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Research Article

Economic analysis of Nile tilapia (*Oreochromis niloticus*) production based on farm size and number of rearing tanks

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ABSTRACT. This study evaluated the scale effect of the production, investment, and profitability of tilapia *Oreochromis niloticus* farming through benefit/cost ratio (B/C), the average and marginal return on investment (ROI), net present value (NPV) and the internal rate of return (IRR). The financial return of the annual production based on the number of grow-out tanks was considered a decision criterion for the size or scale to invest in or expand a tilapia aquaculture farm. The model considered two yearly rearing cycles with a density of 35 fish m^{-3} and a mortality rate of 5%. HDPE liner tanks of 16 m in diameter with a volume of 212 m^3 were used as the unit of scale in an outdoor intensive system. The simulation model determined that the farm sizes of 32, 48, 64, and 80 tanks with IRR values of 78, 94, 104, and 111%, respectively, had the highest economic efficiency considering the economic model criteria proposed in this study. Increasing returns to scale were evidenced in farm sizes from 1 to 30 tanks, with a tendency for constant returns to scale in sizes greater than 30. The most indicative scale effect was observed when increasing from 32 to 48 tanks, with a change of -1.5% in the average cost of production, -13.9% in the unit investment cost, 63% in NPV, and 21.1% in IRR. It is recommended to first invest in a system of 32 grow-out tanks and further increase the production scale to 48 tanks to improve the industry's profitability.

Keywords: *Oreochromis niloticus*; aquaculture; economies of scale; profitability; cost of production

INTRODUCTION

In recent years, aquaculture has experienced increased production worldwide and thus has become an essential food supplier with an aquatic origin (Føre et al. 2018, FAO 2022). As the scale of aquaculture increases, the industry faces new biological and socioeconomic challenges that could influence final production goals (Føre et al. 2018). The technical feasibility and economic return of commercial farming depend on the efficient use of invested resources, including technology, production input, infrastructure, and operating costs (Roy et al. 2002, Engle 2007, Gasca-Leyva et al. 2022, Hossain et al. 2022).

Studies that analyze the economic framework of aquaculture are necessary to determine the financial viability of the investments (García-García et al. 2005). Several studies have focused on analyzing the economics of tilapia rearing by considering the systems profitability according to different management factors (harvest, rationing, size heterogeneity) and investment aspects (Ponce-Marbán et al. 2006, Poot-López et al. 2014, Yuan et al. 2017, 2020). For example, Ponce-Marbán et al. (2006) analyzed the economic feasibility of implementing tilapia polyculture with Australian red claw (*Cherax quadricarinatus*) in Yucatan, finding that this strategy can increase the profitability (22-23% gain in net revenue), shorten investment return time and attenuate price-related risks. In another study, Poot-López et al. (2014) analyzed different feeding rates and harvest sizes in tilapia production in Yucatan, indicating that the optimal harvest size would be

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300 g for a size-dependent price. For a fixed price, the recommended size was 200 g per fish.

Nonetheless, an efficient upgrade of production costs can be achieved through the economies of scale (Roy et al. 2002, Kumar et al. 2020, Hossain et al. 2022), where optimal combination between the facilities and the use of production factors is a decision criterion that considers the economies of scale to achieve minimum total production costs (Bailly & Lagos 1991). Other examples of studies focusing on analyzing strategies to strengthen the production economics through cost improvements and determining the best scale of production can be found in the rearing of sturgeon (*Acipenser transmontanus*) by Logan et al. (1995), rearing of gilthead bream (*Sparus aurata*) by Gasca-Leyva et al. (2002) and De Benito et al. (2012); or shrimp (*Penaeus vannamei*) by Tian et al. (2000) and González-Romero et al. (2014). These studies aimed to determine the installed capacity and the added benefit to the system's productivity.

