Economic feasibility and risk analysis of Pacific whiteleg shrimp (*Litopenaeus Vannamei*) production in low-cost salt mixtures

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Abstract

This study examines the overall economic viability of recirculating aquaculture shrimp production using low cost salt mixtures. A comprehensive stochastic bioeconomic model that incorporates biological data and operational costs is used to assess a series of financial performance measures through a series of sensitivity and stress analyses on key input parameters including the cost of salt. Results from the analyses suggest that scaling production will decrease the risks involved in terms of costs. Small changes in the grow-out survival percentage, electricity usage, discount rate, selling price, and salt costs have significant effects on net present values and consequently on profitability. Scaling up production can mitigate some of these risks, but for small-scale farmers, the results of this study show that there are risks involved and obtaining price premiums are necessary to make this a sound investment. The adoption of low cost salt mixtures have a positive effect on mitigating risk in shrimp production, particularly smaller operations.

KEYWORDS
Bioeconomic modeling, marine shrimp, low-cost salt mixtures, recirculating aquaculture system, biofloc.

1 | INTRODUCTION

The most common farmed shrimp is the Pacific Whiteleg Shrimp (*Litopenaeus vannamei*), which is a tropical marine shrimp that is native to the Eastern Pacific coast from Mexico to Peru (FAO, 2006). It is the principal species of both outdoor pond and Recirculating Aquaculture System (RAS)[1] production worldwide, accounting for nearly half of global shrimp production in 2017 (FAO, 2019). Wild-caught, commercial landings of shrimp in the US have remained largely stagnant the last decade while imports have increased over the years. The quantity of shrimp imported in 2018 totaled 1.5 billion pounds amounting to 28% of the total value of all edible seafood imports, which was an increase of 68.6 million pounds from 2017 (NOAA, 2020). In terms of volume of all US edible seafood imports, shrimp accounts for 25%, second after fish fillets, which accounts for 26% (NOAA, 2020).

The 2018 Census of Aquaculture indicates total aquaculture shrimp production valued at $45.6 million (USDA, 2019). *L. vannamei* aquaculture occurs in ponds and RAS in three stages: Hatchery, nursery, and grow-out with each phase requiring different levels of technology, investment, and managerial oversight. The biofloc media is commonly used in RAS systems, but there are no industry standards or model for biofloc RAS systems; water exchange levels, filtration methods, tank size, and management practices vary across the industry. This lack of standardization and operating procedures can discourage institutional investors. Most farmers begin production at the nursery and grow-out stages, opting to purchase post larval (PL) shrimp from specialized hatcheries.

There have been several economic research studies in the field of aquaculture, but very little in RAS shrimp farming in the US. There is increased interest in RAS shrimp production, but many farms have struggled to stay in business as there is limited information on commercial large-scale shrimp operations. Additionally, there is limited substantive economic research on costs, production, and success stories, which is needed for informed decision making by prospective farmers and investors interested in RAS shrimp farms. RAS is generally capital intensive and one way for farmers to increase profits is to reduce costs. The key input costs are energy, feed, salt and labor. Despite these inherent disadvantages, there are opportunities for US producers to be profitable in RAS shrimp production. Shrimp producers have focused on niche markets to charge a higher price. Some farms sell to high end establishments, while others have had success selling fresh shrimp directly to consumers either on site or at farmer's markets.

The goal of this study is to provide some insights into some of the costs of RAS shrimp farms and examine their overall economic viability by incorporating economic and biological data from both research facilities and commercial farms. A comprehensive stochastic model is used to estimate the economic feasibility of RAS shrimp production. This involves developing a bioeconomic model that incorporates biological growth data, operational costs, and variable costs to assess a series of financial performance measures; and analyzing the economic performance of low-cost salt mixtures (LCSMs) through a series of sensitivity and stress analyses on key input parameters including the cost of salt. LCSMs are cheaper non-sea-salt

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[1] Recirculating aquaculture systems recycle all or part of the water used in the production system and are usually used under intensive cultivation methods.

ionic solutions that can be used for marine shrimp production compared to the commonly used regular sea salt. Results from this study could have significant impact on the industry's profitability and future growth.

2 : MATERIALS AND METHODS

2.1 | Bioeconomic modeling in aquaculture

Bioeconomic modeling of shrimp farms has mostly focused on large-scale, outdoor pond production compared with RAS farms. This is because global shrimp farming is primarily done in large, outdoor ponds. Valderrama and Engle (2001, 2002) examined the inherent risk associated with shrimp pond farmers in Honduras and analyzed their profitability through certain risk scenarios. Data for the study was obtained from 21 farms relating to costs of production, feed conversion ratio, stocking density, and feeding rates, and farm size. The authors created three farm scenarios based on total hectares in production: small (10-150 ha), medium (150-400 ha), and large (>400 ha) and created enterprise budgets for each of these scenarios and performed Monte Carlo simulations using a series of distributions on key variables within the budgets. Ionno et al., (2006) also modeled a series of trout farm production scenarios in a bioeconomic framework and generated a series of financial performance measures such as internal rate of return (IRR), net present values (NPV), and payback period (PP). The authors used actual commercial data from an existing RAS trout farm in Australia. The study found that economies of scale were vital to the financial viability of RAS farms but also found that the NPVs of the different scenarios were largely negative. Unlike Valderrama and Engle (2001, 2002), Ionno et al (2006) assumed a deterministic model and did not use stochastic simulations for the model's key variables, outputs, and assumptions.

Posadas and Hanson (2006) utilized a series of biological parameters, capital costs, variable costs, and shrimp prices to generate a series of financial and economic performance measures including yearly cash flows, NPV, IRR, and total costs of production. The biological parameters include growth rates, survival rates, stocking and harvesting sizes, which were assumed to be deterministic. Zhou (2007) utilized the Posadas-Hanson model to create an inventory and net profit maximization tool to decide the optimal harvest week for prospective shrimp farmers using experimental data. Using this data along with historic shrimp prices, Zhou (2007) formulated an optimal harvesting strategy to achieve maximum net revenue. Moss and Leung (2006) also utilized the Hanson-Posadas model to compare costs of shrimp production between earthen ponds and RAS. The RAS facility they modeled was large, comprising 80 individual raceway tanks that are 54.9 m long, 9.1 m wide, and 1.3 m deep. The pond system consisted of 10 each 2.02-hectare ponds. A sensitivity analysis showed that survival was the biggest contributor to variation in total cost for the ponds, while the key contributors to cost variation in the RAS farms were evenly spread among survival and weekly growth rates.

