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System Dynamics Model of Technology Transition under Resource Constraints: A Catfish Farming Case

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Abstract:
Background. This study deals with a System Dynamics (SD) model to investigate technology transition under resource constraints, using small-scale catfish farming as a case study. In this context, land availability constitutes the resource constraint. To address this constraint, it is necessary to achieve catfish productivity gains through technological intensification, such as the use of aquaponics.
Methods. The SD model captures feedback interactions among production, operating costs, revenue, profit, and reinvestment by setting aside a portion of profits. The SD model's behavior is analyzed by generating six scenarios over 25 years to examine the effects of feed price fluctuations, fingerling price fluctuations, and alternative reinvestment rates. Model outcomes were evaluated using production, profitability, and the benefit–cost ratio (BCR) as an economic performance indicator.
Result. The results show that feed and fingerling price fluctuation exerts a strong negative effect on profitability and economic feasibility, while higher reinvestment rates accelerate aquaponics adoption and improve long-term performance.
Conclusion. BCR analysis indicates that technology transition in land-limited catfish farming is feasible only when BCR remains above unity, supporting sustained reinvestment.
Implementation. The study highlights the importance of reinvestment strategies and feed and fingerling costs management in enabling resilient technological upgrading in spatially constrained aquaculture systems.

Keywords: System Dynamics model, Technology Transition, Catfish Farming

INTRODUCTION

Productivity in resource-constrained environments aims to maximize output value by optimizing available inputs through efficiency and appropriate technology. This strategy focuses on minimizing waste, enhancing system performance, and implementing suitable technological solutions to ensure sustainable productivity despite resource limitations. In aquaculture, this is exemplified by the shift of conventional to aquaponic technology, which combines fish farming and plant cultivation, promoting nutrient recycling, lowering resource use, and increasing production density while fostering environmental sustainability.

Aquaculture is increasingly vital for global food production due to declining capture fisheries and rising demands for aquatic protein. (FAO, 2020). In Indonesia, small-scale aquaculture is crucial for local livelihoods and food security, yet farmers face land availability challenges, particularly in peri-urban areas with limited plots. Conventional pond systems require significant space, making land a key barrier to production growth. (Kumar & Engle, 2016). This constraint is especially pronounced in catfish (Clarias spp.) farming, where production growth is often limited by fixed pond area rather than biological potential. (Engle & Stone, 2014). Consequently, enhancing productivity through technological intensification has become essential for maintaining catfish production amidst these constraints.

Under these constraints, productivity enhancement necessitates the adoption of land-efficient technologies rather than horizontal expansion. Aquaponics—integrating recirculating aquaculture with hydroponic plant production—offers land-use efficiency, improves nutrient recycling, reduces water consumption, and generates dual outputs within a compact system. (Goddek et al., 2019; Graber & Junge, 2009; Kyaw & Ng, 2017; Reyes Lastiri et al., 2018; Sundari et al., 2020; Tokunaga et al., 2015; Tyson et al., 2011). As a result, aquaponics provides a technological pathway for increasing output without expanding physical space. However, empirical adoption rates remain low, suggesting that technological feasibility alone is insufficient to trigger widespread transition. Instead, economic capacity—particularly profitability and reinvestment potential—plays a decisive role in enabling or inhibiting technology uptake.

Economic feasibility further complicates the transition process. Feed constitutes 60–70% of operational costs in catfish farming. (Hasan & New, 2013), and fingerlings represent the second-largest cost component (Engle & Stone, 2014). Both inputs are subject to substantial price fluctuations driven by global commodity markets, supply chain disruptions, and seasonal dynamics. (Tacon & Metian, 2015). Cost fluctuations negatively affect profit margins and hinder farmers' ability to reinvest, disrupting the process of converting financial surpluses into technological advancements. This indicates that the technology transition is influenced by various economic feedbacks, interactions, and delays, making it inappropriate for assessment through traditional static analytical methods like cost–benefit analysis.

Technology transition in aquaculture is inherently dynamic, involving feedback interactions among production capacity, operating costs, profit generation, and reinvestment behavior over time. In land-constrained catfish farming, rising input costs—particularly feed prices—can erode profitability, weaken reinvestment capacity, and slow or even reverse technological upgrading (Tacon & Metian, 2015). Conversely, sustained reinvestment can enhance production efficiency, offset cost pressures, and reinforce long-term adoption trajectories. Capturing these interacting processes requires a modeling approach capable of representing endogenous feedback and long-term system behavior.

System Dynamics (SD) offers a suitable framework for analyzing such complex transitions, as it explicitly models feedback loops, accumulation processes, and non-linear dynamics. (Forrester, 1994; Sterman, 2000). SD has been applied in various agricultural and aquaculture contexts to examine technology diffusion, resource constraints, and policy interventions (Isa et al., 2021; Li et al., 2012). However, existing SD studies rarely focus explicitly on land-constrained catfish farming, nor do they systematically evaluate how economic feasibility evolves during technology transition under input price fluctuation.

Moreover, while economic feasibility is central to adoption decisions, it is often treated implicitly in dynamic models. Clear performance indicators are needed to assess whether technological intensification remains economically sustainable over time. In this regard, the benefit–cost ratio (BCR) provides a transparent and widely used metric for evaluating economic feasibility (Cao Thi, 2025). When applied as an evaluation tool for model outcomes, BCR enables assessment of whether efficiency gains from technology adoption are sufficient to sustain reinvestment and long-term transition.

Against this background, this study develops a System Dynamics model to analyze technology transition in land-constrained small-scale catfish farming, with a specific focus on the shift from conventional pond systems to aquaponics. The model captures feedback interactions among production, costs, profit, and reinvestment, and is simulated under multiple scenarios of input price fluctuations and reinvestment strategies. Model outcomes are evaluated using production indicators, profitability, and BCR as a measure of economic feasibility. By integrating dynamic modeling with explicit economic evaluation, this study aims to identify key leverage points that enable resilient and economically feasible technology transition in land-limited aquaculture systems.

This article is organized as follows: Section 1 describes the introduction, Section 2 presents the literature review, Section 3 defines the research method, Section 4 shows the results and discussion, and Section 5 states the conclusion.