Recently, Hossain et al. (2022) performed a study to exhibit economies of scale and profit sensitivity in carp pond polyculture farming in Bangladesh; it was determined that the optimum farm size was approximately 3.5 ha until the average unit cost of production started to decrease due to inefficiently used inputs, even though it resulted in higher productivity. Theodorou et al. (2010) showed that investment tends to be feasible and profitable for different Mediterranean mussel (*Mytilus galloprovincialis*) farm sizes when they get government subsidies and are larger than 2 ha. Additionally, Zongli et al. (2017) and Yuan et al. (2020) analyzed the technical-economic efficiency in tilapia production to determine the effect of the productivity factors and the optimal farm size using in-land pond systems in China. The results showed that tilapia farmers operate 21% below the optimal production frontier, where allocative inefficiency of feed quantity was the primary cause of profit decrease. They proposed strategies such as scaling farm size moderately, thereby achieving the advantage of economies of scale.

Mexico remains a significant tilapia producer in Latin America, with 72,595.06 metric tons (MT) of production valued at US$ 119,171,280.28 in 2020 (CONAPESCA 2020). Most domestic production has been destined for subsistence use or local sale. However, the tilapia market has grown in volume and product quality, as it is considered an excellent substitute for other whitefish (Poot-López et al. 2014, Suárez-Puerto et al. 2021). In Yucatan, Mexico, tilapia aquaculture was initially developed in concrete tanks and financed by the federal government because aquaculture production was focused on the social development of low-income families (semi-intensive farming). However, during the last two decades, the production of this species has shifted from self-consumption systems to commercial (intensive cultivation) due to increased demand and private capital (Poot-López et al. 2014, Suárez-Puerto et al. 2021). This dynamic has led to the vulnerability of production profitability due to increased production costs and low prices. Nile tilapia *Oreochromis niloticus* culture in Yucatan can be classified as low-technology farms because they usually have 1-4 tanks, with a maximum tank volume of 117.8 m^3 and a density of around 8-38 fish m^3 (Flores-Nava et al. 2016, Paredes-Trujillo et al. 2016), with also medium to high technology farms have around of 5-13 tanks, with a maximum tank volume of 240 m^3 and densities around 21-46 fish m^3 (Poot-López et al. 2014, Flores-Nava et al. 2016, Paredes-Trujillo et al. 2016).

The analysis in the studies mentioned above was based on the socioeconomic and production data; however, its scope is limited since there is no information available on the tilapia economics that includes a scale of production evaluation based on the number of grow-out tanks and the indivisibility of capacities (on economic terms) of the applied technology, infrastructure, and operating equipment (Edwards & Starr 1987, Salvanes 1989). This economic data is necessary to enable producers, investors, or decision-makers to develop an efficient operating plan to increase productivity and production efficiency and improve initial or expanding investments to keep a competitive production within the market.

This study aimed to determine the optimal commercial farm size in tilapia aquaculture capable of resulting in higher profitability based on the number of tanks, but also through the evaluation of economic performance indicators (net present value NPV, internal rate of return IRR, and benefit/cost ratio B/C) by using a static economic model as reference and using biological and economic data of tilapia in-land tank intensive rearing production systems in Yucatan, Mexico. Different investment alternatives are discussed in this analysis.

MATERIALS AND METHODS

Data source

Data to generate the proposed technical-economic model was obtained from the current operation and production of commercial semi-intensive and intensive farms of Nile tilapia located in the Yucatan State of Mexico, where circular tanks made of cement or coated with a polyethylene film of 6-16 m diameter range were used. Water was acquired from wells via motor pumps (capacity based on the groundwater level). Tanks were designed to receive aeration through a blower and air diffusers (rocks, hoses, disks).

For this study, 12 farms or variable sizes were analyzed, and 21 producers were interviewed. Data concerning technical details, costs of equipment income, and operation was corroborated with consulting agencies (over five years' experience) related to tilapia production. Collected data were compiled in the Microsoft Excel Solver Add-In.

Model description

In this study, biological and economic data were considered to analyze the production of tilapia production. An economic model of constant production and without inflation was developed, in which three sub-models were included: biological, technical, and economic (Baca 2013), as described below.

Biological submodel

This component was collected from data associated with the average growth of the organisms from 1 to 450 g based on the experimental data from each farm. It was then integrated into the technical submodel to detect technical and economic variations according to the production capacity or farm size.

Technical submodel

This model considered a density of 35 fish m^{-3} and a mortality rate of 5% for each of the two rearing cycles per year. The final number of organisms (N) from fingerlings to harvest, biomass (B; t), and amount of consumed feed (A; kg) was estimated according to Bjørndal (1990).

