

System Dynamics Modeling of Robusta Coffee Quality Standard in Indonesia for Global Market Expansion

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ABSTRACT

Indonesia has significant potential for robusta coffee bean production. However, inconsistent export quality remains a major constraint in penetrating the global market. Addressing quality variability is crucial for enhancing the competitiveness and international positioning of Indonesian Robusta coffee. This study aims to develop a quality standardization model for Robusta coffee beans using a system dynamics approach to support quality improvement and ultimately expand the export market for high-quality coffee. This study uniquely links quality governance, farm practices, and export performance through a system dynamics framework for sustainable Robusta coffee development. The model was developed based on primary data derived from indepth interviews and Group Model Building (GMB) workshops involving key stakeholders, complemented by secondary data sourced from relevant research institutions. The system was modeled and simulated using Powersim software. The simulation applied Good Agricultural Practices (GAP) and Good Handling Practices (GHP) through enhanced production inputs, technological adoption, and farmer-level management, which can significantly improve bean quality. The simulation resulted in reduced defect rates, improved bean quality, and increased grade 1–2 export shares. Strengthened quality governance ensures standard consistency, supports farmer welfare, and expands export markets, serving as a reference for sustainable quality policy development in Indonesia's robusta coffee sector.

Key words: Export; good agricultural practices (GAP); quality standardization.

1 INTRODUCTION

Smallholder coffee farming contributes to nearly 80% of total coffee production, serving as a key mechanism for distributing farmers' welfare (Vellema et al., 2015). As a major coffee-producing country, Indonesia competes with other producing nations in delivering high-quality Robusta coffee beans. Nearly 99.5% all of Indonesia's domestic Robusta coffee bean production originates from smallholder plantations (BPS-Statistics Indonesia, 2025). However, several fundamental challenges persist, including inconsistent quality, price fluctuations, lengthy export-related administrative and bureaucratic procedures, limited access to banking and credit facilities, and insufficient government support (Kaido, Takashino & Fukuyaki, 2021). Farmers' practices significantly influence the final quality of coffee, ranging from planting, harvesting, to post-harvest processing stages (Savitri et al., 2022).

Despite Indonesia's substantial potential in Robusta coffee bean production, suboptimal harvest outcomes are primarily attributed to limited technical skills, particularly in post-harvest handling (Dharmaputra et al., 2021; Fufa, Etana & Aga, 2019). Both pre-harvest (on-farm) activities and post-harvest processing contribute significantly to overall coffee bean quality, accounting for approximately 40% and 60%, respectively (Haile & Kang, 2019). Coffee beans not only

serve as the foundational input for all coffee-based beverages but also represent a significant source of income for several subtropical countries (Hall, Trevisan & De Vos, 2022).

The criteria for determining the quality of Robusta coffee beans at the producer level directly affect the final presentation and experience at the consumer level. This is consistent with Mera, Corrales and Mesa (2022) who emphasized that assessing coffee bean quality begins with sampling and identifying the coffee type from cultivation at the farm level to preparation in the cup. At the production stage, quality is influenced by farm management practices, post-harvest handling, and prevailing market prices (Leroy et al., 2006). The physical characteristics of Robusta coffee beans significantly affect the sensory quality of the final beverage. Moreover, coffee cup quality at the consumer level is not only shaped by roasting techniques but also by the specific type and variety of coffee beans selected (Hall, Trevisan & De Vos, 2022).

One of the key factors contributing to the decline in Robusta coffee bean quality is the presence of defects in the beans. In Indonesia, the national standard SNI 01-2907-2008 classifies coffee quality based on a defect value system. This standard aligns with the guidelines of the International Coffee Organization (ICO), which has defined global coffee bean quality standards since October 1, 1983. As shown in Table 1, coffee bean quality is categorized by grade, where a higher defect value indicates a lower grade. In general, Indonesian

Robusta coffee beans are exported at Grade 4 quality, lower than Vietnam, which exports Robusta coffee beans at Grade 1. According to Wibowo and Handayani (2022), the primary cause of coffee bean defects is poor oversight during the processing stage. However, other contributing factors also play a role, including human error, environmental conditions, machinery, raw materials, and processing methods. The higher the defect value, the lower the coffee quality, which directly results in lower market prices. On the other hand, coffee price is a crucial indicator that can drive improvements in farmer welfare (Fitriani, Arifin & Ismono, 2021).

Table 1: Coffee Bean Grades and Defect Values.

Coffee Bean Grades	Defect Values
Grade 1	0 - 11
Grade 2	12 - 25
Grade 3	26 - 44
Grade 4a	45 - 60
Grade 4b	61 - 80
Grade 5	81 - 150
Grade 6	151 - 225

Source: AICE (2025).

The quality at the farmer (producer) level directly impacts quality at the industrial level. Coffee bean quality at the industry level is considered critical in the export market (Girma, 2020). Therefore, the coffee industry is encouraged to improve both quality and sustainable, circular production yields continuously (Hall, Trevisan & De Vos, 2022). In Indonesia, supply chain management for producing high-quality coffee remains limited, resulting in a relatively low level of global competitiveness (Rahardjo et al., 2020). This is reflected in Indonesia's position behind its main competitor, Vietnam, in terms of coffee bean competitiveness (Suryana et al., 2024). A key contributing factor is that Indonesia's coffee farming structure is still largely dominated by smallholder farmers, with harvesting often carried out before full ripeness (Purwawangsa, Irfany & Haq, 2024). Thus, to increase the competitiveness, increasing quality of coffee among smallholder farmers are essential.

Coffee quality in smallholder farmers is driven by a complex relationship of variables that forms a system. Coffee quality is strongly influenced by defect levels and the implementation of Standard Operating Procedures (SOPs). SOP implementation affects both environmental and processing risks, while environmental risk subsequently influences the level of defects. Environmental risk encompasses various external factors that are largely beyond farmers' control, including climate variability, excessive rainfall, high humidity, pest and disease outbreaks, and suboptimal natural drying

conditions. Meanwhile, processing risk relates to technical practices during harvesting and post-harvest handling, such as non-selective cherry picking, uneven fermentation, inadequate washing, inconsistent drying, insufficient sorting, and improper storage conditions. Both types of risk increase the likelihood of defects, including broken beans, black beans, moldy beans, insect-damaged beans, and immature beans, all of which directly reduce coffee quality. Therefore, higher environmental and processing risks lead to greater defect incidence, resulting in lower overall coffee quality produced by smallholder farmers. A decline in coffee quality leads to lower farm-gate prices, which subsequently discourages farmers from consistently implementing cultivation and post-harvest practices in accordance with Standard Operating Procedures (SOPs). This complex system can be modeled adequately by a dynamic model. Dynamic system uses causal relationships in constructing a model of complex (Purnomo et al., 2024). A dynamic system can produce a model through positive and negative feedback, structuring the interactions among system variables (Ramos et al., 2021), enabling a deeper understanding of the variables influencing coffee quality.