Research on sustainable aquaculture under resource constraints is developing in several mainstreams:

1. Land Constraints and Aquaculture Intensification. Previous studies have confirmed that land constraints are driving a shift from horizontal expansion to technological intensification. In the context of small-scale aquaculture, productivity is more often limited by the size of the pond than by the biological potential of the fish. Therefore, land-intensive technology is the main focus in increasing production.
2. Aquaponics as a Land-Saving Technology Solution. Aquaponics has been widely recognized as an integrated production system that improves the efficiency of land, water, and nutrients while generating dual output (fish and crops). Previous research has largely addressed the technical, environmental, and economic feasibility of aquaponics, but its adoption at the smallholder level is still relatively low due to initial investment needs and economic uncertainty.
3. Dynamics of Production Costs and Economic Feasibility. The aquaculture literature confirms that feed and seed costs are the largest and most volatile component of costs. These fluctuations significantly affect the profitability and ability of farmers to reinvest in technology. However, most economic studies still use a static cost–benefit analysis approach that does not capture long-term dynamics.
4. System Dynamics (SD) in Aquaculture. The System Dynamics approach has been used to model complex agricultural and aquaculture systems, including ecological, economic, and policy interactions. However, the application of SD in the transition of small-scale aquaculture technology with limited land, especially catfish farming, is still very limited and rarely explicitly integrates economic feasibility indicators.

LITERATURE

Land Constraints and Aquaculture Intensification

Land availability limits the capacity of small-scale farmers to expand pond-based aquaculture systems. In regions with high population density or competing land demand, physical expansion becomes infeasible, thereby restricting production growth (Kumar &

Engle, 2016). Under such conditions, intensification through technological upgrading becomes the primary pathway for achieving higher output.

Aquaponics as a Land-Efficient Production System

Aquaponics integrates recirculating aquaculture with hydroponic plant cultivation, offering high land-use efficiency and reduced water consumption compared to traditional ponds (Goddek et al., 2019; Tyson et al., 2011). Studies show that aquaponics systems can improve nutrient recycling, minimize waste discharge, and support profitable production when managed effectively (Love et al., 2015). However, adoption remains limited due to high initial investments and requirements for stable operational profitability. Figure 1 shows the Aquaponics system.

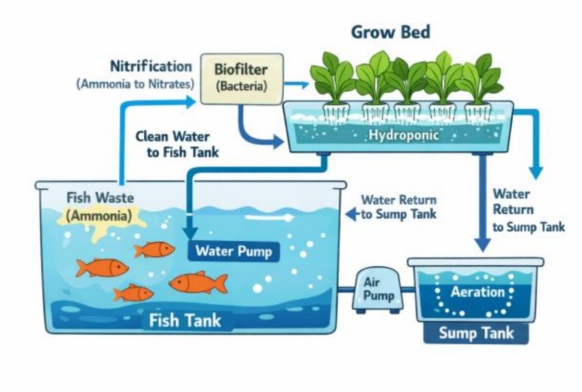

Figure 1. The Aquaponics system

Economic Feasibility and Input Costs Dynamics

Feed costs account for the majority of variable expenses in catfish farming, often exceeding 60% of total cost (Hasan & New, 2013). Fingerling costs represent another major expenditure (Engle & Stone, 2014). Fluctuation in these inputs—driven by global commodity markets, supply chain instability, and local availability—reduces profit margins and undermines farmers' capacity to reinvest in new technologies (Tacon & Metian, 2015). While traditional cost–benefit analyses provide useful snapshots of economic performance, they fail to capture dynamic feedback effects such as declining reinvestment capacity following profit erosion. To address this limitation, performance indicators such as the benefit–cost ratio (BCR) are commonly used to evaluate economic feasibility as an outcome of dynamic processes rather than as a static decision criterion (Cao Thi, 2025).

System Dynamics Applications in Aquaculture

System Dynamics (SD) has been widely used to model ecological, economic, and sustainability-related processes in aquatic systems. Studies include nutrient transformations in ponds (Jiménez-Montealegre et al., 2002), livestock-derived food systems ((Queenan et al., 2020), eco-agriculture modeling (Li et al., 2012), sustainability assessments (Moallemi et al., 2021), and aquaculture policy simulations (Isa et al., 2021; Li et al., 2012). SD enables a better understanding of long-term behavior arising from feedback structures, making it well-suited to evaluating technological transition in aquaculture systems under constraints.

Research Gap

Although previous studies highlight (1) the importance of land constraints, (2) the benefits of aquaponics, (3) the influence of input price fluctuation, and (4) the usefulness of SD modeling, no existing study integrates these elements into one dynamic framework. This gap motivates the development of a model that captures how land constraints, cost fluctuations, and reinvestment interactions shape technology transition trajectories.

Contribution of This Study

Building on the above gaps, this study develops a System Dynamics model to analyze technology transition in land-constrained small-scale catfish farming, focusing on the shift from conventional pond systems to aquaponics. By evaluating model outcomes using production indicators, profitability, and the benefit–cost ratio (BCR), the study provides new insights into the conditions under which technological intensification can be economically sustained. This integrated approach contributes to both the methodological literature on SD modeling and the applied literature on sustainable aquaculture development under spatial constraints.

Based on the literature review and the position of this article, there are several main research gaps:

1. There is no integrated dynamic model yet. Previous studies have not simultaneously integrated land limitations, fluctuations in the price of key inputs (feed and seeds), and reinvestment mechanisms within a single System Dynamics framework for small-scale catfish farming.
2. Economic feasibility has not been analyzed as a dynamic process. Most studies assess the feasibility of aquaponics statically, thus unable to explain how declining profits affect

reinvestment and how reinvestment affects long-run technology adoption and production.

3. Lack of focus on catfish cultivation in urban/peri-urban areas. Although catfish is an important commodity in Indonesia, elementary school research examining the technological transition of catfish under urban land constraints is still scarce.
4. Lack of explicit economic indicators in the SD model. Many SD models do not use indicators that are easy for decision-makers to interpret. The Benefit–Cost Ratio (BCR) is rarely used as the primary indicator for dynamically assessing the sustainability of the technology transition economy.

METHOD

System Dynamics Modeling Approach

The study employs a System Dynamics methodology, following established procedures for modeling complex systems. (Forrester, 1994; Sterman, 2000). The model simulates yearly dynamics over 25 years to capture long-term production, profitability, and reinvestment behavior under conditions of technology transition.