Economic submodel

Technical-biological parameters were considered for this model and the recorded interactions between the market and production system. As a result, this model depends on the scale of the farm (number of tanks), tank rearing capacity (m^3), employee number per farm, rearing density, investment, and operational costs. For this analysis, the volume of production (B; kg), net income (NI; US$), and production cost (CT; US$) were estimated via the following expressions:

$$\text{Net income (NI): } NI = pB - CT \quad (1)$$

where pB represents the gross income per sale each year (US$), CT (US$) is the total cost of production, B represents total biomass per year, and p is the constant price (US$) of sales per kg.

Total cost of production (CT)

$$CTi = CVi + CFi \quad (2)$$

CF is the fixed costs, and CV (US$) is the sum of variable costs in annual production (US$). Variable costs ($CV$) associated with the production level were estimated based on function (3):

$$CVi = cS + caAi + C_e + C_{mo} + DP + C_o \quad (3)$$

where S represents the number of fingerlings, c is the unit cost per fingerling (US$ fingerling^{-1}), A is the consumed feed through time (kg), and ca is the cost of feed (US$ kg^{-1}). C_e is the electric energy cost (US$ yr^{-1}), C_{mo} is the variable labor cost (US$ yr^{-1}), DP is the depreciation of initial investment (US$ yr^{-1}), and C_o includes other variable costs estimated at 5% over the cost of feed and fingerlings per rearing cycle (US$ yr^{-1}); which is estimated by:

$$C_o = 0.05(Cs + caA) \quad (4)$$

where the independent fixed costs of the farm size were considered (US$ yr^{-1}), as well as the non-variable labor cost (salary of the production technician and vigilant) and the land property's annual rent cost (permits, local taxes) calculated by

$$CF = C_{mof} + C_r \quad (5)$$

where C_{mof} is the labor cost, and C_r is the rent cost.

The economic data (prices and costs) are shown in US$; currency exchange to Mexican pesos was performed using equivalence tables of the period when data was analyzed.

Evaluation of economic profitability

Returns to scale and the average cost of production when rearing units increase (number of tanks) were analyzed. An annual discount rate of 5% was estimated as the opportunity cost. The economic evaluation was based on annual metric tons production; the system's NPV, IRR, and B/C were analyzed according to Allen et al. (1984) and Bailly & Lagos (1991).

Economic indicators to determine the optimal farm size (OFS)

The selection of farm size was based on financial indicators (Table 1) and was used for the scale of production and economic return analysis. These indicators examine the cost-benefit and cash flow over

Table 1. Indicators of economic and financial performance as a selection criterion for the optimal farm size (OFS). NPV: net present value, IRR: internal rate of return, B/C: benefit/cost ratio, and ROI: return on investment.

Indicator	Selection criterion
Investment unit cost	Farm sizes with the lowest investment cost per kg of tilapia produced were selected.
Average cost of production	Farm sizes with the lowest value in the average cost of production and lower than the selling price were selected.
Marginal cost of production	Farm sizes with marginal cost equal to the average cost of production were selected.
B/C	Farm sizes with the highest ratio (>1) were selected.
ROI	Farm sizes with a recovery of 100% or more of the initial investment in a productive period of five years were considered.
NPV	Farm sizes that resulted in a discount rate greater than or equal to zero were selected.
IRR	Farm sizes with an IRR equal to or greater than the discount rate and meeting at least a TREMA of 20% were selected.

short and long periods to identify investment and production alternatives.

Data source and model assumptions

Technical and management values for this analysis were based on the information provided by the producers and regional market. Two production cycles per year, each six-month cycle, were considered. For both rearing cycles, 7800 fingerlings of size 1-1.5 g were used; the harvest size was 450 g per fish. Circular galvanized mesh tanks coated with HDPE geomembrane liner of 16 m in diameter with a volume of 212 m^3 were used in this study; this is the most employed type for outdoor systems for tilapia rearing in the state of Yucatan, Mexico. Considering the production and commercialization context of this species and using as reference the largest tilapia farm in Yucatan, the production model was scaled to a limit size of 100 rearing tanks. The feed cost was estimated based on development stages (nursing, fingerlings, pre-grow-out, and grow-out), rearing days, and feed producers' schedules. For a 16 m diameter tank with a density of 35 fish m^{-3}, the consumed feed was estimated as 4509.60 kg with a value of US$ 3656.16 per production cycle.