Trapani et al., (2014) compared two different methods of oceanic sea bass production: Inshore and offshore at different levels of production, investment, and management. The key output variables in the study were IRR, NPV, and discounted PP and reported that offshore production yielded superior economic profitability. The authors performed a sensitivity analysis assuming 5, 10, and 15% increases on the cost of fingerlings, the cost of feed, and the sales price of the sea bass. Increases in feed and fingerling costs did adversely affect both systems but were not a strong indicator of financial performance in comparison to one another. The sales price had a more significant effect on both production scenarios, with the offshore system containing less variation in its NPV.

Bisesi (2007) examined the efficacy of non-sea-salt ionic solutions in *L. vannamei* pond production. Written from a biological perspective, this study examined growth, survival, total harvest weight, and feed conversion ratios and reported potential savings pond farmers could expect if switching from the regular sea salt to the cheaper, non-sea-salt mixture. The study found that if a farmer decided to completely switch to the non-sea-salt alternative, they could potentially save about $70,000 for each stocked pond.

2.2 | Model framework

To assess the economic viability of RAS shrimp farms, this analysis adopted a modified version of the Posadas-Hansen bioeconomic model (Posadas and Hanson, 2006), which comprises an excel spreadsheet that incorporates an extensive list of biological parameters, variable costs, and capital costs and generates an assortment of financial and economic performance measures. The model is interactive, in that there are multiple worksheets of biological parameters and costs that are manually entered by the user. These include survival rate (%), weekly growth rate (grams), stocking size (grams), and desired harvest size (grams). Data entered also includes capital and variable costs of feed costs, energy costs, labor costs, PL costs, borrowing rates, tax rates, and selling price per pound. The model's outputs include the NPV, stocking and harvesting schedules, monthly and yearly cash-flows, itemized costs, and power usage. Zhou, (2007) discusses the mathematical computations and functions in this model.

The Posadas-Hansen model assumes that a farm will receive consistent supply of PLs for stocking purposes and that all the shrimp produced will be sold at the price designated for the given year. It also assumes that the farm will produce continuous crops. There is consideration for implementing a nursery if desired, which requires separate parameters that are manually input by the user. If the user decides to bypass the nursery stage of production and source larger PLs for the grow-out stage, the model will not incorporate the production and cost inputs for the nursery section. It is assumed that a nursery in this context is simply additional tank(s). It is not uncommon for larger, commercial aquaculture operations to have designated buildings or facilities for each stage of production, but in this study the nursery stage is assumed to take place in a single facility. All scenarios in this study do incorporate a nursery stage.

Several modifications are made to the Posadas-Hansen framework. This is done to ensure thorough analysis and to accommodate for developments in RAS shrimp management practices. A Modified Accelerated Cost Recovery System (MACRS) 150% depreciation schedule of assets is added in accordance with the Farmer's Tax Guide (U.S. Department of the Treasury, 2019b). Vehicles and buildings are depreciated on a 10-year schedule while the remaining physical assets are depreciated on a 5-year schedule. The calculated depreciation of assets is then used to compute discounted cash-flows and the NPV of the operation.

Added salt is included as a variable input in the model. The Posadas-Hansen model assumes that the facility is located adjacent to the ocean and added salt is not needed. Per the data collection, the salt level in the farm scenarios is kept at 15 ppt (parts per thousand) for the grow-out facility and 30 ppt for the nursery facility. To attain a level of 15 ppt, 40 lbs. of salt per cubic meter of water is required, while 80 lbs. per cubic meter is needed to attain a salinity level of 30 ppt. Every tank is filled to 90% water volume capacity and all the water is drained, refilled, and salted every six crops or every other production year. Fifty lbs. of supplementary salt per tank is added in the years that the full water exchange does not occur.

The modeled farm is in the Midwestern US where the winter season can be severe. *L. Vannamei* is a warm water species and requires a water temperature of 23-30^{o}C to grow properly (Bisesi, 2007). Maintaining an indoor air temperature slightly below the farm's water temperature can reduce condensation and possible mold issues (Ray, 2019). To ensure the facility can maintain year-round production in the colder months, insulation is added as an additional start-up cost at $2.15 per square foot of warehouse space. Annual maintenance of farm machinery and infrastructure is estimated at 5% of the initial cost. Certain items such as the rearing tanks are assumed to be replaced every five years.

Unlike the Posadas-Hansen model that assumes deterministic values for its inputs and generates a ten-year production schedule and financial performance measures, this study assumes that the key input variables are stochastic. These include survival rate, weekly growth rate, PL cost, electricity costs, and selling price. Each variable is given an independent stochastic input for each year of production in the model. This in turn derives yearly production and financial metrics associated with the parameter input for that given year. These modifications are included to account for greater variation associated with the costs, production, and financial performance of RAS shrimp farms on a year-to-year basis.

Once the model's variables were designated stochastic and their appropriate distribution selected, Monte Carlo Method (MCM) was used to generate a random number within each distribution and stored from iterations. A thousand of these iterations were created for aggregate values in the form of a distribution. The study used Palisade's @Risk Software (Palisade, 2019) to assess risk and derive statistical inferences from the deterministic, stochastic, and output variables. Correlations between all variables, both deterministic and stochastic, were assumed to be zero. The triangular probability distribution was used relying on three inputs of worst-case, most likely, and best-case where the middle value (the most likely) as its peak, and the upper value (maximum) and lower value (minimum) form the outer bounds.

Three different RAS farm scenarios were tested in this study: An 8-tank system, 16-tank system, and 24-tank system. There were several assumptions regarding the model's framework. Land is not included as a capital cost. Labor is a fixed cost and has a consistent supply of PLs to stock the nursery. Another assumption is that all the shrimp produced is sold at the same price for that given year. All simulations were done independently of each other and have no effects on other variables.

2.3 | Data source and variable distribution

Data for this study came from both research and commercial sources. Six RAS shrimp farmers from the US Midwest provided data and various biological parameters such as survival, variable costs, capital costs, and selling prices. For the designated stochastic variables within the model, the participating farms were asked to provide a range of values in the form of "best case", "worst case", and "most likely" in order to mirror the necessary inputs for the distributions. Research data, provided by Kentucky State University's Aquaculture Research Center (KSUARC), was used in places where commercial data was lacking. Energy costs were collected from empirical averages, while variable costs including feed, PLs, and salt were derived from KSUARC.