System Identification

The research proposes transforming the nursery ponds into aquaponic systems, leveraging profits to improve production efficiency. Catfish is a reasonable consideration for adopting aquaponic technology. (Bosma et al., 2017). Catfish farming begins with the spawning of broodfish, followed by fingerlings in a nursery pond, and foodfish in a grow-out pond. (Kumar et al., 2019).

Aquaponics requires investment and operational costs. The investment costs to build Aquaponics include the costs of building open greenhouses, fish tanks, and grow beds, plumbing, aeration, labor, and Aquaponics installation costs (Benjamin et al., 2020; English, 2015; Lapere, 2010; Quagrainie et al., 2017). For subpolar areas, e.g., Finland, it requires additional artificial light (Martin, 2017). Aquaponics operational costs include the price of fingerling and vegetable seedlings, feeding costs, electricity, labor, and transportation (Benjamin et al., 2020; English, 2015; Lapere, 2010; Quagrainie et al., 2017) and costs of water warming, greenhouse heating, and greenhouse illumination for subpolar areas (Martin, 2017).

This study investigates a local catfish farmers' association in Bandung, Indonesia, as a research object that will be identified. The association has 10 nursery ponds and 12 grow-out ponds, using conventional methods. Currently, the nursery ponds have been built under a conventional greenhouse in a tropical area, using biofloc technology. Consequently, building an open greenhouse and additional artificial light, water warming, greenhouse heating, and greenhouse illumination as described by Benjamin et al. (2020, English (2015), Lapere (2010), and Quagrainie et al. (2017) are ignored.

The fingerlings are spread to the conventional nursery ponds every 3 months with an average density of 3,600 fingerlings per pond. The fingerlings could be transferred from the nursery to the grow-out pond at 95%, but the foodfish mortality rate in the grow-out ponds was 10%. When the fish are harvested, they weigh 10 to 20 times more (Avery, n.d.). The farmers harvest the food fish every 2 weeks, 0.5 tons, and sell them to the local market at a selling price of Rp. 17,000/kg. Hence, the farmers get a revenue of Rp . 221 million/year. This fish production only satisfies a small part of Bandung City's high and persistent demand. Bandung City has a population of 2.5 million people with a growth rate of 2.5%. It is assumed that 20% of the population consumes 3 kg of catfish per person per year, with a growth rate equal to the population growth rate.

Developing conventional nursery ponds to Aquaponics technology only requires an investment of Rp . 1 million to buy a water pump, piping, and installation costs. Meanwhile, producing catfish requires operational costs as follows:

Fingerling	Rp.. 6 million/ton
Fingerling feed	Rp.. 3.8 million/ton
Vegetable seed	Rp.5,000/pond.
Maintenance	Rp. 42,000/year. pond
Labor	Rp. 7.2 million/year. pond
Transportation	Rp . 390,000/year. pond
Electricity	Rp . 60,000/year. pond

In the real world, feed and fingerling prices fluctuate frequently, although the selling price of foodfish remains relatively consistent. Feed and fingerling prices account for the majority of operating expenditures, affecting revenues. Farmers sell food fish to market sellers rather than directly to consumers, so the selling price is relatively consistent.

Conceptualization of the Model Using the Causal Loop Diagram (CLD)

CLD is constructed to represent the real system. This study extends the CLD on the conversion of conventional nursery ponds to Aquaponics ponds developed by (Prasetyaningsih et al., 2020). Figure 2 shows the CLD of relationships among variables of the development of conventional nursery ponds to the Aquaponics technology. As shown in Figure 2, the catfish farming business comprises five elements: foodfish demand, foodfish production, revenue, profit, and the development of conventional nursery technology into Aquaponics. The CLD has two balancing loops (B1, B2) and two reinforcing loops (R1, R2).

Foodfish demand is influenced by the population that consumes them. The increase in population will positively impact foodfish demand. Meanwhile, the population is influenced by the population growth rate. This population growth creates a reinforcing loop R1. The increase in foodfish demand has positive implications for foodfish production, which, in turn, affects the number of catfish ponds required. However, the land is expensive, so the farmers are encouraged to convert the conventional nursery technology to Aquaponics technology to increase food fish production. It causes foodfish requirements to decrease. This circle creates a balancing loop B1.

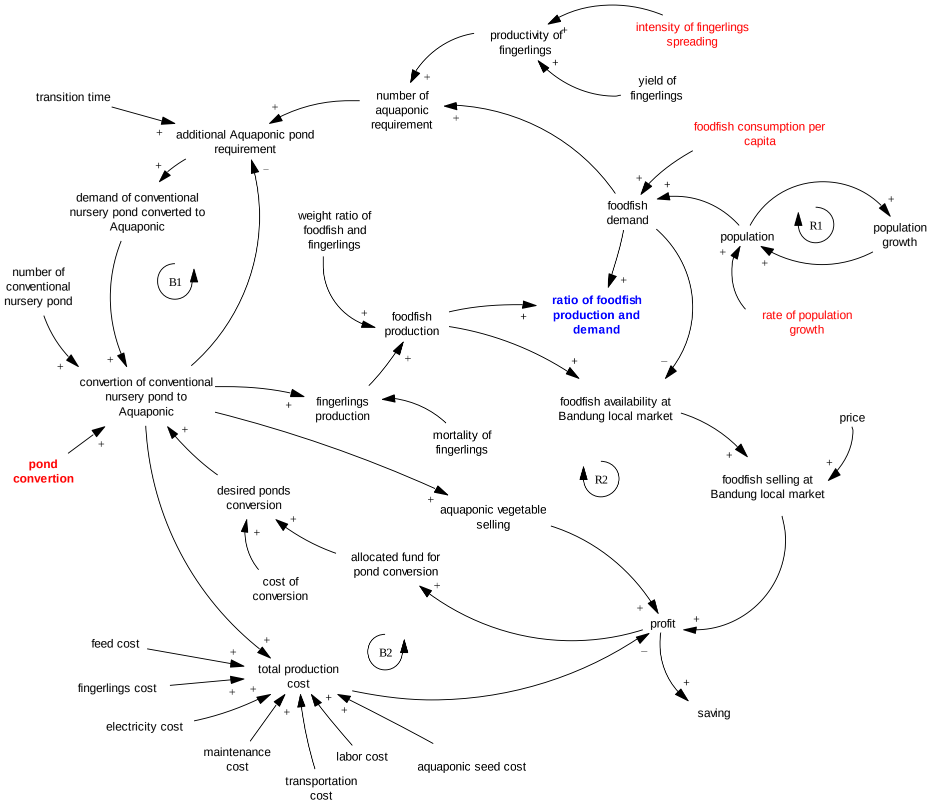

Figure 2. Causal Loop Diagram of the conversion of conventional to Aquaponics technology

Furthermore, increasing foodfish production will increase sales and revenue. By allocating a portion of profits to convert conventional nursery ponds to Aquaponics, the number of Aquaponics, as well as foodfish production, will increase. This circle generates the reinforcing loop R2. Conversion of conventional nursery ponds to aquaponics increases operating costs and reduces revenue. This creates a balancing loop B2. These structures follow dynamics commonly found in agricultural and aquaculture SD models (Isa et al., 2021; Li et al., 2012).