Sensitivity analysis

A sensitivity analysis was performed to evaluate possible uncertainty sources related to the economic model, where sale price and feed cost were considered with up to ±20% in fluctuation and assuming that the price of the product changes with the market. In contrast, feed costs involve 40-60% of operation costs (Poot-López et al. 2014, Yuan et al. 2017). This analysis calculated the percental change over IRR based on the core model.

RESULTS

Production economies and investment

Results from the simulation of production and initial investment at different numbers of tanks for tilapia farms in Yucatan, Mexico, are shown in Figure 1. Simulated results generated an annual biomass of 6.67 t of tilapia per HDPE liner tank of 16 m in diameter with a volume of 212 m^3, where 50 tanks corresponded to 333.45 and 666.9 t for 100 tanks. Evaluation of the divisibility and adequacy capacity of the investment assets showed that investment increased according to the farm size and production, indicating that building and operating a farm of a single rearing tank requires an initial investment of US$ 119,342.66, increasing to US$ 277,515.13 for 50 tanks and US$ 467,456.74 for 100 tanks.

The NPV and the IRR relationship to the farm size increment over a short-term period (five years) are shown in Figure 2. Farms with one to six tanks produced negative returns within a short-term period. Positive values were reached after farms were scaled to seven tanks (US$ 8372.57), showing a linear increase with a higher number of tanks until the simulation of 100 rearing tanks (US$ 1,952,678.02 in five years). Positive tendencies were shown in IRR and return on investment (ROI) up to an asymptote. An IRR of 8% was observed when increasing from six to seven tanks, resulting in higher returns than the estimated discount rate (5%). However, a farm size of 10 tanks (22% IRR) was needed to reach a minimum acceptable rate of

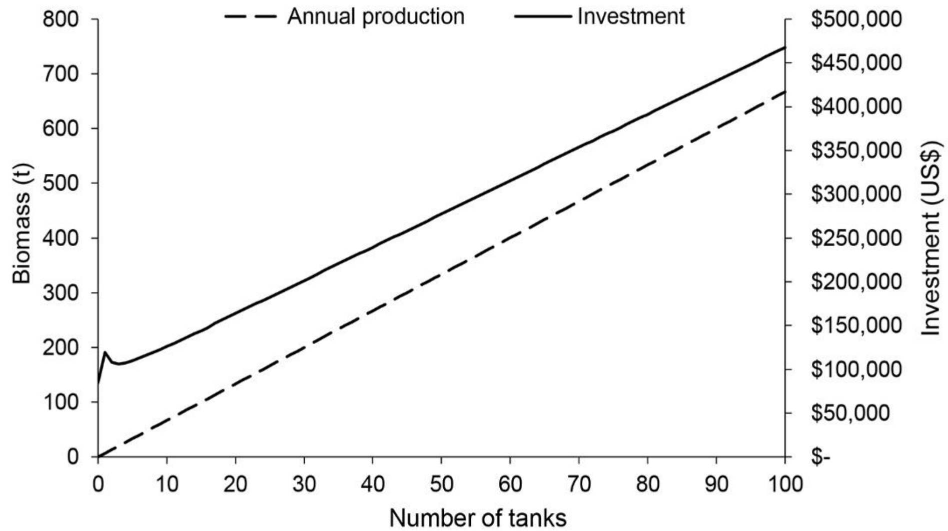

Figure 1. Initial investment and annual production of Nile tilapia about the number of production units.