Previous studies using dynamic systems in coffee production or supply chain has been conducted well (Bashiri et al., 2021; Kamal et al., 2025; Kurniawan, Suharno & Rachmina, 2023; Purnomo et al., 2024; Purnomo et al., 2025; Rosiana et al., 2024). However, a study that focuses on coffee quality among smallholder farmers, particularly in Indonesia, using a dynamic system has not been conducted yet. Based on these considerations, the objective of this study is to develop a quality standardization model for Robusta coffee beans using a system dynamics approach to promote the increase in export volume of high-quality Robusta coffee. It is expected that this improvement will enhance Indonesia's competitiveness in the international market. The analysis considers key factors such as farmer motivation and the implementation of Good Agricultural Practices (GAP) and Good Handling Practices (GHP). GAP refers to the practices from all on-farm activities from land preparation to harvesting, while GHP is the practices covered all post-harvest activities. The use of production inputs, technology, management, and incentive programs is also considered to be included in the analysis.

2 MATERIAL AND METHODS

2.1 Type and Source of Data

This study utilized both primary and secondary data. The research was conducted in Lampung Province, the largest robusta coffee producer in Indonesia (BPS, 2023). Furthermore, as Lampung's coffee farming is dominated by smallholder farmers, which is the same to Indonesia situation. Primary data were collected in Tanggamus Regency, an area

with the highest level of farmer participation in the Lampung Province. A participatory approach was employed through indepth interviews with 50 farmers. In addition, Group Model Building (GMB) workshops were conducted involving key stakeholders, including farmer group management (15 people), processors or industry representatives (5 people), and government officials (10 people).

Secondary data were obtained from a variety of sources, including the International Coffee Organization (ICO), BPS–Statistics Indonesia, Indonesian Coffee and Cocoa Research Institute (ICCRI), Association of Indonesian Coffee Exporters and Industries (AICE), and published scientific journals. Although this study was conducted only in Lampung Province, the model developed can be used as a reference for improving the quality of Robusta coffee beans in other main production regions. This is supported by the relatively similar cultivation characteristics found across Robusta-producing areas in Indonesia.

2.2 Data Analysis and Processing Methods

The analytical method employed in this study is the system dynamics approach. This approach is capable of capturing the complexity, interrelationships, and temporal dynamics among variables within the quality system. System dynamics can analyze challenges and simulate various policies, providing a comprehensive overview of both the short-term and long-term impacts of the policies implemented (Feryanto et al., 2025). If compared to other approaches such as econometric, optimization, or statistical methods which are generally static and linear these methods are less appropriate for capturing feedback mechanisms and the inherent complexity of dynamic systems (Tramontana & Gardini, 2021). This is because system dynamics incorporates feedback loops among variables and enables the simulation of various policy scenarios. Data processing was conducted using Powersim Studio 10. This approach was utilized to construct a model that emphasizes efforts to improve the standardization of Indonesian Robusta coffee bean quality for integration into the global market. The modeling process followed five main stages: problem articulation, formulation of a dynamic hypothesis, development of a simulation model, model testing, and policy design and evaluation (Sternan, 2000). These stages are essential to ensure that the model accurately reflects the complexities of the Robusta coffee supply chain and supports strategic decision-making for quality enhancement and export competitiveness.

2.2.1 Problem Articulation

Problem articulation is the initial step in understanding the structure and behavior of a system (Muflikh, Smith & Aziz, 2021). In the context of Robusta coffee production, farmers as the primary producers play a critical role in determining the quality of coffee beans. One key issue at the farmer level is the low rate

of coffee plant rejuvenation, which contributes to low production volumes. Additionally, farmers face a persistent challenge of high defect levels in coffee beans. These defects are attributed to various factors, including human error, environmental conditions, machinery limitations, material quality, and inadequate processing methods. As a result, the quality of the beans declines, leading to lower market prices. Therefore, the implementation parameters of GAP and GHP become important factors in improving quality. This is determined by variables such as farmer motivation, management, technology, and production inputs. This is particularly problematic in the global coffee market, where demand is focused on high grade Robusta coffee beans with minimal defects.

2.3 Formulation of Dynamic Hypothesis

Once the problem has been identified, the next stage involves formulating a dynamic hypothesis by modeling the structure of the coffee bean system and linking it to its observed behavior. The dynamic hypothesis is illustrated using a Causal Loop Diagram (CLD). The CLD represents the causal relationships within the system that govern its dynamic behavior (Rich, Rich & Dizyee, 2018; Mai & Smith, 2015). A positive causal relationship exists when an increase in one variable leads to an increase in another variable. Conversely, a negative causal relationship occurs when an increase in one variable leads to a decrease in another. The Causal Loop Diagram (CLD) for the Robusta coffee bean quality standardization model is presented in Figure 1.

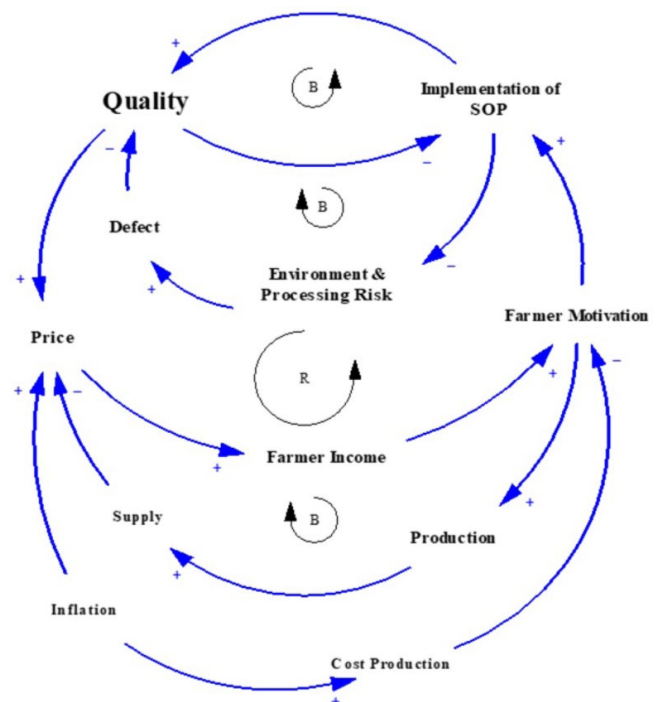


Figure 1: Causal Loop Diagram (CLD) of the Robusta Coffee Bean Quality Standardization Model for Global Market Expansion.