Stock–Flow Diagram (SFD) Representation

SFD is constructed from the CLD and depicted in Figure 3, comprising three stocks: the number of conventional ponds, the number of Aquaponics ponds, and the population. The interaction of stocks, variables, historical data, and constants is articulated through a mathematical formula. Current state data is utilized as Business as Usual (BaU) for modeling the existing system.

Table 1. Key variables in the System Dynamics model

No	Variable	Type	Description	Unit
1	Conventional nursery ponds	Stock	Number of ponds using traditional technology	pond
2	Aquaponics ponds	Stock	Number of ponds converted to aquaponics systems	pond
3	Population	Stock	Residents in Bandung are consuming catfish	person
4	Seeding rate	Flow	Fingerlings are added to nursery ponds each cycle	fingerling/cycle
5	Conversion rate	Flow	Number of traditional ponds converted per year	pond/year
6	Foodfish production	Auxiliary	Annual harvested catfish mass	ton/year
7	Fingerling density	Parameter	Stocking density in each nursery pond	fingerling/pond
8	Mortality rate	Parameter	Loss of fingerlings or foodfish during growth	%
9	Feed cost	Variable 10cost	Feed expenditure per production cycle	IDR/year
10	Fingerling cost	Variable cost	Procurement cost of new fingerlings	IDR/year
11	Other operational costs	Variable cost	Maintenance, labor, electricity, etc.	IDR/year
12	Selling price	Parameter	Market price of harvested catfish	IDR/kg
13	Revenue	Auxiliary	Total income from fish sales	IDR/year
14	Profit	Auxiliary	Revenue minus total production costs	IDR/year
15	Profit allocation rate	Policy variable	Share of profit reinvested for pond conversion	%
16	Investment for conversion	Parameter	Cost required to upgrade a pond to aquaponics	IDR/pond

The model formulation aligns with theories of production and business revenue, with the stock variable representing the accumulation of variables over simulation time. The simulation spans 25 years, but only the first 5 years are reported in this study. The key variables in the System Dynamics model are defined in Table 1.

The most important mathematical formulas in SFD are as follows:

1) Investment to develop a conventional nursery pond to Aquaponics is used to buy a water pump, piping, and installation costs.
2) Production costs include feed cost, fingerling cost, maintenance cost, Aquaponics fingerling cost, maintenance cost, electricity cost, labor cost, and transportation cost. The equation is as follows:

   Total Production Cost = Feed Cost + Fingerling Cost + Operational Costs ....(1)
3) Foodfish production is a multiplication of some variables, i.e., fingerling production of the conventional nursery and the Aquaponics, the weight ratio of foodfish and fingerling, conversion factor of fingerling to foodfish. The equation is as follows:

   Foodfish Production = (Fingerling Production) x (Weight Gain) x (Conversion Factor) ....(2)
4) Foodfish demand is determined by multiplying the percentage of the population who consume foodfish and their consumption level per capita. The equation is as follows:

   Catfish Demand = (Population) × (Consumption Rate) × (%Fish Consumers) ....(3)
5) Revenue is the multiplication of the foodfish production and the foodfish price. The equation is as follows:

   Revenue = (Foodfish Production) × (Selling Price) ....(4)
6) Profit is the difference between revenue and production cost. The equation is as follows:

   Profit = Revenue − Total Production Cost ....(5)

Model Verification and Validation

The System Dynamics model was verified through structural review of feedback loops, dimensional consistency checks, and extreme condition tests. The manuscript discusses the mathematical expression of variable interrelations in the SFD; however, it does not provide a detailed illustration of this concept. The verification results confirm that the model behaves logically and is suitable for analyzing technology transition in land-constrained catfish farming systems.

Model validation was conducted by comparing simulated behavior with observed patterns in real-world catfish farming systems. Noting that the SD model needs to be validated with BaU data. If the units align and the simulation results accurately reflect the real system, the dynamic model is deemed valid for analyzing changes in related variables.

The model validation is as follows:

The fingerling density of BaU is 3,600 fingerling/pond. It is assumed that the number of fingerlings is 200 fingerlings/kg. Hence, the fingerling density at BaU is equivalent to 0.018 tons/pond.

The annual foodfish production can be determined as follows:

$$\left(0.018\frac{\text{ton}}{(\text{pond})(\text{spread})}\right)(10\ \text{pond})\left(4\frac{\text{spread}}{\text{year}}\right)(0.95)(0.9)\left(20\frac{\text{weight of foodfish}}{\text{weight of fingerly}}\right)$$

$$= 12.312\ \text{tons/year}$$

Foodfish demand at Bandung city is a multiplication of (0.2) (2,500,000 people) (3 kg/person. year) (1ton/1000kg), which is equivalent to 1,500 tons/year.