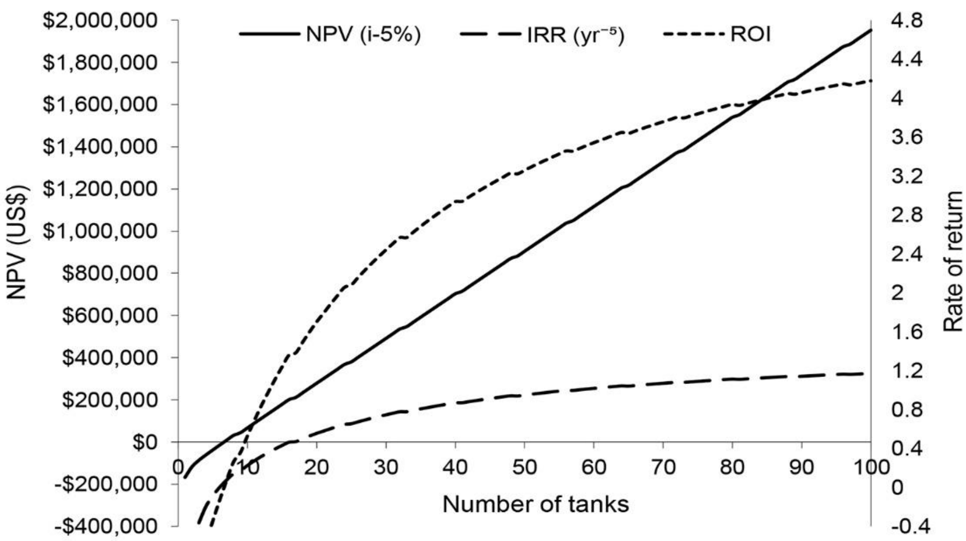

Figure 2. Evolution of economic and financial indicators about the number of production units in a five-year projection. NPV: net present value, IRR: internal rate of return, ROI: return on investment.

return (MARR) of 20%. IRR decreased in farm sizes greater than 80 tanks, with a tendency to a constant maximum limit concerning the production scale.

ROI increased according to the farm size, which suggests a scaled economy, yet marginal levels were increasing up to an asymptote, where the indicator was reduced with a constant tendency. Thus, a farm of 50 grow-out tanks would generate a return of 257% from the initial investment during five years of production, while a return of 418% would be obtained from a grow-out farm of 100 tanks (Fig. 2).

Marginal and average cost analysis

Simulated results of investment and production indicate that a farm size of a single grow-out tank holds a unit cost of investment of US$ 17.90 per kg of tilapia. In contrast, a farm size of 30 grow-out tanks reported a unit cost reduction of US$ 1.01, and the unit cost per 100 grow-out tanks was reduced to US$ 0.70 (Fig. 3).

Additionally, the total average cost decreased in agreement with the farm size, showing increasing returns to scale in smaller sizes of production (1 to 30 tanks) (Fig. 3). In farm sizes greater than 30 tanks, the average cost reduction was minimal where a constant

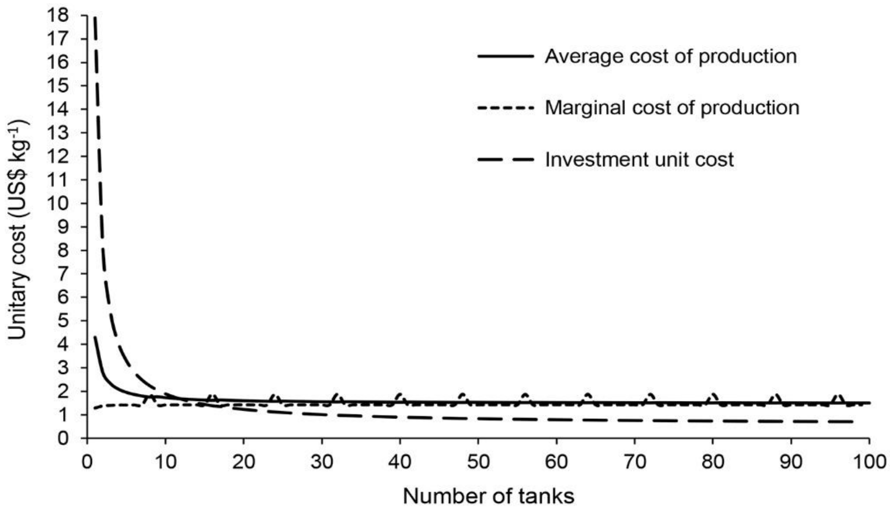

Figure 3. Average cost of production**,** the marginal cost of production, and investment unit cost about the number of production units in a five-year projection.

return behavior of scale of production is assumed. Hence, the average cost of operating a system composed of a single grow-out tank of tilapia would be US\$ 4.29 kg^{-1}. A farm size of 31 tanks reduces the average cost to US\$ 1.55 kg^{-1}, and a farm size of 100 tanks reduces the cost to US\$ 1.50 kg^{-1}. From three grow-out tanks onwards, the average cost of production (US\$ 2.32 kg^{-1}) is lower than the sale price (US\$ 2.62 kg^{-1}), indicating a profit margin or economic return.