As shown in Figure 1, defect levels and the implementation of Standard Operating Procedures (SOPs) are key determinants of coffee quality within the production system. Coffee quality is inversely related to the implementation of standard operating procedures (SOPs), where increased adherence to SOPs improves quality outcomes. SOP implementation also reduces environmental and processing risks, which in turn lowers the likelihood of defects. In turn, higher defect rates negatively impact coffee quality. This reciprocal relationship forms a closed causal structure where SOP implementation indirectly improves quality through risk mitigation and defect reduction, forming a balancing feedback loop within the system. In the coffee production system, higher quality leads to higher prices received by farmers, which in turn increases their income. As farmers' income rises, their motivation to maintain and improve farming practices also strengthens. Greater motivation positively influences production, ultimately leading to increased supply. However, prices are also affected by inflation, which raises production costs. As production costs increase, farmers' motivation may decline, potentially offsetting some of the positive feedback effects. Thus, the interaction among quality,

price, income, motivation, and production costs forms a dynamic system structure that shapes overall production outcomes.

2.3 Formulation of a Simulation Model

The formulation of a simulation model is intended to clarify ambiguous concepts and resolve contradictions (Sterman, 2000). Effective modeling serves as a bridge between the virtual world represented by the model and the real world, promoting the achievement of model simplification. In this context, the formulation process is grounded in scientific discipline and logical reasoning, and is inherently iterative. The structure of the coffee bean quality standardization model is presented in Figure 2.

In building the model, several types of variables are used. Constants represent fixed values, such as the price of each grade. Stock describes variables that can increase or decrease over time, such as total production or land area. Rate (flow) indicates changes over a time dimension, for example, the annual rate of production growth. Meanwhile, auxiliary variables are used to explain the relationships between variables, such as the quality gap. External factors are also considered, such as price volatility, which is reflected through the inflation

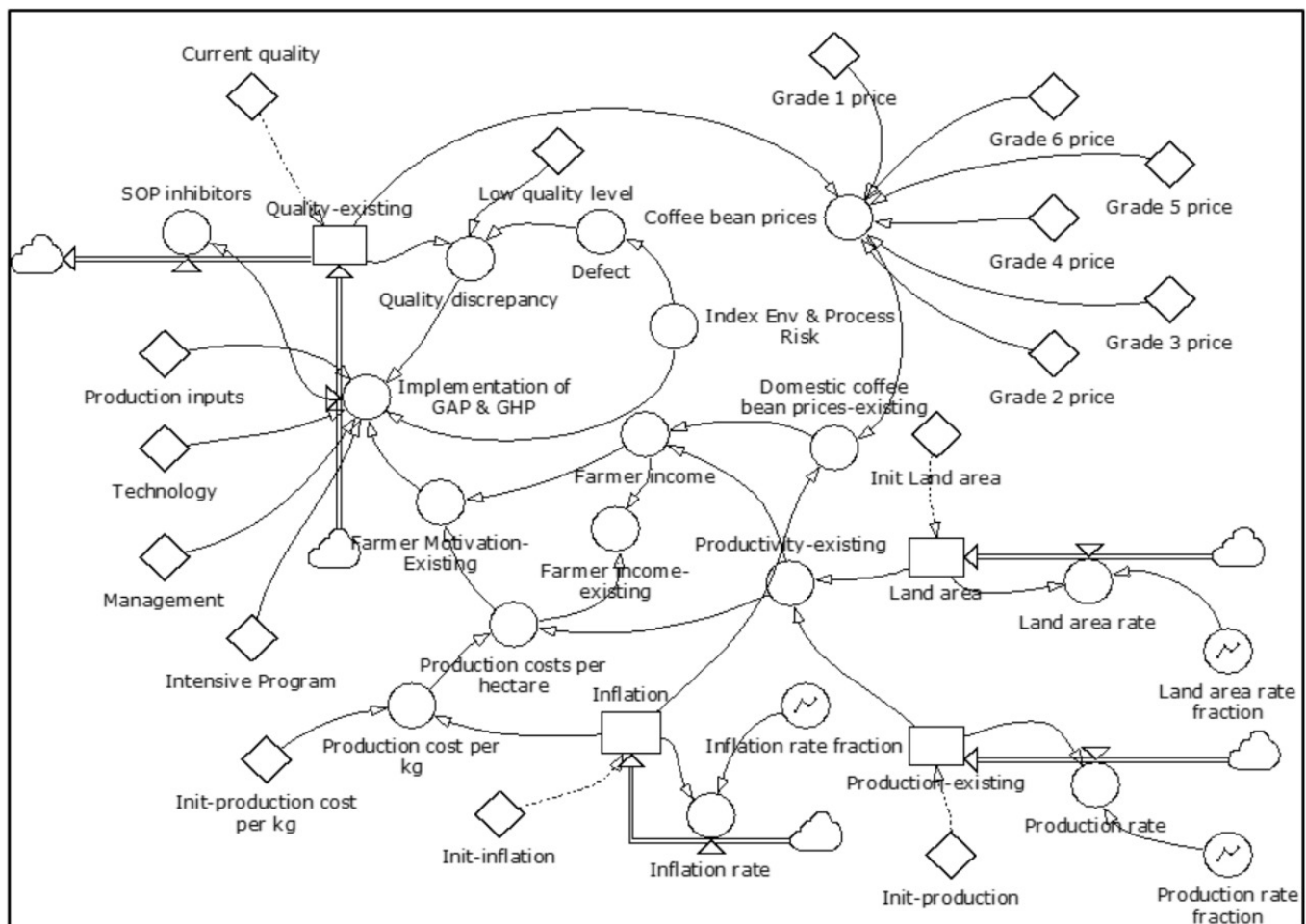


Figure 2: Structure of the Coffee Bean Quality Standardization Model for Global Market Expansion.

variable. However, other external variables like climate factors are not included in the model, as the researcher assumes that changes in the production flow already capture the effects of climate variation. In other hand, production fluctuations may

be influenced by factors such as weather conditions, pests, and other environmental disturbances. The formulation of the Robusta coffee bean quality standardization model, developed for global market expansion, is presented in Table 2.