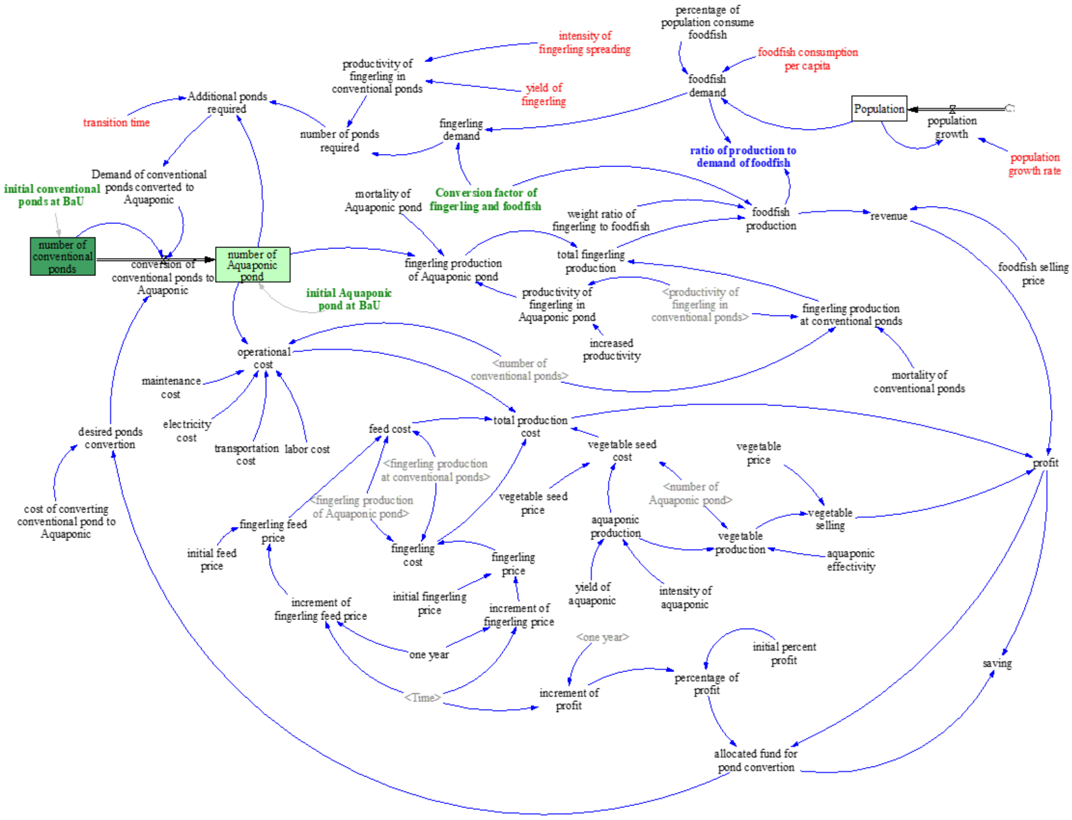

Figure 3. Stock and Flow Diagram of the development of a conventional nursery pond to Aquaponics

Foodfish production only meets 0.82% of foodfish needs, so the ratio is 0.82%, meaning that all foodfish production can be sold to the Bandung local market. The selling price of catfish is Rp. 17,000/kg, then the annual revenue is Rp. 209.3 million/year. The total operational cost is Rp. 140.4 million/year. Hence, the profit is Rp.68.9 million/year or Rp.5.7 million/month.

Table 2 presents a comparison of the real system with simulation results of a dynamic model using BaU data. The simulation result of foodfish production (13 Ton/year) closely matches the real system (12.312 Ton/year). Differences in revenue and profit levels stem from its close production level discrepancies, so it can be disregarded. Thus, the dynamic model accurately represents the real system and is suitable for analyzing the transition from conventional nurseries to Aquaponics.

Table 2. Comparison result of the simulation at BaU and the real system

Variable	Unit	Simulation result	Real system
Number of conventional nursery ponds	Pond	10	10
Number of Aquaponics	1 Pond	0	0
Foodfish production	Ton/year	12.312	13.0
Foodfish demand	Ton/year	1,500	1,500
The ratio of production to demand of foodfish	Dimensionless	0.0082	0.0087
Revenue	Rp/year	209,304,000	221,000,000
Total production cost	Rp/year	140,424.000	140,424,000
Profit	Rp/year	68,880,000	80,576,000

Scenario Design

Six scenarios were developed to evaluate the effects of cost fluctuations and reinvestment behavior on the transition to technology. Feed and fingerling prices were selected because they constitute the largest and most volatile components of operational costs. Reinvestment is modeled as a percentage of profit allocated for the acquisition of additional aquaponics units. Table 3 describes the six scenarios.

Six scenarios were simulated: a baseline scenario (scenario 1), individual feed and fingerling price fluctuations (scenarios 2 and 3), a combined cost-fluctuation scenario (scenario 4), and two higher-reinvestment scenarios (scenarios 5 and 6). These reflect realistic economic stresses observed in aquaculture systems (Hasan & New, 2013).

Table 3. Six scenarios for analyzing SD Model behaviour

Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4		Scenario 5	Scenario 6
	Reinvestment	Feed price fluctuation	Fingerling feed price fluctuation	Feed price fluctuation	Fingerling feed price fluctuation	Reinvestment	Reinvestment
1st	1.5%	0%	0%	0%	0%	0%	0%
2nd	1.5%	50%	50%	50%	50%	2%	2%
4th	1.5%	100%	100%	100%	100%	5%	150%
5th	1.5%	200%	150%	200%	150%	8%	150%
11th	1.5%	300%	180%	300%	180%	10%	200%
21st	1.5%	400%	200%	400%	200%	10%	200%
25th	1.5%	500%	300%	500%	300%	15%	300%

Performance Indicators

Model performance was evaluated using a set of economic and technological indicators, with particular emphasis on the BCR as a measure of economic feasibility. BCR was defined as the ratio between total revenue and total production cost for each simulation period, capturing the combined effects of production efficiency, input price dynamics, and technology transition. A BCR value greater than one indicates economically feasible production, while values approaching or below unity signal financial stress and limited reinvestment capacity. In addition to BCR, supporting indicators included aquaponics capacity, total production volume, profit, and reinvestment flow. Together, these indicators allow assessment of how economic feasibility and technology transition co-evolve under land constraints and input price fluctuation.

RESULTS

Table 4. Simulation result under normal conditions

Year	0	1	2	3	4	5	6
Foodfish demand (Ton/year)	1,500	1,538	1,576	1,615	1,656	1,697	1,740
Number of Aquaponics ponds	0	1	2	3	4	6	8
Foodfish production (Ton/year)	12.3120	13.7347	15.1574	16.5802	18.0029	20.8483	23.6938
Revenue (Rp. Million)	209.304	233.490	257.676	281.863	306.049	354.421	402.794
Total production cost (Rp. Million)	140.424	147.807	155.190	162.574	169.957	184.723	199.490
Profit (Rp. Million)	68.880	86.169	103.458	120.747	138.036	172.614	207.192

Table 4 presents the simulation results for the transition condition of a conventional nursery pond into an aquaponics system, assuming all variables remain unchanged (normal condition). Year zero is used to represent BaU data. Table 4 indicates that by setting 1.5% of the profit allocated to the development process, the foodfish production increases. Finally, revenue and profit increase as well, although total production cost increases.