The behavior of the marginal costs concerning the average costs indicates the cases of efficiency or inefficiency of tilapia production according to the increment of the tank numbers (Fig. 3). When marginal costs are equal to the average costs, these tend to decrease or to be constant, which gives significant profitability or efficiency in the production. When marginal costs are higher than the average costs, the latter increase. The optimal points or major profitability are determined mainly by fixed costs, hired labor to meet the demand of the number of tanks, initial investment, and investment depreciation, given that these factors display discontinuities in the technology use and the farm's operation.

Profitability and technical efficiency

Different selection criteria were chosen to define the optimal farm size (Table 1) and discard farm sizes of lesser profitability that fail to meet each criterion. Only marginal costs were specific relative to farm sizes; the other indicators showed limits or points of interest to be considered in selecting the optimal size. Farm sizes that displayed the points of higher technical efficiency were attributed to those where marginal cost was higher than the average cost of production, as observed in 8, 16, 24, 32, 40, 48, 56, 64, 72, 80, 88, and 96 grow-out tanks.

According to the ROI indicator, an investment return of 111% was obtained from 14 grow-out tank systems during five years, whereas B/C values of 1.70 were obtained in farm sizes with 32 rearing tanks. IRR is higher than the annual discount rate (5%) from the seventh grow-out tank onwards, only increasing by 5.8% between 80 to 100 grow-out tanks, similar to the average cost of production, which remains constant (US\$ 1.50).

Therefore, based on the preliminary results of the economic and investment analysis, only four farm sizes were considered within the optimal range of production: 32, 48, 64, and 80 grow-out tanks (Table 2). The behavior of the average cost of production and the investment unit cost suggests that tilapia production in rearing tanks is sensible to the economy of scale. In other words, it has a favorable development against production increments, yet with minor changes (which tend to be constant) at larger farm sizes. The investment depreciation showed to be relatively low; nonetheless, this is a relevant factor in this study, as it adds variability explained by the efficiency of the technical capacity and divisibility in the operation of the investment assets following the production scale.

Table 3 summarizes the behavior of profitability among optimal farm sizes. The four analyzed farm sizes affirm high returns, with IRR values above the minimum expected profitability for a risk investment (MARR 20%). However, the average cost of production

Table 2. Costs and benefits of annual Nile tilapia production by optimal farm sizes.

Farm size	Units	32 tanks	48 tanks	64 tanks	80 tanks
Initial Investment	US$	208,612.18	269,492.52	330,372.85	391,180.69
Production	t yr^{-1}	213.40	320.10	426.80	533.50
Variable costs					
Feed	US$ yr^{-1}	233,994.62	350,991.92	467,989.23	584,986.54
Hatchlings	US$ yr^{-1}	25,970.29	38,955.43	51,940.57	64,925.71
Labor	US$ yr^{-1}	11,877.94	17,816.91	23,755.89	29,694.86
Electricity	US$ yr^{-1}	18,285.71	27,428.57	36,571.43	45,714.29
Others	US$ yr^{-1}	12,998.25	19,497.37	25,996.49	32,495.61
Total variable costs	US$ yr^{-1}	303,126.80	454,690.21	606,253.61	757,817.01
Fixed costs					
Labor	US$ yr^{-1}	9142.86	9142.86	9142.86	9142.86
Land rent	US$ yr^{-1}	952.38	952.38	952.38	952.38
Total fixed costs	US$ yr^{-1}	10,095.24	10,095.24	10,095.24	10,095.24
Annual depreciation	US$ yr^{-1}	16,592.66	22,680.69	28,768.73	34,851.93
Gross income	US$ yr^{-1}	558,925.71	838,388.57	1,117,851.43	1,397,314.29
Total cost	US$ yr^{-1}	329,814.70	487,466.14	645,117.57	802,764.18
Subtotal	US$ yr^{-1}	229,111.01	350,922.43	472,733.86	594,550.11
Income tax (15%)	US$ yr^{-1}	34,366.65	52,638.36	70,910.08	89,182.52
Profit share (10%)	US$ yr^{-1}	22,911.10	35,092.24	47,273.39	59,455.01
Net income	US$ yr^{-1}	171,833.26	263,191.82	354,550.39	445,912.58

Table 3. Economic profitability of annual Nile tilapia production by optimal farm sizes. Net present value (NPV) and internal rate of return (IRR) were estimated for a period of five-year operation. B/C: benefit/cost ratio, and ROI: return on investment.