The composition of the LCSM used was from Parmenter et al., (2009). The LCSM was mixed with the industry's standard commercial instant sea salt (ISS) at varying levels: (i) 100% LCSM, (ii) 75% LCSM, 25% ISS, (iii) 50% LCSM, 50% ISS, (iv) 25% LCSM, 75% ISS, and (v) 100% ISS. This study focuses on the cost of LCSMs and the effect on overall profitability. It assumes that the shrimp's biological performance is not affected by the adoption of LCSMs.

TABLE 1 Biological parameter values for grow-out scenarios

Variables	Units	8-Tank	16-Tank	24-Tank
Stocking size	grams	1	1	1
Stocking density	PL/m3	300	300	300
Desired harvest size	grams	22	22	22
Gross feed conversion	#	1.4	1.4	1.4
Shut down period	day/crop	2	2	2
Start-up period	Days	180	180	180
Rate of capacity usage year 1	%	51	51	51
Rate of capacity usage year 2-10	%	100	100	100
Number of weeks in operation	weeks/year	52	52	52

Table 1 presents the biological input parameters for grow-out scenarios for all three RAS farm scenarios. The data from this table was drawn from both the KSUARC and commercial farmers. The 'Stocking Size' is the size of the shrimp when it enters the grow-out stage, while the 'Stocking Density' is the amount of shrimp per cubic meter of water volume in each grow-out tank. The 'Desired Harvest Size' of 22 grams, is the size the shrimp will be grown to. This amounts to roughly 20-21 shrimp per pound. The 'Gross Feed Conversion' is the amount of feed it takes to generate one pound of biomass. For this study, it was assumed that it would take 1.4 pounds of feed to generate 1 pound of biomass. The 'Shut Down Period' is the time it takes to prepare in between crops. The 'Start-Up Period' refers to the amount of time it takes the farmer to construct and begin operations. For this study it was assumed to be 6 months or 180 days. The 'Rate of Capacity Usage Year 1' calculates how much of the total farm's production capacity is being used. The 6-month start-up period is half a year, so the capacity usage is close to 50%.

After this start-up period in year one, it is implied that the farm is operating year-round at 100% capacity which explains the inputs for the last two variables in Table 1.

TABLE 2 Distribution and stochastic biological parameter values for grow-out scenarios

Variables	Units	Distribution	Range	8 Tank	16 Tank	24 Tank
Survival year 1	%	Triangular	Minimum	40	40	40
			Likeliest	40	40	40
			Maximum	45	45	45
Survival year 2	%	Triangular	Minimum	45	45	45
			Likeliest	45	45	45
			Maximum	60	60	60
Survival year 3-10	%	Triangular	Minimum	50	50	50
			Likeliest	60	60	60
			Maximum	75	75	75
Growth rate year 1	g/week	Triangular	Minimum	1.1	1.1	1.1
			Likeliest	1.2	1.2	1.2
			Maximum	1.3	1.3	1.3
Growth rate year 2	g/week	Triangular	Minimum	1.2	1.2	1.2
			Likeliest	1.3	1.3	1.3
			Maximum	1.4	1.4	1.4
Growth rate year 3-10	g/week	Triangular	Minimum	1.3	1.3	1.3
			Likeliest	1.4	1.4	1.4
			Maximum	1.5	1.5	1.5

Table 2 presents the stochastic variables and their distribution for the three grow-out scenarios. Using the Monte Carlo Method, @Risk centers the probability mass around the ‘Likeliest’ input. For example, in Table 2 under ‘Survival year 3-10, 90% of the random numbers drawn will lie between 53.54% and 70.67%. 'Survival Year 1’ (40, 40, 45) and ‘Survival Year 2’ (45, 45, 60) are lower than that of ‘Survival Year 3-10' (50, 60, 75). By shifting the ‘most likely’ parameter closer to the minimum, the probability that lower numbers are drawn during MCM simulation increases. This was implemented to ensure a lower number is drawn in those two years, representing a learning curve in acquiring necessary managerial skills and practices in the initial years. By year three, the survival rate percentage distribution will remain constant to signify an acquisition of necessary managerial skills. The minimum and likeliest values for survival are identical in both distribution of ‘Survival Year 1’ and ‘Survival Year 2’ (Table 2).

Tables 3 and 4 present the respective biological input parameters and distribution for the nursery stage for all three RAS farm scenarios. The data was also collected from the KSUARC in addition to the commercial farmers polled in this study. Both farmers and researchers indicated that the survival rates for the nursery phase of RAS production were significantly higher than that of the grow-out stage. The justification and clarification for the variables in Tables 3 and 4 are the same as descriptions for Tables 1 and 2 respectively.

TABLE 3 Biological parameter values for nursery

Variables	Units	8-Tank	16-Tank	24-Tank
Stocking Size	grams	0.004	0.004	0.004
Stocking Density	PL/m3	2,100	2,100	2,100
Desired Harvest Size	grams	1	1	1
Gross Feed Conversion	#	1.25	1.25	1.25
Shut Down Period	Day/Crop	2	2	2
Rate of Capacity Usage Year 1	%	51	51	51
Rate of Capacity Usage Year 2-10	%	100	100	100
Number of Weeks in Operation	Weeks/Year	52	52	52

TABLE 4 Distribution and stochastic biological parameter values for nursery

Variables	Units	Distribution	Range	8-Tank	16-Tank	24-Tank
Survival Year 1	%	Triangular	Minimum	70	70	70
			Likeliest	70	70	70
			Maximum	80	80	80
Survival Year 2	%	Triangular	Minimum	75	75	75
			Likeliest	75	75	75
			Maximum	85	85	85
Survival Year 3-10	%	Triangular	Minimum	80	80	80
			Likeliest	85	85	85
			Maximum	95	95	95
Growth Rate Year 1	g/week	Triangular	Minimum	0.175	0.175	0.175
			Likeliest	0.175	0.175	0.175
			Maximum	0.18	0.18	0.18
Growth Rate Year 2	g/week	Triangular	Minimum	0.18	0.18	0.18
			Likeliest	0.18	0.18	0.18
			Maximum	0.185	0.185	0.185
Growth Rate Year 3-10	g/week	Triangular	Minimum	0.185	0.185	0.185
			Likeliest	0.190	0.190	0.190
			Maximum	0.20	0.20	0.20

The facility and investments for each farm scenario is presented in Table 5. All the commercial farmers that participated in this study had systems containing 8-10 total tanks. The 16-tank and 24-tank scenario’s 'Total Start-Up Costs’ were scaled based on the costs provided from these farmers. Farm set-ups vary significantly in this industry as do the total costs therefore this study used very conservative estimates for all the model’s inputs.