Baseline Technology Transition (Scenario 1)

The baseline results for Scenario 1 are summarized in Table 4. Under stable input prices and a reinvestment rate of 1.5% of yearly profit, aquaponics adoption increases gradually over the 25-year simulation period. Year 1 represents the business-as-usual condition with no aquaponics units, while subsequent years show steady growth driven by profit-based reinvestment.

As indicated in Table 4, the incremental expansion of aquaponics capacity leads to continuous increases in production, revenue, and profit despite fixed land availability. These results demonstrate that even a low reinvestment rate can support slow but sustained technology transition in land-constrained catfish farming systems, providing a baseline for comparison with subsequent scenarios.

With stable input prices and 1.5% profit reinvestment, aquaponics adoption increases gradually. Production and revenue rise over time due to increasing efficiency, consistent with prior findings on recirculating systems (Goddek et al., 2019).

Sensitivity analysis

Sensitivity analysis is carried out by simulating the 6 scenarios using Vensim PLE software. Simulation results of all scenarios can be seen in Table 5. The number of Aquaponics growth, foodfish production growth, revenue growth, profit growth, and total production cost growth can be seen in Figures 4 to 8, respectively.

Feed Price Fluctuation (Scenario 2)

The results of Scenario 2 are reported in Table 5 and Figures 4-8. Fluctuation in feed price substantially reduces profitability, leading to a marked decline in reinvestment capacity. As shown in Table 5, the number of aquaponics units developed over time is significantly lower than in Scenario 1. The suppressed adoption slows production growth, confirming feed cost as the dominant constraint on technology transition.

Fluctuation in feed price severely reduces profitability, consistent with feed’s dominant cost share in aquaculture. (Hasan & New, 2013). Reinvestment declines sharply, slowing aquaponics adoption and suppressing long-term production.

Fingerling Price Fluctuation (Scenario 3)

Table 5. Simulation results of all scenarios

Time	0	1	2	3	4	5	6
Number of Aquaponics (unit)							
scenario #1	0	1	2	3	4	6	8
scenario #2	0	1	2	3	4	5	6
scenario #3	0	1	2	3	4	5	6
scenario #4	0	1	1	1	1	1	1
scenario #5	0	1	1	1	1	1	1
scenario #6	0	1	1	2	3	4	5
Foodfish production (ton/year)							
scenario #1	12.312	13.735	15.157	16.580	18.003	20.848	23.694
scenario #2	12.312	13.735	15.157	16.580	18.003	19.426	20.848
scenario #3	12.312	13.735	15.157	16.580	18.003	19.426	20.848
scenario #4	12.312	13.735	13.735	13.735	13.735	13.735	13.735
scenario #5	12.312	13.735	13.735	13.735	13.735	13.735	13.735
scenario #6	12.312	13.735	13.735	15.157	16.580	18.003	19.426
Revenue (Rp.Million)							
scenario #1	209	233	258	282	306	354	403
scenario #2	209	233	258	282	306	330	354
scenario #3	209	233	258	282	306	330	354
scenario #4	209	233	233	233	233	233	233
scenario #5	209	233	233	233	233	233	233
scenario #6	209	233	233	258	282	306	330
Profit (Rp.Million)							
scenario #1	68.9	86.2	103	121	138	173	207
scenario #2	68.9	72.4	83.2	93.1	102	104	103
scenario #3	68.9	75.3	79.5	81.5	81.2	87.8	93.6
scenario #4	68.9	61.6	46.2	30.7	15.3	1.83	(11.7)
scenario #5	68.9	61.6	46.2	30.7	15.3	1.83	(11.7)
scenario #6	68.9	61.6	46.2	42.3	35.2	27.5	17.0
Total Production Cost (Rp.Million)							
scenario #1	140	148	155	163	170	1.85	199
scenario #2	140	162	175	190	206	229	254
scenario #3	140	159	179	202	227	245	264
scenario #4	140	172	188	203	219	232	246
scenario #5	140	172	188	203	219	232	246
scenario #6	140	172	188	216	248	281	316

Scenario 3, presented in Table 5 and Figures 4-8, shows that fluctuating fingerling prices result in a moderate reduction in aquaponics adoption. Although profitability decreases, reinvestment remains sufficient to sustain a gradual technology transition. Compared with Scenario 2, the impact on production and profit is less pronounced, indicating that fingerling price fluctuation is a secondary constraint.

Fingerling price increases result in moderate declines in profit and reinvestment. Technology transition continues but at a reduced pace, mirroring the lesser economic weight of fingerlings (Engle & Stone, 2014).

Combined Feed and Fingerling Price Fluctuation (Scenario 4)

The outcomes of Scenario 4 are summarized in Table 5 and Figures 4–8. The fluctuation in feed and fingerling prices generates compounded cost pressure, sharply reducing profit and reinvestment. As shown in Table 5, aquaponics adoption nearly stagnates during the early simulation period, resulting in prolonged suppression of production and revenue.