Table 2: Model Formulation.

No	Variable	Formula	Unit
1	Quality-existing	'Current quality'	Grade
2	Current quality	4	Grade
3	Low quality level	6	Grade
4	Quality discrepancy	'Low quality level'-'Quality-existing'-(100*Defect)	Grade
5	Defect	3.30-'Index Env & Process Risk'	%
6	Index Env & Process Risk	0.8	%
7	Implementation of GAP & GHP	'Farmer Motivation-Existing'*(0.5*Management+0.2*Technology+0.3*Production inputs)*'Quality discrepancy'/'Intensive Program'*'Index Env & Process Risk'	% per year
8	Production inputs	35	%
9	Technology	20	%
10	Management	50	%
11	Intensive Program	3	Times per year
12	Farmer Motivation-Existing	IF('Farmer income'>'Production costs per hectare';1;0)	1 = Motivation 0 = No Motivation
13	Farmer income	'Productivity-existing'*'Domestic coffee bean prices-existing'	IDR per ha
14	Domestic coffee bean prices-existing	'Coffee bean prices'+('Coffee bean prices'*Inflation)	IDR per kg
15	Coffee bean prices	IF('Quality-existing'>=6;'Grade 6 price';(IF('Quality-existing'>=5;'Grade 5 price';(IF('Quality-existing'>=4;'Grade 4 price';(IF('Quality-existing'>=3;'Grade 3 price';(IF('Quality-existing'>=2;'Grade 2 price';(IF('Quality-existing'>=1;'Grade 1 price';0<<_IDN_IDR/_IDN_Kg>>))))))))))	IDR per kg
16	Grade 6 price	20,000	IDR per kg
17	Grade 5 price	23,000	IDR per kg
18	Grade 4 price	25,000	IDR per kg
19	Grade 3 price	28,000	IDR per kg
20	Grade 2 price	30,000	IDR per kg
21	Grade 1 price	35,000	IDR per kg
22	Farmer income-existing	'Farmer income'-'Production costs per hectare'	IDR per ha
23	Production costs per hectare	'Productivity-existing'*'Production cost per kg'	IDR per ha
24	Production cost per kg	'Init-production cost per kg'+('Init-production cost per kg'*Inflation)	IDR per kg
25	Init-production cost per kg	13.598	IDR per kg
26	Inflation	'Init-inflation'	%
27	Init-inflation	1.56	%
28	Inflation rate	Inflation*'Inflation rate fraction'	% per year
29	Inflation rate fraction	GRAPH(TIME;2018;1;{2.46//Min:-1;Max:10//}<<%/ _IND_year>>)	% per year
30	Production-existing	'Init-production'	Kg
31	Init-production	116.281.000	Kg
32	Production rate	'Production-existing'*'Production rate fraction'	Kg per year
33	Production rate fraction	GRAPH(TIME;2018;1;{5.89;0.17;-0.88//Min:-1;Max:10//}<<%/ _IDN_year>>)	% per year
34	Land area	'Init Land area'	Ha
35	Init Land area	156.474	Ha
36	Land area rate	'Land area'*'Land area rate fraction'	Ha per year
37	Land area rate fraction	GRAPH(TIME;2018;1;{0.03;-0.32;0.01//Min:-1;Max:10//}<<%/ _IDN_year>>)	% per year
38	Productivity-existing	'Production-existing'/'Land area'	Kg per ha

2.4 Model Testing

Model testing involves comparing the simulated behavior of the model with the actual behavior of the system. This process is conducted through model verification and validation. Verification and validation are performed to examine the accuracy of the model structure and to ensure that it produces minimal errors when compared to actual (baseline) data. Validation testing is conducted using statistical methods to assess the degree of deviation between the simulation results and historical data. The model validation was conducted over three years (2019–2021), with key variables including production, productivity, and land area. According to Hanke, Wincham and Reitsch (2001) model accuracy can be measured using the Mean Absolute Percentage Error (MAPE). A MAPE value of less than 5 percent indicates a highly accurate model. If the MAPE falls between 5 and 10 percent, the model is considered correct. However, an MAPE percentage greater than 10 percent suggests the model is inaccurate and should be restructured accordingly. The MAPE formula is presented in the following Equation 1:

$$MAPE = \frac{1}{n} \sum_{t=1}^n \left| \frac{Y_t - \hat{Y}_t}{Y_t} \right| \quad (1)$$

Y_t = Existing/actual data value in year t

$\hat{Y}_t$ = Scenario/Simulated value in year t

n = Number of years (observation periods)

In addition to MAPE, Theil's Inequality Statistic (U) was used to measure the goodness of fit between the simulation results and the actual data (Stermann, 2000). Interpretation score: a) U-Theil value of 0 indicates a perfect fit between the model and the actual data, b) U-Theil value ≤ 0.1 indicates a very good fit, c) $0.1 < \text{U-Theil value} < 0.3$ indicates a reasonable fit, d) U-Theil value > 0.3 indicates that the model poor fit. The formula is as follows in Equation 2:

$$U = \frac{\sqrt{\frac{1}{n} \sum_{t=1}^n (S_t - A_t)^2}}{\sqrt{\frac{1}{n} \sum_{t=1}^n S_t^2} + \sqrt{\frac{1}{n} \sum_{t=1}^n A_t^2}} \quad (2)$$

A_t = actual value

S_t = simulated value

n = number of observations

2.5 Policy Design and Evaluation

Policy design involves more than merely adjusting parameter values; it may also encompass the development of entirely new strategies, structures, and decision-making rules. In this study, efforts to enhance the quality of coffee beans are pursued by increasing the number of farmers applying GAP &

GHP in post-harvest processes. This is implemented through the following interventions:

- Agricultural input improvements (increased to 50% from a baseline of 35%)
- Technology adoption (increased to 40% from a baseline of 20%)
- Management enhancement (increased to 60% from a baseline of 50%)

The subsequent phase involves policy evaluation, aiming to ensure that the enhancement of export quality standardization for the global market can be effectively achieved.