TABLE 5 Facility and infrastructure values for both grow-out and nursery

Variables	Units	8-Tank	16-Tank	24-Tank
Rearing Tank Volume	m3	16.1	16.1	16.1
Water Volume	%	90	90	90

Total Rearing Houses	#	1	1	1
Total Grow-Out Tanks	#	7	14	21
Total Nursery Tanks	#	1	2	3
Total Structural Space	Square ft.	2,800	5,600	8,400
Total Start-Up Cost	$	$65,000	$115,000	$165,000

Table 6 details the usage parameters. All costs and usage rates were derived from commercial farmers and research facilities. PL10 Cost Year 1-10' refers to the shrimp being purchased from hatcheries that are then stocked in the nursery tanks. Like the biological parameters in Table 2, there are ten individual cell inputs for PL10 costs in the model, and each year of production is linked to that specific input. This model assumes a consistent supply of PLs, but since these hatcheries are vulnerable to risk themselves, price variation on a yearly basis was built into each scenario. 'Capital Costs' inputs were obtained from banking professionals in addition to commercial farmers who had sought financing. 'Electricity Usage' was obtained from commercial farmers. Usage varied amongst the farmers who provided electricity data for this study. Some farmers have diversified farming operations that are all connected to a single meter. Calculating an accurate range of electricity usage for these operations was challenging as some farmers declined to provide data.

The distribution of salt costs presented in Table 6 assumes that the most likely value will be around $1,500/ton, implying that a mixture of both LCSM and ISS salts is used in the initial, baseline simulation. Salt usage was calculated based on commercial farming data. It was assumed that the grow-out phase for each scenario had salt concentration at roughly 15 ppt (parts per thousand) salinity while the nursery stage was 30 ppt. Salinity levels of 15 and 30 ppt could be attained by adding 40 pounds and 80 pounds respectively of salt per cubic meter of water. These inputs are presented in Table 7.

TABLE 6 Distribution and stochastic cost and usage parameter values for both grow-out and nursery

Variables	Units[1]	Distribution	Range	8 Tank	16 Tank	24 Tank
PL10 Cost Year 1-10	$/1000	Triangular	Minimum	29.00	29.00	29.00
			Likeliest	30.00	30.00	30.00
			Maximum	40.00	40.00	40.00
Grow-Out Salt Cost	$/Ton	Triangular	Minimum	800	800	800
			Likeliest	1,500	1,500	1,500
			Maximum	2,300	2,300	2,300
Nursery Salt Cost	$/Ton	Triangular	Minimum	800	800	800
			Likeliest	1,500	1,500	1,500
			Maximum	2,300	2,300	2,300
Grow-Out Feed Cost	$/Ton	Triangular	Minimum	1,400	1,400	1,400

			Likeliest	1,450	1,450	1,450
			Maximum	1,500	1,500	1,500
Nursery Feed Cost	$/Ton	Triangular	Minimum	6,000	6,000	6,000
			Likeliest	7,000	7,000	7,000
			Maximum	8,000	8,000	8,000
Capital Cost	%	Triangular	Minimum	5	5	5
			Likeliest	6	6	6
			Maximum	8	8	8
Electricity Usage	Kwh/Tank /Month	Triangular	Minimum	500	500	500
			Likeliest	700	700	700
			Maximum	900	900	900

[1] $/Ton refers to English Tons

TABLE 7 Cost and input parameter values for farm scenarios

Variables	**Units**	**8-Tank**	**16-Tank**	**24-Tank**
Added Salt Per m3 – Grow Out (15ppt)	lbs.	40	40	40
Added Salt Per m3 – Nursery (30 ppt)	lbs.	80	80	80
Electricity Cost – Year 1*	$/kwh	$0.110	0.110	0.110
Electricity Cost – Year 2*	$/kwh	$0.111	0.111	0.111
Electricity Cost – Year 3*	$/kwh	$0.112	0.112	0.112
Electricity Cost – Year 4*	$/kwh	$0.113	0.113	0.113
Electricity Cost – Year 5*	$/kwh	$0.114	0.114	0.114
Electricity Cost – Year 6*	$/kwh	$0.115	0.115	0.115
Electricity Cost – Year 7*	$/kwh	$0.116	0.116	0.116
Electricity Cost – Year 8*	$/kwh	$0.117	0.117	0.117
Electricity Cost – Year 9*	$/kwh	$0.118	0.118	0.118
Electricity Cost – Year 10*	$/kwh	$0.119	0.119	0.119
Telephone Expense	$/week	$25.00	$25.00	$25.00
Gasoline Cost	$/gal	$2.25	$2.25	$2.25
Propane Cost	$/gal	$2.50	$2.50	$2.50
Hauling Cost	$/lb	$0.10	$0.10	$0.10
Annual Labor (Fixed)	$	$10,000	$20,000	$30,000
Capital Outlay Index	%	100%	100%	100%
Annual Liability Insurance	$	$600	$900	$1,200
Corporate Tax Rate	%	21%	21%	21%

***** The electricity costs assume a $0.001 increase per year (U.S. Department of Energy, 2019b)

This study assumed that each farm scenario exchanged their water every six crops and added fresh salt as well. In the years that water is not exchanged entirely, it was assumed that each scenario added roughly 50 pounds of salt per tank to account for variance in water loss. For the nursery phase, the salinity was roughly 30 ppt due to the nursery shrimp requiring a salinity level resembling full strength seawater. The same water exchange schedule as the grow-out stage was applied to the nursery stage. More salt was needed per tank in the nursery stage due to the higher ppt, but with far fewer tanks.