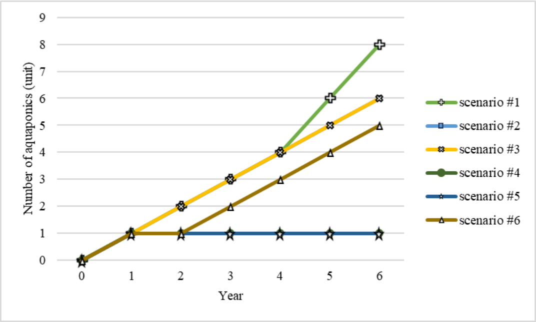

Figure 4. Number of Aquaponic Growth

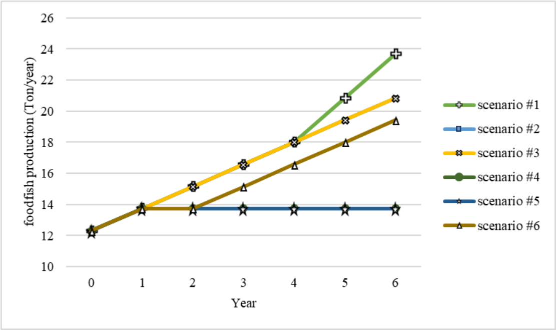

Figure 5. Foodfish Production Growth

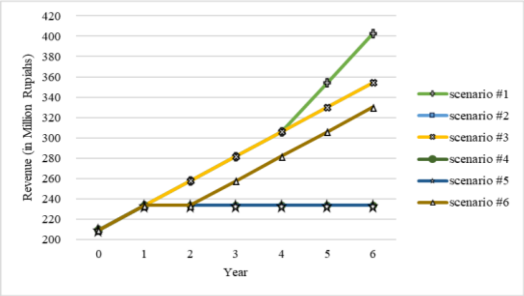

Figure 6. Revenue Growth

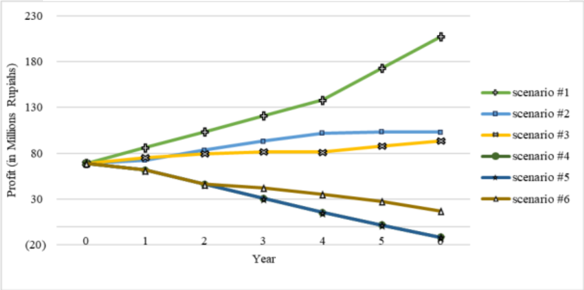

Figure 7. Profit Growth

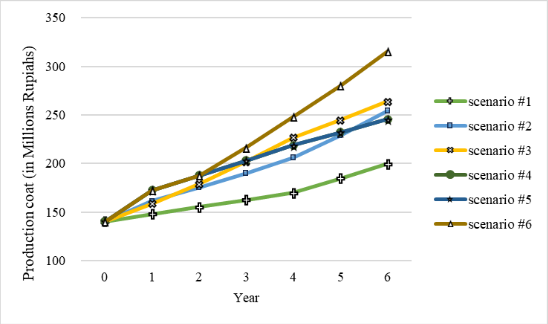

Figure 8. Total Production Cost Growth

Simultaneously increased feed and fingerling prices produce compounded cost pressures. Aquaponics adoption nearly stalls during the early years, illustrating the vulnerability of the smallholder system to multi-input fluctuation (Tacon & Metian, 2015).

Dual Cost Fluctuation with Higher Reinvestment (Scenario 5)

Under Scenario 5, where the reinvestment rate is increased to 2% to 15%, the results in Table 5 and Figure 4 indicate a partial recovery in technology transition despite elevated input costs. Aquaponics capacity expands at a moderate pace, leading to gradual improvements in production and profitability relative to Scenario 4.

Raising reinvestment rates 2% to 15% substantially accelerates technology transition even under cost fluctuations. Stronger capital accumulation reinforces the production–profit loop, enabling sustained adoption.

Dual Cost Fluctuation with High Reinvestment (Scenario 6)

The results for Scenario 6, shown in Table 5 and Figures 4–8, demonstrate that increasing the reinvestment rate from 15% to 300% substantially accelerates aquaponics adoption. Despite persistent cost pressures, production, revenue, and profit recover over time. These results highlight reinvestment as a critical leverage point for sustaining technology transition under severe input price fluctuation.

Cross-Scenario Comparison

Figures 4–6 display similar growth patterns, indicating that increases in aquaponics capacity consistently drive foodfish production and revenue growth, despite variations in feed prices, fingerling prices, and profit allocation for reinvestment. In contrast, profit declines sharply when feed prices and fingerling prices increase simultaneously, and becomes negative in Scenarios 4 and 5, as shown in Figure 7 and Table 5. An opposite trend is observed for total production costs, which rise markedly under the same scenarios, reflecting the compounded impact of the increase in feed and fingerling prices (Figure 8).

A comparison across Scenarios 1–6 (Tables 4-5; Figures 4–8) reveals three key insights. Feed price fluctuations are the primary constraint because they directly reduce profits and limit reinvestment. Higher reinvestment rates strengthen system resilience, while early profitability determines whether technology transition can be sustained over the long term.

DISCUSSION

This article has some clear and powerful scientific novelties:

1. Integration of System Dynamics with Economic Feasibility Indicators (BCR)This study explicitly integrates the Benefit–Cost Ratio (BCR) into the evaluation of the results of elementary school simulations, so that economic feasibility is not only conceptual, but also dynamically measurable.
2. Focus on technological transition under land constraints. Unlike previous studies of aquaculture elementary schools, this article models explicitly the transition from conventional ponds to aquaponics under fixed land conditions, making land constraints a major structural constraint.
3. Simultaneous analysis of input price fluctuations and reinvestment strategies. This study systematically evaluates feed price fluctuations, seed price fluctuations, a combination of the two, and variations in the reinvestment rate to identify leverage points for the sustainability of technology adoption.
4. Empirical contributions to the Indonesian context. This study is based on data and real conditions of small-scale catfish farmers in Bandung, thus making a strong contextual contribution to the literature on tropical aquaculture and developing countries.

This discussion synthesizes system behavior across all simulations by integrating the quantitative indicators reported in Tables 6 with the dynamic patterns shown in Figures 4–8, with explicit attention to the role of the BCR as a measure of economic feasibility and technology transition feasibility.

Across all scenarios, the results confirm that land constraints redirect growth pathways from spatial expansion toward technological intensification. Under stable economic conditions, the gradual increase in aquaponics capacity (Table 4; Figures 4 and 5) leads to steady improvements in production efficiency and economic performance. The observed increase in BCR over time indicates that efficiency gains outweigh cost growth, supporting sustained reinvestment. This finding is consistent with (Love et al., 2015) and (Goddek et al., 2019), who reported that aquaponics improves land-use efficiency and economic returns when managed under stable operating conditions.

Input cost fluctuation significantly alters this relationship. As summarized in Tables 5 and 6, scenarios involving feed price increases exhibit the strongest deterioration in economic performance. This behavior is clearly reflected in Figures 7 and 8, where rising feed costs drive total production costs upward faster than revenue, causing BCR values to decline toward or below unity. These results align with (Hasan & New, 2013) and (Tacon & Metian, 2015), who emphasized that feed constitutes the dominant cost component in aquaculture and critically determines financial feasibility. The comparatively smaller impact of fingerling price increases on BCR further supports empirical findings by (Engle & Stone, 2014), which identifies fingerlings as a secondary—but not structurally dominant—cost driver.

