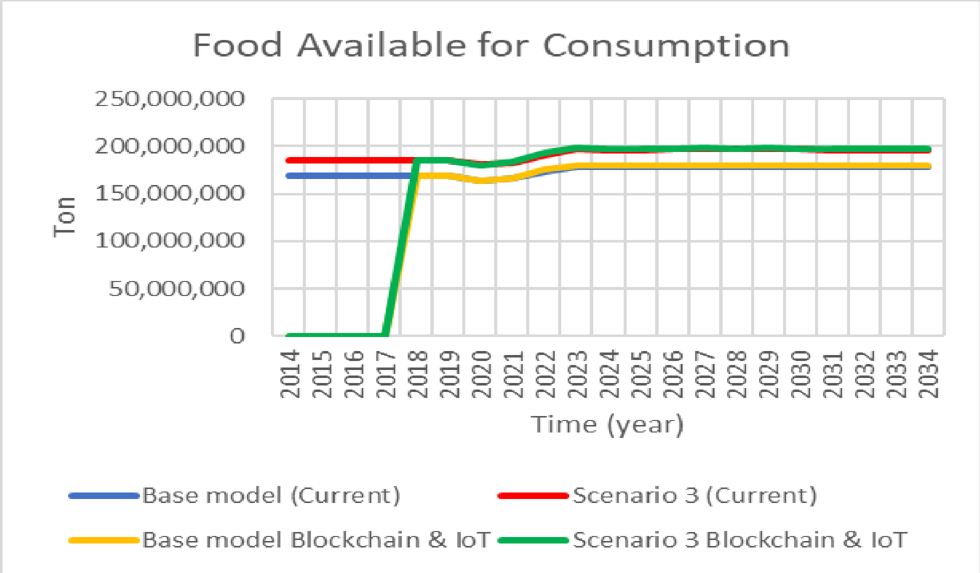

Figure 10. Simulation results of scenario 3 on food available for consumption

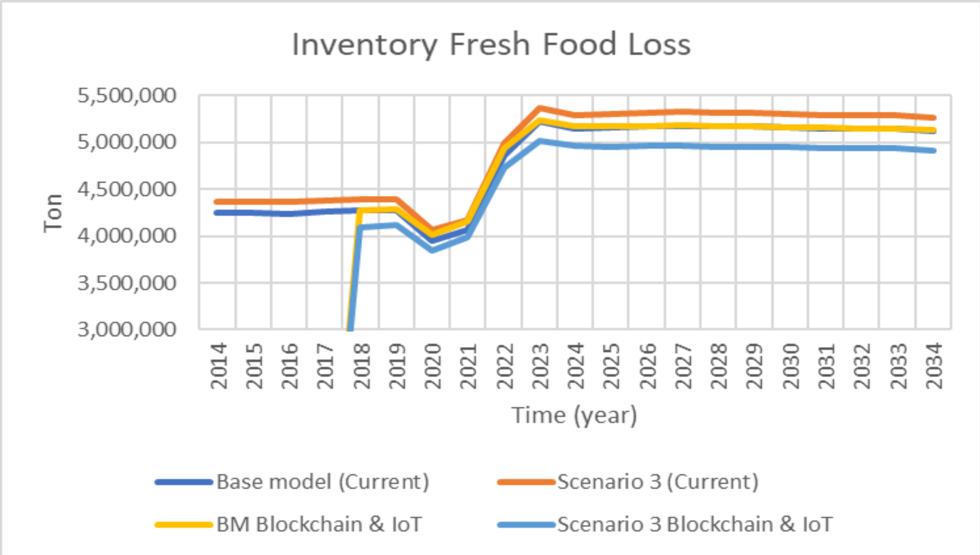

Figure 11. Simulation results of scenario 3 on fresh food inventory loss

Table 4. Comparison between scenarios

	Scenario 1	Scenario 2	Scenario 3
Food available for consumption	4 %	8 %	10 %
Inventory fresh food loss	31 %	3 %	-4%

4. Conclusion

This study successfully built a system dynamics model that describes the relationship between elements in the traceability of the halal supply chain and food safety. The implementation of Blockchain and IoT technology has been proven to be able to increase the availability of optimal food available for consumption. Model validation shows that the simulation is in accordance with real conditions. The scenario development process includes increasing growth efficiency, increasing investment rates, and increasing farmers' storage capacity. The results of the scenario development show that the scenario of increasing farmers' storage capacity has the most positive impact, namely increasing food available for consumption by 10% and reducing fresh food inventory loss by 4%. This study provides recommendations that the use of traceability technology is very important to strengthen food security and the competitiveness of halal products.

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