According to historical prices provided by the U.S. Department of Energy, electricity prices increase around $0.001 per kilowatt hour every year (U.S. Department of Energy, 2019b). Gasoline and propane costs were taken from national averages provided by the EIA for 'Heating Oil and Propane' and 'Petroleum & Other Liquids' (U.S. Department of Energy, 2019c, 2019a). 'Telephone Expense" was calculated to be around $100 per month or $25 per week. 'Hauling Cost' implied a fixed rate for additional hired labor to harvest and/or haul finished product. 'Annual Labor' costs were assumed to be fixed in this case, and the justification for these values was based on the commercial data provided. It is also assumed that the increase in scale of production equates to an equal increase in fixed labor costs. 'Capital Outlay Index' assumes that each scenario is financed entirely. 'Annual Liability Insurance' was calculated to be 1% of the total investment. 'Corporate Tax Rate' was derived from the Internal Revenue Service's flat corporate rate of 21% (U.S. Department of the Treasury, 2019a)**.**

The distribution of shrimp selling prices was determined from data collected from commercial farmers. A triangular distribution with a minimum of $16/lb, likeliest of $18/lb and maximum of $20/lb were used for all farm scenarios. All shrimp sold in each scenario are head-on, whole shrimp. Like the biological parameters in Table 2 and the 'PL10 Costs' in Table 6, there are ten individual cell inputs for shrimp prices, and each year of production is linked to that specific input. This was implemented to assume future market price fluctuations for RAS-grown shrimp.

Table 8 calculates the break-even prices for each farm scenario. To calculate the break-even price, all stochastic variables were made deterministic by using the middle or 'most likely' value and the total costs (Variable Costs + Fixed Costs + Depreciation) were then divided by the 'Total Units Sold' (pounds of shrimp). All the variables in Table 8 were totaled over a ten-year production schedule.

TABLE 8 Break-even prices for each farm scenario – deterministic model

Variables	Units	8-Tank	16-Tank	24-Tank
Selling Price	$/lb	$18.00	$18.00	$18.00
Total Units Sold	lbs	27,442	54,884	82,327
Total Revenue	$	$493,963.88	$987,927.77	$1,481,891.65
Total Depreciation	$	$71,307	$127,648.16	$183,988.44
Total Variable Costs	$	$221,918.06	$409,434.35	$595,335.30
Total Fixed Costs	$	$152,447.19	$281,632.16	$414,796.03
Total Costs	$	$445,673.13	$818,714.67	$1,194,119.77
Profit	$	$48,290.75	$169,213.09	$287,771.88
Break-Even Price	$/lb	$16.24	$14.92	$14.50

The annual number of crops or ‘turns’ is an important factor when planning livestock production. Using the same deterministic model, the number of annual crops for each scenario was 3.40 when operating at 100% capacity. The model uses the data inputs from Tables 1-3 to generate the length of each crop and divides it by the number of weeks in operation. To operate at 100% capacity, each farm scenario is in operation 52 weeks per year. Since each scenario uses the same biological inputs, the number of crops remains the same. However, the size of the crops does vary between each scenario considerably since each scenario’s production is governed by the number of tanks.

3 | RESULTS

3.1 | Stress and sensitivity analysis

The NPV takes into consideration the time value of money. A positive NPV signifies a worthwhile investment in that the projected earnings will exceed the overall costs, while a negative NPV signifies the opposite in that the project will result in a loss. The stochastic distribution of the discount rate used to calculate each scenario’s NPV is the triangular distribution with a minimum of 7%, likeliest of 9% and maximum of 11% for all farm scenarios.

The sensitivity analyses first examined how Grow-out survival in year 3, discount rate, and selling price variables affect the key output variable NPV. The largest contributor to the NPV mean variance was then selected for subsequent stress analysis. A simulation of 1,000 iterations was then run for each stressed input variable, generating separate NPV data controlling for salt costs. All simulations were done independent of each other. The NPV data generated by the stressed input variables were then compared to the base NPV data.

A second sensitivity analysis was performed to examine the effect of different salt ratios with a separate series of stress analyses. The baseline NPV scenario implies that a 50:50 ratio of LCSM and ISS is used. About 90% of the salt cost distribution values within the baseline NPV scenario, were between $1,029 and $2,055 (Table 9). Other probability deciles is also presented in Table 9. All farm scenarios will draw from the same distribution.

Table 9 Probability deciles of the triangular distribution for salt $/ton

Probability Decile	Units	Low	High
10%	$	$1,487	$1,565
20%	$	$1,448	$1,607
30%	$	$1,406	$1,652
40%	$	$1,361	$1,700
50%	$	$1,312	$1,752
60%	$	$1,258	$1,810
70%	$	$1,197	$1,876
80%	$	$1,124	$1,954
90%	$	$1,029	$2,055
100%	$	$800	$2,300

3.2 | 8-tank scenario

After 1,000 iterations using both the model's deterministic values and stochastic key variable inputs, the probability ranges and summary statistics are presented in Tables 10-12. The probability decile ranges are catalogued in Table 10. The probability deciles were obtained from the various stochastic variables and their assigned distribution values, in addition to the deterministic variables provided for the 8-tank RAS system. The results in Table 10 are the range of NPV values and the probability of their occurrence. For example, there is a 10% chance that the NPV of an 8-tank RAS system will fall within the range of $6,272 and $8,356. As the probability decile decreases, the range decreases as well.

Table 10 Probability Deciles of Aggregated NPVs for the 8-Tank System

Probability Decile	Units	Low	High
10%	$	$6,272	$8,356
20%	$	$5,335	$9,376
30%	$	$4,070	$10,500
40%	$	$2,946	$11,493
50%	$	$1,756	$13,079
60%	$	$582	$14,667
70%	$	-$963	$16,469
80%	$	-$2,911	$18,290
90%	$	-$6,307	$21,359
100%	$	-$20,459	$35,562

In Table 11, the summary statistics generated show that the mean, median, and mode resemble a normal distribution. The expected value for kurtosis within a normal distribution is 3.00 while the skewness is 0.00. The aggregated NPV values for the 8-tank system display slightly higher kurtosis at 3.23.

Table 11 Summary Statistics for the 8-Tank System

Summary Statistic	Units	Value
Minimum	$	-$19,195.36
Maximum	$	$36,247.32
Mean	$	$7,530.59
Mode	$	$6,946.64
Median	$	$7,458.83
Standard Deviation	$	$8,576.07
Skewness	#	0.14
Kurtosis	#	3.14

From the sensitivity analyses, the grow-out survival percentage, electricity usage, discount rate, selling price, and salt costs have the biggest effect on NPV mean variance (Table 12). The probability of a net loss can be found on the bottom row. The percentage values in parenthesis represent the portion of the distribution the values are drawn from. The first column corresponds to the baseline scenario and yielded a 17.4% likelihood of a net loss. The second simulation, which drew from the lower 5% of the variable controlling for grow out survival % in year 3 of production, increased the probability of a net loss to 36.2%. The third simulation, which drew from the lower 5% of the variable controlling for electricity usage in kwh/year, decreased the probability of a net loss to 3%. The fourth simulation, which drew from the upper 5% of the variable controlling for discount rate %, increased the probability of a net loss to 40.3%.