Table 6. Benefit-cost ratio

Time	0	1	2	3	4	5	6
Scenario 1							
Revenue (Rp.million)	209	233	258	282	306	354	403
Total prod. Cost (Rp.million)	140	148	155	163	170	1.85	199
BCR	1.49	1.58	1.66	1.73	1.80	1.92	2.02
Scenario 2							
Revenue (Rp.million)	209	233	258	282	306	330	354
Total prod. Cost (Rp.million)	140	162	175	190	206	229	254
BCR	1.49	1.45	1.47	1.48	1.49	1.44	1.39
Scenario 3							
Revenue (Rp.million)	209	233	258	282	306	330	354
Total prod. Cost (Rp.million)	140	159	179	202	227	245	264
BCR	1.49	1.47	1.44	1.40	1.35	1.35	1.34
Scenario 4							
Revenue (Rp.million)	209	233	233	233	233	233	233
Total prod. Cost (Rp.million)	140	172	188	203	219	232	246
BCR	1.49	1.35	1.24	1.15	1.07	1.01	0.95
Scenario 5							
Revenue (Rp.million)	209	233	233	233	233	233	233
Total prod. Cost (Rp.million)	140	172	188	203	219	232	246
BCR	1.49	1.35	1.24	1.15	1.07	1.01	0.95
Scenario 6							
Revenue (Rp.million)	209	233	233	258	282	306	330
Total prod. Cost (Rp.million)	140	172	188	216	248	281	316
BCR	1.49	1.35	1.24	1.19	1.14	1.09	1.05

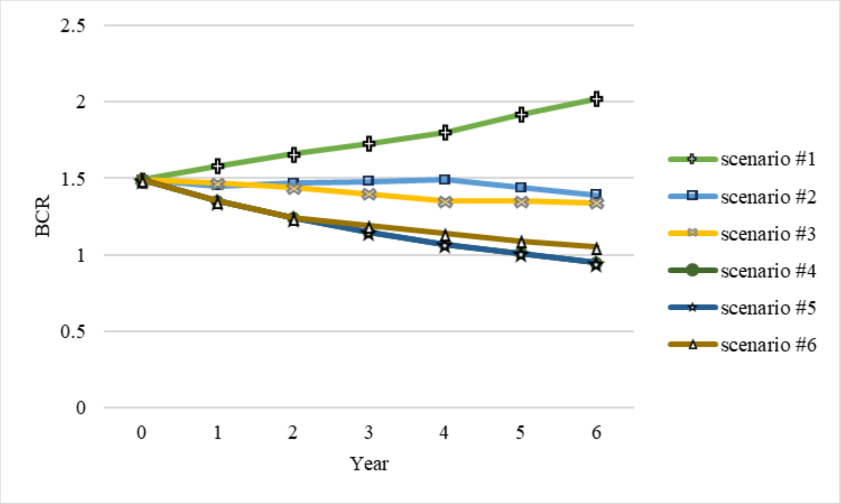

Figure 9. Benefit-Cost Ratio

Reinvestment intensity emerges as the key endogenous mechanism that restores and sustains favorable BCR levels. As shown in Table 6 and illustrated in Figure 9, higher reinvestment rates accelerate aquaponics adoption, enhance production efficiency, and moderate the relative growth of costs, thereby shifting BCR back above critical thresholds. This reinforcing dynamic is aligned with System Dynamics theory as articulated by Forrester (1994) and Sterman (2018), where capital accumulation and efficiency gains strengthen reinforcing feedback loops capable of overcoming cost-induced balancing forces. Similar conclusions have been reported in SD-based agricultural and aquaculture models by (Li et al., 2012) and (Isa et al., 2021), which identify reinvestment as a primary leverage point for long-term system transformation.

The integrated trajectories shown in Figures 4–9 also reveal strong path dependence in BCR dynamics. Systems experiencing early-stage profit and BCR suppression exhibit delayed reinvestment and persistently weaker technology transition, even when economic conditions improve later. Conversely, systems with sufficient early reinvestment rapidly achieve higher BCR levels, enabling self-reinforcing transition pathways. This behavior is consistent with sustainability modeling studies by (Moallemi et al., 2021), which highlight the presence of tipping points and lock-in effects in resource-constrained production systems.

Overall, the combined evidence from Tables 4–6 and Figures 4–9 demonstrates that technology transition in land-constrained aquaculture is economically feasible only when BCR remains sufficiently above unity to sustain reinvestment. Aquaponics emerges as a feasible land-efficient technology when efficiency gains compensate for rising input costs, as reflected in improving BCR trajectories. These findings align with empirical aquaculture economics literature (Belton et al., 2018; Love et al., 2015) and reinforce the view that strengthening reinvestment capacity and stabilizing feed costs are critical strategies for enabling sustainable technological upgrading in small-scale aquaculture systems.

State-of-the-art research shows that although aquaponics and System Dynamics have been extensively studied, they are rarely integrated to analyze the transition of small-scale aquaculture technologies under land constraints, accounting for economic dynamics. The research gap lies in the absence of a dynamic model that simultaneously accounts for land limitations, fluctuations in input costs, reinvestment, and economic feasibility. The novelty of this research is the development of a System Dynamics model that explicitly evaluates the transition of catfish technology to aquaponics using BCR indicators, enabling identification of the minimum economic conditions for a sustainable technological transition.

CONCLUSION

Using a System Dynamics (SD) model, this study shows that small-scale catfish farmers operating under land constraints can improve production performance by transitioning from conventional ponds to aquaponics, provided that economic efficiency remains adequate. The results indicate that aquaponics becomes a practical option only when the BCR remains above unity, which depends strongly on control of feed and fingerling costs and on consistent reinvestment. Strengthening reinvestment mechanisms and managing feed price exposure are, therefore, essential for enabling sustainable technological upgrading in land-limited catfish farming

This study employs a simplified System Dynamics model that does not account for farmer heterogeneity or stochastic fluctuations in input prices, which may influence BCR dynamics and adoption behavior. Future research could incorporate stochastic pricing, behavioral decision rules, or hybrid SD–agent-based models better to capture heterogeneous technology transition pathways under land constraints.

Implication

The findings show that technology transition in land-constrained catfish farming is feasible only when the BCR remains above unity. Strengthening reinvestment capacity and stabilizing feed costs are therefore critical to sustain economic feasibility and accelerate aquaponics adoption. Policy interventions such as credit access and cooperative investment schemes can support these objectives, particularly in spatially constrained production. Policy interventions such as credit access and cooperative investment schemes can support these objectives, particularly in spatially constrained production systems.

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