3 RESULTS

3.1 Model Validation

Model validation in model development is conducted to assess the correctness of the model structure by ensuring minimal error when compared to actual (baseline) data, thereby enabling objective conclusions (Hartrisari, 2007). In this study, the validity test to measure model accuracy was carried out using the Mean Absolute Percentage Error (MAPE). The validation period covered three years (2019–2021), with the variables measured including production, productivity, land area, and quality. Based on the results, the MAPE values for all four variables were below 5% (Table 3). According to Hanke, Wincham and Reitsch (2001) a MAPE value of less than 5% indicates that the model is highly accurate. Based on U Theil value, the model shows very good validity for the production and productivity variables, and reasonable validity for the land area and quality variable. Therefore, it can be concluded that the model structure has been correctly validated.

Table 3: Model Validation Test Results.

No	Variable	Mean Absolute Percentage Error (MAPE) Value	U Theil Value
1	Production	3.82 %	0.015
2	Productivity	3.37 %	0.022
3	Land area	3.27 %	0.192
4	Quality	2.84 %	0.140

3.2 Coffee Bean Quality Standardization Model

Based on the developed model, in existing conditions, the results indicate a decline in both production and productivity by 0.88% per year and 0.90% per year (Figure 3 & Figure 4). This was attributed to land conversion and climate change. This decline led to a reduction in farmers' incentives from farm yields by 0.85% per year (Figure 5). Income was a crucial factor in the sustainability of land management. The reduction in incentives led to suboptimal land management, as farmers lack the motivation to enhance harvest quality. Without intervention, coffee quality will

progressively deteriorate from Grade 4 (defect value 45-80) to Grade 5 (defect value 81-150) (Figure 6).

Efforts to increase production were undertaken through a policy scenario that includes improvements in agricultural inputs, technology, and farm-level management. The results show that under the scenario conditions, production and productivity increase by 1.5% per year and 1.49% per year (Figure 3 and Figure 4).

Productivity was identified as a variable that directly influences farmers' income and shapes the social and economic

dynamics within agricultural communities. With improvements in inputs, technology, and farm-level management, farmers' income was projected to increase by 6.32 % annually (Figure 5).

An increase in incentives could stimulate farmers to pursue innovation and adopt enhanced, sustainable farming practices. This encouraged farmers to optimize the implementation of Good Agricultural Practices (GAP) in coffee cultivation and Good Handling Practices (GHP) during post-harvest processing, leading to an improvement in coffee quality from Grade 4 (defect value 45–80), to Grade 1 (defect value 0 – 11) (Figure 6).

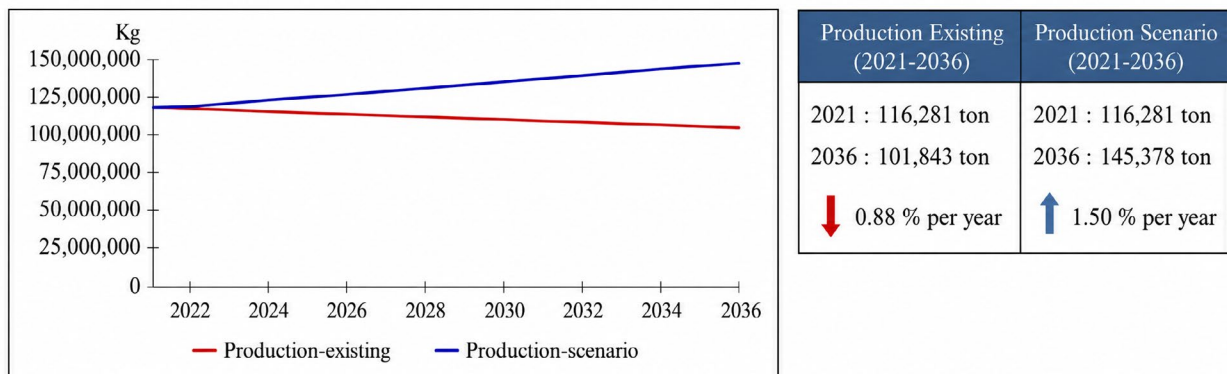


Figure 3: Comparison of Coffee Bean Production (Kg) in Existing and Scenario Conditions.

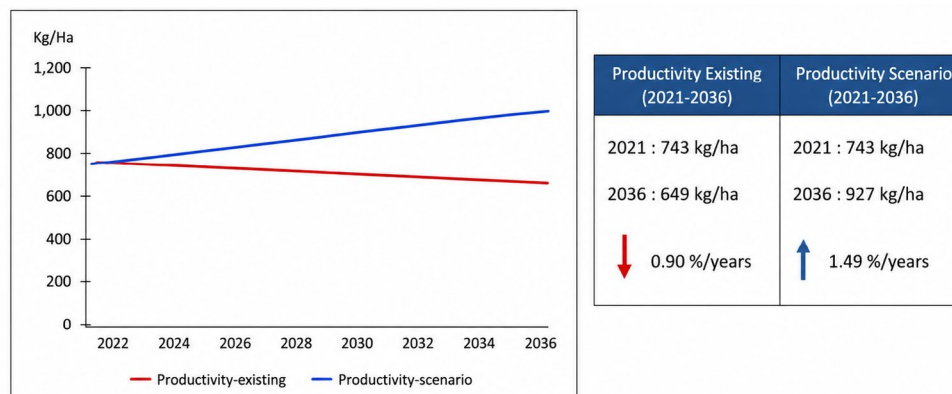


Figure 4: Comparison of Coffee Bean Productivity (Kg per ha) in Existing and Scenario Conditions.