To simulate an additional year of learning on the farmer's behalf, grow-out survival percentage for the third year of production was drawn from the lower 5% of the distribution. To simulate a higher alternative investment, the discount rate will be higher – only pulling from the upper 5% of the initial distribution. A drop in the selling price is shown by drawing from the lower 5% of the variable controlling for price. The stress tests for these three variables support downside risk analysis, while the stress test for electricity usage (kwh per year) supports upside risk analysis, simulating a reduction in overall electricity usage (Table 12).

Pulling from only the lower bound (0-5%) of the distribution for 'Survival Year 3', resulted in a negative effect on the aggregated NPVs by decreasing the minimum value and increasing the probability of a loss. The stress conducted on the discount rate had a similar effect by increasing the probability of a loss and the minimum value, while decreasing the remaining summary statistics. The stress test on the electricity usage, where only values from the lower bound (0-5%) of the distribution were drawn, resulted in a positive effect on aggregated NPVs as both the minimum value and probability of a loss were decreased while the remaining summary statistics increased. The last column of Table 12 showed the effect on NPV if the values for annual selling price were pulled from the lower 5% of each distribution. It had a significant effect by increasing the likelihood of a loss to over 93% and reducing the mean NPV. All simulations were conducted independently of each other and the results of each stress test assume ceteris paribus.

TABLE 12 Summary statistics of aggregated NPVs from stress tests on four additional variables for the 8-tank system

Summary Statistic	**Baseline Scenario**	**Grow-Out Survival Year 3 (0-5%)**	**Kwh Per Year (0-5%)**	**Discount Rate (95-100%)**	**Selling Price (0-5%)**
Min	$-19,195.36	$-25,563.67	$-9,657.57	$-20,974.31	$-35,365.25
Max	$36,247.32	$29,921.06	$42,489.28	$25,037.58	$11,469.06
Mean	$7,530.59	$2,929.01	$14,135.44	$2,003.74	$-11,085.79
Mode	$6,946.64	$1,552.68	$11,074.20	$-1,535.12	$-8,563.49
Median	$7,458.83	$2,816.10	$14,096.44	$1,845.73	$-10,944.67
Std Dev	$8,576.07	$8,143.00	$8,149.31	$7,439.89	$7,305.01
Skewness	0.14	0.13	0.12	0.10	0.01
Kurtosis	3.14	3.17	3.09	3.01	2.97
(NPV<0)	17.40%	36.20%	3%	40.30%	93.2%

To simulate the implementation of various salt ratios, a series of stress tests were conducted on the variable controlling for salt costs. It is assumed that the ‘Baseline Scenario’ uses roughly a 50/50 mix of ISS and LCSM salt mixture. The ratio of ISS and LCSM mixtures and the portion of the variable’s distribution are as follows: (a) 100% ISS solution - the cost was drawn only from the upper 5% of the distribution (lower bound $2,055 and upper bound $2,300); (b) 75% LCSM, 25% ISS mix - the cost was drawn only from the upper 75-95% of the initial salt cost distribution (lower bound $1,752 and upper bound $2,055), (c) 25% LCSM, 75% ISS mix - the cost was drawn only from the lower 5-25% of the initial salt cost distribution (lower bound $1,029 and upper bound $1,312); and (d) 100% LCSM solution - the cost was drawn only from the lower 0-5% of the initial salt cost distribution (lower bound $800 and upper bound $1,029.13).

Table 13 shows the results from each stress test. The four columns to the right of the ‘Baseline Scenario” represent four separate scenarios in which the different salt ratios are implemented. Adoption of 100% ISS and the 100% LCSM mixtures had the most significant impact on the probability of a net loss. From Table 13, the adoption of 100% ISS increased the probability of a net loss from 17.40% (baseline) to 34.0% while the adoption of 100% LCSM reduced the probability of a net loss from 17.4% (baseline) to 7.40%. A mix ratio of 75% ISS and 25% LCSM increased the likelihood of a net loss from 17.40% (baseline) to 24.50%, while a ratio of 25% ISS and 75% LCSM decreased the likelihood of a net loss from 17.40% (baseline) to 11%. The results show that the implementation of LCSMs in RAS farming can reduce the likelihood of a net loss assuming *ceteris paribus* regarding the other stochastic variables within the model.

TABLE 13 Summary statistics of aggregated NPVs from stress tests on salt costs for the 8-Tank System

Summary Statistic	**Baseline Scenario**	**100% ISS (95-100%)**	**75% ISS 25% LCSM (75-95%)**	**25% ISS 75% LCSM (5-25%)**	**100% LCSM (0-5%)**
Min	$-19,195.36	$-24,089.73	$-17,783,14	$-19,656.46	$-14,070.79
Max	$36,247.32	$34,900.52	$37,359.28	$37,464.28	$39,927.09
Mean	$7,530.59	$3,764.30	$5,840.15	$10,486.43	$11,760.59
Mode	$6,946.64	$3,133.30	$3,173.81	$8,695.01	$11,621.77
Median	$7,458.83	$3,775.09	$5,384.19	$10,294.53	$11,363.35
Std Dev	$8,576.07	$8,453.74	$8,685.11	$8,753.85	$8,523.95
(NPV<0)	17.40%	34.0%	24.50%	11.0%	7.40%

From Table 13, the adoption of 100% ISS decreased the average NPV from $7,530.59 to $3,764.30 while the adoption of 100% LCSM increased the average NPV from $7,530.59 to $11,760.59. A mix ratio of 75% ISS and 25% LCSM decreased the average NPV from $7,530.59 to $5,840.15, while a ratio of 25% ISS and 75% LCSM increased the average NPV from

$7,530.59 to $10.486.43. The results show a 212.4% increase in the average NPV between the 100% ISS solution and a 100% LCSM solution.

3.3 | 16-tank scenario

After 1,000 iterations of MCM, the probability deciles were obtained from the various stochastic variables and their assigned distribution values, in addition to the deterministic variables provided for the 16-tank RAS system. The results in Table 14 are interpreted as the range of NPV values and the probability of their occurrence. Of the 1000 iterations, none of the NPVs was found to be negative.