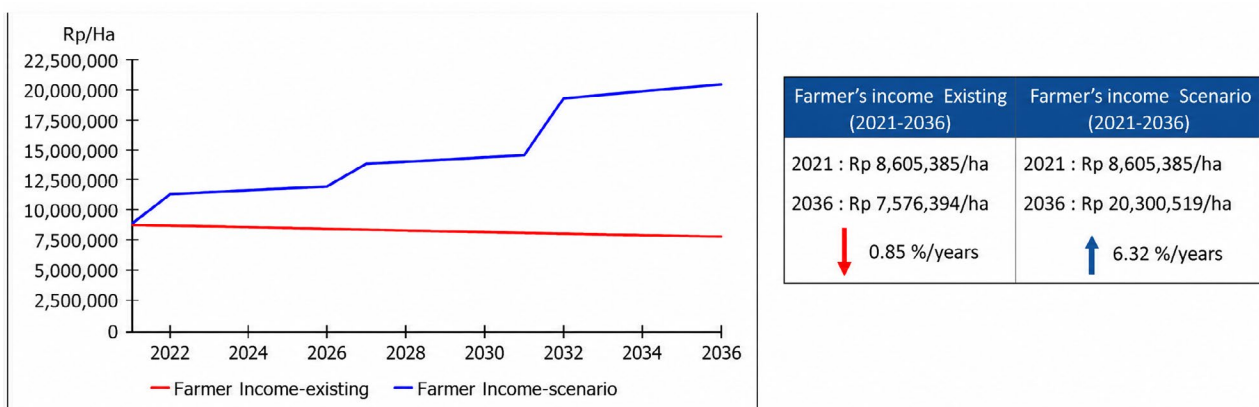


Figure 5: Comparison of Coffee Farmers' Income (IDR per ha) in Existing and Scenario Conditions.

Quality improvements in coffee were projected to substantially transform the grade composition of Indonesian coffee bean exports in the international market. Scenario-based simulations using the dynamic system model revealed a significant shift in grade composition, with Grade 1–2 exports rising sharply to 69.0%, up from a baseline of 10% (Figure 7). This improvement reflected the expected enhancement in coffee quality driven by integrated policy measures aimed at improving agricultural inputs, promoting technological adoption, and strengthening farm-level management. Conversely, the share of Grade 4 exports declined to 25.0%, while Grade 5–6 dropped to 6.0%, indicating better quality as evidenced by reduced defect values.

4 DISCUSSION

4.1 Assessing Coffee Production, Productivity, and Farmers' Income

The coffee bean quality standardization model was a systematic framework designed to ensure quality control from

upstream to downstream processes, including cultivation, harvesting, post-harvest handling, storage, and distribution. In the existing condition, coffee bean production was projected to decline by 0.88% per year from 2022 to 2036 (Figure 3). This decline was primarily attributed to a reduction in cultivated land area at a rate of 0.09% per year, driven by changes in land use and climate change. The conversion of coffee plantations to clove cultivation is reshaping agricultural landscapes in coffee-growing regions and was expected to increase due to its perceived greater profitability (Junais et al., 2024). Additionally, climate change was anticipated to reduce coffee yields and decrease the area suitable for coffee cultivation by 50%–60% by 2050 (Bilen et al., 2022; De Sousa et al., 2019). The decline in land area not only affected production volume but also threatens the sustainability of the coffee industry, the socio-economic well-being of farmers, and contributes to price volatility.

In response to these conditions, efforts to increase production were undertaken through a policy scenario that includes improvements in agricultural inputs, technology, and farm-level management. As shown in Figure 3, in the scenario

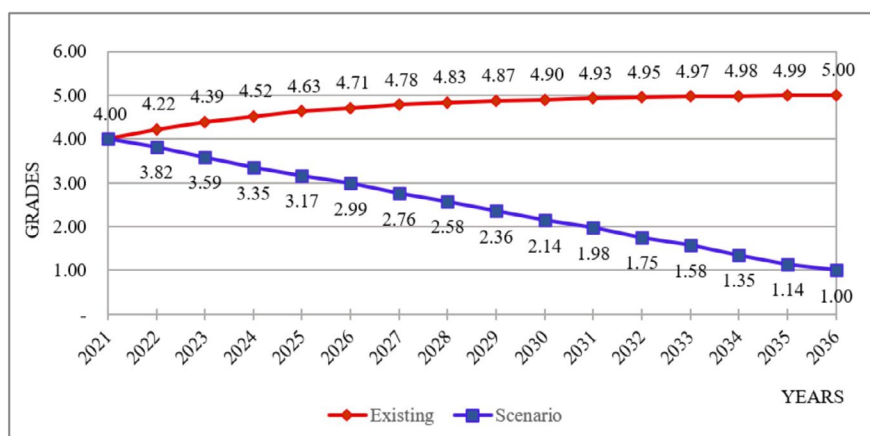


Figure 6: Grade Comparison of Indonesian Coffee Beans (Existing Versus Scenario-Based Quality Improvement).

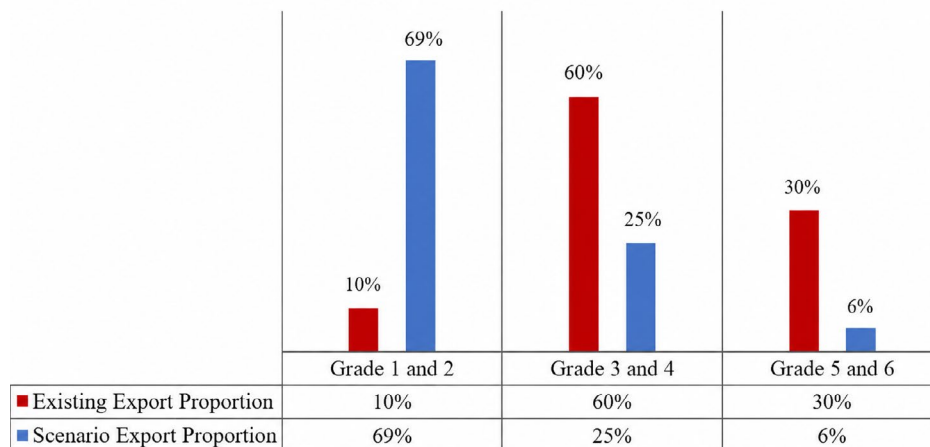


Figure 7: Shifts in the Proportion of Indonesian Coffee Export Grades.

condition, coffee production was projected to increase by 1.5% per year. Successful coffee cultivation, particularly in new planting areas, depends heavily on the use of strong and disease-resistant seedlings (Zambolim, 2021). Technological improvements to boost production are pursued by intensifying coffee production systems through the implementation of Good Agricultural Practices (GAP), which can significantly reduce the risk of defects in coffee beans (Muhie, 2022). Furthermore, improvements in land and water management are achieved through the optimization and sustainable use of land, including the planting of shade trees, which helps prevent soil erosion and contributes to sustainable coffee farming practices (Ismono et al., 2022; Pramastiwi et al., 2010). The optimization of community forest land use through coffee-based agroforestry systems can be further promoted in Eastern Indonesia by utilizing suboptimal land resources, such as peatlands in Central Kalimantan (Sudjarmoko, 2013; Supriadi & Pranowo, 2015). Agroforestry enhances farmers' adaptive capacity and helps mitigate risks and uncertainties (Poncet et al., 2024). This is consistent with Muhie (2022), who states that improving both the quantity and quality of coffee can be achieved by diversifying production areas. Therefore, production enhancement policies need to be accompanied by farmer capacity strengthening and the adoption of sustainable practices to ensure that the expected results can be achieved optimally.

The scenario of increasing coffee bean production through improvements in inputs, technology, and management led to an increase in productivity by 1.49% per year. The productivity level was projected to reach 927 kg/ha by the end of the analysis period (Figure 4). Productivity was largely determined by the quantity of coffee beans produced by farmers within a given land area. One of the key factors in improving productivity is the use of certified superior seedlings (Suganda, Dina & Setyawati, 2024). However, high-quality coffee seeds were often difficult to access at the farm level, which suggests a role for government intervention in replicating stimulant assistance programs aimed at farmer empowerment, as well as in enhancing farmers' capacity to become seed producers. Additionally, gradual coffee tree rejuvenation is needed by the productive age of existing plants to improve both productivity and quality (Amanda & Rosiana, 2023). The application of modern technologies such as drip irrigation, data-driven fertilization, and efficient post-harvest methods can further enhance yields (Gisisi & Purwaningsih, 2025). These agricultural practices are essential for ensuring consistency, quality, and alignment with government policies in providing innovation incentives and investment support (Suryana et al., 2024). Beyond technological adoption, other efforts include the implementation of fair trade certification, intensive farmer training, the involvement of women, and a focus on active farmers (Sarirahayu & Aprianingsih, 2018).

These are part of farm-level management improvements that serve as mechanisms for knowledge transfer and capacity building in both technical and managerial aspects. Strengthening farmers' understanding and awareness of these practices is essential for driving productivity improvements.

Based on the developed model, productivity was identified as a variable that directly influences farmers' income and shapes the social and economic dynamics within agricultural communities. An increase in productivity reflects improved efficiency in input utilization, thereby generating positive impacts on farmers' value added (Aziz & Suryana, 2023). As illustrated in Figure 5, in the scenario condition characterized by improvements in inputs, technology, and farm-level management, farmers' income was projected to increase by 6.32 % annually. In 2036, it was estimated that farmers will earn approximately IDR 20,300,519 per ha. Improvements in agricultural and post-harvest practices in line with Good Agricultural Practices (GAP) significantly enhance income levels (Aulia, Andy & Desi, 2019). Efforts to improve post-harvest quality include selective harvesting (red cherry picking), sorting to remove impurities (such as dust, parchment, and unhulled beans), drying until the moisture content reaches 12 percent, and separating defective beans (Simorangkir & Nia, 2022). Rising income levels also contribute to improved incentives and labor skills (Purnomo et al., 2024). Moreover, farmers who are members of cooperatives tend to achieve better performance and higher income (Mojo, Fischer & Degefa, 2017). This is attributed to capacity-building activities such as training programs conducted at the cooperative and farmer group levels, which strengthen farmers' motivation and skills. The development of a positive mental attitude among farmers not only supports economic outcomes but also plays a crucial role in enhancing the resilience and independence of the coffee agribusiness system. Based on the analysis, the scenario of increasing coffee production and farmers' income has a positive impact on strengthening the competitiveness and sustainability of the national coffee sector. Through consistent policy support, appropriate technology implementation, and farmer capacity strengthening, the coffee agribusiness system can develop to become more resilient, inclusive, and competitive in the global market.

4.2 Analysis of Indonesian Coffee Quality Improvement

The provision of incentives and skill development can encourage farmers to continuously innovate and adopt more efficient and sustainable cultivation practices, thereby reducing production costs. The unique characteristics of coffee in specific growing regions serve as a potential area of innovation for commodity development. Coffee bean quality that reflects distinctive traits aligned with Geographical

Indications can create added value for producers, ultimately enhancing livelihoods and contributing to poverty alleviation (Neilson, Wright & Aklimawati, 2018). Moreover, the level of farmer participation in coffee certification is shown to increase annual income by up to 2.9 times compared to non-certified farmers (Bekere & Megersa, 2021). This is primarily due to the traceability system implemented during the certification process, which begins at the farm level and enables the product to command premium prices that enhance farmer income (Jaya, Yusriana & Ardiansyah, 2019). In addition, sustainable certification practices can reduce negative environmental impacts by more than 50% (Ho et al., 2018). Therefore, in order to increase production, productivity, and quality, government support is required in the form of subsidies or other initiatives targeted at coffee farmers (Paryanto, 2025).

Improvements in coffee bean quality are positively correlated with higher selling prices, which in turn directly contribute to increased farmers' income. In the developed model, quality enhancement is determined by two key variables, namely defect and environment & processing risk, which serve as the primary determinants of coffee quality. The implementation of Good Agricultural Practices (GAP) reduces environmental risk through improved farm management, including effective pest and disease control, proper fertilization, and selective harvesting, thereby minimizing the occurrence of physical and biological defects at the cultivation stage. Meanwhile, the application of Good Handling Practices (GHP) mitigates processing risk by strengthening standards in fermentation, drying, sorting, and storage, which directly reduces the likelihood of post-harvest defects. The simultaneous reduction of these risks systematically lowers defect values, resulting in significant improvements in overall coffee quality and enhancing farmers' opportunities to obtain premium prices and higher incomes.