TABLE 14 Probability deciles of aggregated NPVs for the 16-tank system

Probability Decile	Units	Low	High
10%	$	$51,037	$55,466
20%	$	$48,418	$57,843
30%	$	$45,778	$60,651
40%	$	$43,865	$63,043
50%	$	$41,182	$65,897
60%	$	$37,096	$69,075
70%	$	$34,199	$73,516
80%	$	$29,969	$78,229
90%	$	$24,182	$86,019
100%	$	$7,051	$122,223

TABLE 15 Summary statistics for the 16-tank system

Summary Statistic	Units	Value
Minimum	$	$7,051
Maximum	$	$122,223
Mean	$	$53,872
Median	$	$52,954
Mode	$	$52,338
Standard Deviation	$	$18,649
Skewness	#	0.25
Kurtosis	#	2.88

TABLE 16 Summary statistics of aggregated NPVs from stress tests on four additional variables for the 16-tank system

Summary Statistic	Baseline Scenario	Grow-Out Survival Year 3 (0-5%)	Kwh Per Year (0-5%)	Discount Rate (95-100%)	Selling Price (0-5%)
Min	$7,051	-$1,611	$13,999	-$3,087	$-39,199.84
Max	$122,223	$100,636	$123,699	$90,995	$72,227.34
Mean	$53,872	$44,829	$68,895	$40,782	$13,859.25
Mode	$52,338	$53,538	$60,031	$40,047	$12,879.55
Median	$52,954	$44,394	$68,731	$40,796	$13,425.08
Std Dev	$18,649	$16,847	$17,036	$15,218	$15,841.23
Skewness	0.25	0.11	0.14	-0.013	0.21
Kurtosis	2.88	2.941	2.85	2.85	3.38
(NPV<0)	0.00%	0.30%	0.0%	0.40%	18.0%

In Table 15, the summary statistics show that the mean, median, and mode resemble a normal distribution. The aggregated NPV values for the 16-tank system display a lower kurtosis and higher skewness compared to the aggregated values for the 8-tank system. The distribution of aggregated values for the 16-tank system is skewed more to the right than the 8-tank system.

The same variables used in the 8-tank scenario were incorporated in the stress analysis on NPV for the 16 Tank scenario. The summary statistics in comparison to the Baseline 16-tank system, are presented in Table 16. Pulling from only the lower bound (0-5%) of the distribution for ‘Grow-Out Survival Year 3,’ had a negative effect on the aggregated NPVs by decreasing the minimum value and increasing the probability of a loss. The stress test conducted on the ‘Discount Rate’ had a similar effect by slightly increasing the probability of a loss and decreasing the minimum value, while decreasing the remaining summary statistics. The stress test on the electricity usage had a positive effect on aggregated NPVs. The final column shows the effect a lower selling price has on NPV. The likelihood of a loss increases to 18% and the mean NPV is reduced significantly. All simulations were conducted independently of each other.

To incorporate the adoption of different salt ratios, the same salt cost stress analyses conducted on the 8-tank system were conducted on the 16-tank scenario. Table 17 shows the results from each stress test. The ‘Baseline Scenario’ assumes roughly a 50/50 ratio of ISS and LCSM mixtures. Since the probability of a net loss was 0.00% in the Baseline scenario, the mean NPV was chosen as a performance indicator for the 16-tank scenario. It is assumed that the Baseline scenario uses close to a 50-50 ISS/LCSM ratio. Further implementation of LCSM mixtures increases the average NPV.

TABLE 17 - Summary statistics of aggregated NPVs from stress tests on four additional variables for the 16-tank system

Summary Statistic	Baseline Scenario	100% ISS (95-100%)	75% ISS 25% LCSM (75-95%)	25% ISS 75% LCSM (5-25%)	100% LCSM (0-5%)
Min	$7,050.89	$-12,181.83	$-9,112.31	$-707.43	$6,798.15
Max	$122,223.35	$112,677.37	$112,049.77	$132,272.27	$112,969.84
Mean	$53,872.32	$45,566.78	$49,574.16	$58,020.31	$60,352.29
Mode	$52,338.07	$52,386.38	$48,693.73	$49,358.52	$53,890.93
Median	$52,954.27	$44,445.83	$49,012.75	$58,038.80	$59,609.23
Std Dev	$18,649.51	$18,311.71	$17,558.87	$18,919.41	$18,181.05
(NPV<0)	0.00%	>0.10%	>0.10%	>0.10%	0.00%

3.4 | 24-tank scenario

The probability decile ranges are catalogued in Table 18. After 1,000 MCM iterations, there were zero scenarios where the NPV was negative.

TABLE 18 Probability deciles of aggregated NPVs for the 24-tank system

Probability Decile	Units	Low	High
10%	$	$94,148	$100,164

20%	$	$91,182	$103,188
30%	$	$88,766	$106,490
40%	$	$84,940	$110,235
50%	$	$80,038	$114,258
60%	$	$76,602	$120,417
70%	$	$71,661	$126,386
80%	$	$64,655	$134,251
90%	$	$53,718	$145,689
100%	$	$11,193	$177,836

TABLE 19 Summary statistics for the 24-tank system

Summary Statistic	Units	Value
Minimum	$	$11,193
Maximum	$	$177,836
Mean	$	$98,284
Median	$	$97,360
Mode	$	$91,115
Standard Deviation	$	$27,413
Skewness	#	0.16
Kurtosis	#	3.21

TABLE 20 Summary statistics of aggregated NPVs from stress tests on four additional variables for the 24-Tank System

Summary Statistic	Baseline Scenario	Grow Out Survival Year 3 (0-5%)	Kwh Per Year (0-5%)	Discount Rate (95-100%)	Selling Price (0-5%)
Minimum	$11,193	-$1,283.95	$44,014.60	$9,304.50	-$32,439.35
Maximum	$177,836	$173,150	$192,609.42	$155,102.87	$120,969.85
Mean	$98,284	$83,997	$119,434.33	$75,888.02	$38,042.86
Mode	$91,115	$87,959	$121,068.84	$70,117.91	$37,370.50
Median	$97,360	$84,584	$118,955.41	$76,758.12	$37,454.43
Std Dev	$27,413	$26,6412	$25,873.20	$23,483.44	$23,214.53
Skewness	0.16	0.0191	0.1277	-0.0655	0.2155
Kurtosis	3.21	2.80	2.7091	2.8552	3.0031
(NPV<0)	0.00%	<0.10%	0.00%	0.00%	5.00%

In Table 19, the summary statistics show that the mean, median, and mode also resemble a normal distribution. The 24-tank system displayed kurtosis and skewness that resembled that of the 8-tank system.

The same variables were incorporated in the stress analysis on NPV for the 24 Tank scenario. The summary statistics in comparison to the Baseline, are presented in Table 20. Pulling from only the lower bound (0-5%) of the distribution for ‘Grow-Out Survival Year 3’ had a negative effect on the aggregated NPVs by decreasing the minimum value. The stress test conducted on the 'Discount Rate' decreased the minimum value, while decreasing the remaining summary statistics. The stress test on the electricity usage had a positive effect on aggregated NPVs. 'Selling Price (0-5%)' had a negative effect on all summary statistics and increased the probability of a loss to 5.00%.

To simulate the adoption of the different salt ratios, the same salt cost stress analyses were conducted on the 24-tank scenario. The results of each simulation are summarized in Table 21. Since the probability of a net loss was 0.00% in the Baseline scenario, the mean NPV was chosen as a performance indicator for the 24-tank scenario. It is assumed that the Baseline scenario uses close to a 50-50 ISS/LCSM ratio. Figure 14 shows that further implementation of LCSMs increases the average NPV.

TABLE 21 Summary statistics of aggregated NPVs from stress tests on salt costs for the 24-tank system

Summary Statistic	Baseline Scenario	100% ISS (95-100%)	75% ISS 25% LCSM (75-95%)	25% ISS 75% LCSM (5-25%)	100% LCSM (0-5%)
Min	$11,193	$6,720	$9,604	$21,713	$17,911
Max	$177,836	$175,537	$175,520	$189,550	$210,114
Mean	$98,284	$85,394	$89,274	$105,135	$108,569
Mode	$97,360	$77,651	$91,099	$106,436	$112,974
Median	$91,115	$84,985	$88,525	$104,202	$107,327
Std Dev	$27,413	$27,595	$27,189	$27,260	$28,019
(NPV<0)	0.00%	0.00%	0.00%	0.00%	0.00%

4.0 | DISCUSSION

The 8-tank scenario's initial probability of success was lower than that of the 16-tank and 24-tank scenarios and was far more sensitive to the stressed variables. The baseline scenario yielded a probability of a net loss of 17.4%. The first stress analysis on the grow-out survival percentage in year 3 of production doubled the probability of a net loss to 36%. This scenario was highly sensitive to electricity usage and the discount rate as well. The probability changes the net loss to 3% for lower electricity usage and to over 40% for a higher discount rate. For the 8-tank scenario to be feasible, a decrease in yearly kwh of electricity and high survival rates are needed. The 8-tank scenario's sensitivity to the discount rate shows that an alternative investment of similar resources and capital could prove to be a better decision. If the LCSM has no effect on the survival, growth, or overall performance of the shrimp, increasing the LCSM ratio can have a positive effect on the financial performance of the 8-tank scenario and could mitigate some internal risks.

The 16-tank scenario's initial probability of success was higher than the 8-tank system and was less sensitive to the stressed variables. The baseline scenario yielded a 0.0% probability of a net loss. The first stress analysis on the grow-out survival percentage in year 3 of production increased the probability of a net loss to 0.4%. This scenario was sensitive to electricity usage and the discount rate as well, but from a downside risk perspective, the probability of a loss was not affected. The results from these simulations show that the increase in production can greatly mitigate some of the internal risks of the smaller system. An increase in LCSM for the 16-tank system also had a positive effect on mean NPV.

The 24-tank scenario's initial probability of success was higher than the 16-tank. The stress test on electricity, grow out survival in production year 3, and the discount rate affected the NPV the least of all three scenarios. The baseline scenario yielded a 0.0% probability of a net loss. The first stress analysis on the grow-out survival percentage in year 3 of production did not change the probability of a net loss. This scenario was sensitive to electricity usage and the discount rate as well by reducing mean NPV, but the probability of a loss was not affected. Stressing the price of shrimp had a significant effect by increasing the probability of a loss to 5% and reducing the mean NPV by 61%. The farmers interviewed in this study receive a price premium by selling directly to consumers and restaurants, but this market has limited sales volume, causing farmers to explore other wholesale distribution channels where offered prices will be lower but at higher sales volume. An increase in LCSM for the 24-tank system also had a positive effect on mean NPV, but the increase was less significant in comparison to the 8-tank and 16-tank systems.

The results from this study show that an increase in production scale lowers internal risks and increases profitability. The 8-tank system, given its smaller production capabilities is more vulnerable to fluctuations in certain key variables when compared to larger production systems. The use of LCSMs for each system has a positive effect, especially in the 8-tank system. For RAS ventures to succeed, standardizing RAS technology and increasing research in both production economics and management will be paramount to their success.

5.0 | CONCLUSION

As the world population continues to increase, new technologies aimed at increasing efficiencies in our global food system will continue to be a topic of great discussion. Recirculating Aquaculture Systems (RAS) have been touted as one of the technologies that can be used for seafood production to help meet the increased global protein demand due to their year-round production capabilities, location flexibility, and smaller environmental impact in comparison to wild-caught seafood and large-scale pond aquaculture. Results from the analyses suggest that scaling production will decrease the risks involved in terms of costs. More production and increased revenue can offset the various risks associated with many of the variable inputs assuming there is a secured market and high prices. This of course depends on maintaining high prices in the future. If the price were to drop as more producers enter the market, this would cause some profitability challenges. There is lack of data and many of the assumptions embedded in this study including labor, selling prices, land values, electricity usage, etc. would need adjustments when scaling RAS shrimp operations. None of the scenarios include the opportunity cost of the owner/operator’s time either. Despite these limitations, this study is one of the more thoughtful, analytical studies of the internal risks and performance of domestic RAS shrimp farms ever conducted.

Small changes in certain input factors and biological parameters can have a significant effect on the farm’s profitability. Scaling up can mitigate some of these risks, but for small-scale farmers, the results of this study show that there are risks involved and obtaining price premiums are necessary to make this a sound investment. Due to the technological and biological complexities of biofloc RAS, proper management becomes critical. Potential farmers can get into shrimp farming as a diversified farming operation in addition to other existing agricultural ventures to minimize risks in their overall farming portfolio.

The adoption of LCSMs can have a positive effect on mitigating risk in these systems, particularly smaller operations. However, further research is needed to fully assess their effect on the biological performance of shrimp production, particularly in a full-scale commercial setting.

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