The dynamic system model developed in this study produces a comparison of export quality, represented by the grade and defect value of exported coffee beans in both conditions (Figure 6). In the existing condition, the average grade of Indonesian Robusta coffee exported in 2021 was classified as Grade 4 (defect value 45–80), while by 2036, it was projected to decline to Grade 5 (defect value 81–150). This indicated a deterioration in the export quality of Indonesian coffee beans. To resolve this issue, a dynamic system simulation was employed by integrating a policy scenario designed to enhance quality through improvements in agricultural inputs, technological adoption, and farm-level management practices. The results showed that in the scenario condition, there was a significant improvement in the quality of Indonesian exported coffee beans. Specifically, the average grade improved from Grade 4 (defect value 45–80) in 2021 to Grade 1 (defect value 0–11) by 2036, indicating a notable decrease in defect value and thus an overall quality enhancement.

The effective and efficient implementation of Good Agricultural Practices (GAP) in coffee farming is influenced by a range of interrelated factors. In addition, one of the most critical components of Good Handling Practices (GHP) during post-harvest processing that affects coffee quality is the drying process (Tesfa, 2018). Proper drying reduces moisture content to an optimal level, allowing for longer storage without compromising quality. Furthermore, the involvement of multiple stakeholders, such as the Geographical Indication Concerned Community, plays a vital role in providing farmer-level extension services and technical assistance, which in turn contributes to quality improvement (Rosiana & Feryanto, 2022). Therefore, the adoption of technology, the advancement of knowledge, and emphasis on quality have a direct impact on the development of Coffee Social Networks (CSNs), which drive the growth of the coffee agroindustry (Pereira et al., 2022). Based on this, synergistic support between technological innovation, institutional strengthening, and the implementation of agricultural practices is essential to reinforce the sustainability of the national coffee agribusiness system development.

4.3 Global Market Analysis of Shifts in Indonesian Coffee Export Grade Composition

Improvements in coffee quality were projected to significantly shift the composition of Indonesian coffee bean exports across grade categories in the international market. In existing conditions, Indonesia's Robusta coffee exports are predominantly composed of Grade 3–4 beans (60%), followed by Grades 5 and 6 (30%), with only 10% comprising high-quality beans (Grades 1 and 2) (AICE, 2025). Scenario-based simulation results derived from the dynamic system model indicated a substantial reconfiguration of this composition, with the proportion of Grade 1–2 exports increasing markedly to 69% a significant improvement from the baseline of 10% (Figure 7). This shift reflected the anticipated enhancement in coffee quality as a result of integrated policy interventions targeting improvements in agricultural inputs, technological adoption, and farm-level management practices. On the other hand, Grade 3–4 coffee exports fell to 25%, and Grade 5–6 fell to 6%. This indicated an improvement in quality as indicated by a decrease in defective values.

The projected improvements in coffee quality also emphasize how crucial it is for Indonesia to meet the standards and demands of international markets. In the international market, Indonesia faces regulatory challenges such as food safety standards, including limits on Ochratoxin A (OTA) and pesticide residues (e.g., carbaryl), particularly in the European and Japanese markets, which are among Indonesia's main coffee importers (Nugroho, 2014). Therefore, compliance with export quality standards is essential for producers and must

be achieved through improvements in production systems (Kaido, Takashino & Fukuyaki, 2021). In addition, quality enhancements should be aligned with the demands of target markets to effectively respond to non-tariff barriers imposed by importing countries (Suryana et al., 2023; Rosiana et al., 2017). The implementation of Good Agricultural Practices (GAP) in farming activities and Good Handling Practices (GHP) in processing serves as an effective guarantee of quality for consumers in the global coffee trade. Certification processes can provide competitive advantages by offering product value propositions (Sudirman, Nuralina & Suprehatin, 2021). Furthermore, certification and adherence to international quality standards can expand market access (Purwawangsa, Irfany & Haq, 2024).

The increase in the export share of Grade 1 and 2 Robusta coffee by 69% (Figure 7) represented a strategic opportunity for Indonesia to strengthen its position in key export markets and expand into new ones. Indonesia holds a similar chance to Vietnam, its main competitor among global Robusta exporters to increase export volumes to the United States, as both countries are currently positioned as rising stars in the global market (Pratita & Budiarto, 2021). This rising star status is characterized by a country's export growth rate exceeding the global export growth rate (Edwards and Schoer, 2002; Ozcelik & Erlat, 2013). This presents a significant opportunity for Indonesia to consolidate its presence in high-potential markets and broaden its export destinations. In addition to the United States, other potential markets for Indonesian Robusta coffee include India, Germany, and the United Kingdom. Moreover, export market development should prioritize expansion into Belgium, Italy, Malaysia, Egypt, and the Russian Federation (Aurelia, Syaikat & Falehan, 2022).

To improve the quality and global competitiveness of Indonesian Robusta coffee beans, an integrated policy framework is required to support the adoption of cultivation and post-harvest technologies at the farm level. It is recommended that the government and relevant stakeholders expand and sustain training programs on Good Agricultural Practices (GAP) and Good Handling Practices (GHP), while also providing incentives for farmers who implement practices aligned with export-quality standards. The provision of certified high yielding seeds and improved access to modern post-harvest technologies is also essential to reduce defect rates in coffee beans. Furthermore, strengthening farmer institutions such as cooperatives or farmer groups can serve as an effective mechanism for knowledge transfer, access to finance, and quality management. To reinforce Indonesia's position in the global market, standardization efforts should be accompanied by the development of integrated certification and traceability systems along the entire value chain, from upstream to downstream. Improving the quality and consistency of Indonesian Robusta coffee through integrated

technological, institutional, and policy support is essential to strengthen its global competitiveness. These efforts will also build consumer trust and increase market demand, thereby expanding Indonesia market reach and reinforcing its position in high value international markets

5 CONCLUSIONS

Simulation results indicate that reducing defects enhances coffee bean quality and increases the export share of Grade 1–2 Indonesian robusta coffee. The model highlights the importance of certified seeds, mechanization, post-harvest innovation, strengthening farmer institutions, appropriate incentives, and traceability as key measures. Integrated quality governance contributes to improved production consistency, enhanced market competitiveness, and supports the sustainable development of Indonesia's robusta coffee sector.

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7 AUTHORS CONTRIBUTIONS

Conceptual idea: Rosiana, N.; Methodology design: Rosiana N.; Feryanto.; Data collection: Herawati.; Maharani I., Data analysis and interpretation: Rosiana, N.; Feryanto; Dewi, T.G., Writing and editing: Rosiana, N.; Dewi, T.G.; Maharani, I.; Feryanto; Herawati.

8 DATA AVAILABILITY STATEMENT

Data available upon request to authors.

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