Indicator	Units	32 tanks	48 tanks	64 tanks	80 tanks
Average cost of production	US$ yr^{-1}	1.55	1.52	1.51	1.50
% variation			-1.5	-0.7	-0.5
Investment unit cost	US$ yr^{-1}	0.98	0.94	0.77	0.73
% variation			-13.9	-8.1	-5.3
B/C		1.70	1.72	1.73	1.74
ROI	%	257	323	365	394
NPV	US$	535,335.90	869,990.35	1,204,644.79	1,539,387.43
% variation			+63	+38	+28
IRR	%	7	94	104	111
% variation			+21.1	+10.8	+6.7

and the investment unit cost decreased to US$ 0.04 and 0.42 with 31 to 80 tanks, respectively. Profitability increases with the farm size; however, the major scale effect was shown when increasing from 32 to 48 grow-out tanks (-1.5% average cost of production, -13.9% unit cost of investment, 63% NPV, and 21.1% IRR).

Sensitivity analysis

Sale price and feed costs were modified by ±20% to quantify changes in different economic and market scenarios (Table 4). Results indicate that sale price fluctuation has greater profitability in IRR than feed cost fluctuation. This result suggests that the system's return or profitability decreases at a low sale price; however, it remains higher to a MARR of 20%.

In an adverse scenario with a decreasing sale price, ROI discards a farm size of 32 tanks since this value unsuccessfully covers 100% of the initial investment over five years. Moreover, the B/C index discards a farm size of 80 tanks because the same gross income was obtained (1.39) when operating with 64 tanks, including a lower initial investment.

The effect of variation in the productive scenarios was more relevant with the farm size of 32 tanks. Sale price variation demonstrated an effect twice as high as the feed cost, with a more remarkable change when

Table 4. Sensitivity analysis results by scenario and optimal farm sizes. B/C: benefit/cost ratio, ROI: return on investment, NPV: net present value, and IRR: internal rate of return.

Scenario	Farm size	Average cost (US$)	B/C	ROI (%)	NPV (US$)	IRR (%)
Base	32	1.55	1.69	257	535,335.90	78
	48	1.52	1.72	323	869,990.35	94
	64	1.51	1.73	365	1,204,644.79	104
	80	1.50	1.74	394	1,539,387.43	111
+20% sale price	32	1.55	2.03	431	898,314.28	120
	48	1.52	2.06	525	1,414,457.91	143
	64	1.51	2.08	584	1,930,601.54	157
	80	1.50	2.09	625	2,446,833.37	166
-20% sale price	32	1.55	1.36	83	172,357.52	31
	48	1.52	1.38	121	325,522.78	42
	64	1.51	1.39	145	478,688.04	49
	80	1.50	1.39	162	631,941.49	53
+20% feed cost	32	1.78	1.47	180	375,776.71	58
	48	1.75	1.49	234	630,651.56	72
	64	1.74	1.50	268	885,526.41	81
	80	1.73	1.51	292	1,140,489.45	86
-20% feed cost	32	1.32	1.99	333	694,895.09	97
	48	1.29	2.03	412	1,109,329.13	116
	64	1.28	2.04	461	1,523,763.17	128
	80	1.27	2.06	495	1,938,285.41	136

Table 5. Percentage of change of the internal rate of return (IRR) estimator by production scenarios and optimal farm sizes.

Scenario	Farm size			
	32 tanks	48 tanks	64 tanks	80 tanks
+20% sale price (%)	+54	+52	+51	+50
-20% sale price (%)	-60	-55	-53	-52
+20% feed cost (%)	-26	-23	-22	-23
-20% feed cost (%)	+24	+23	+23	+23

reducing the sale price by 20%. The significant percentage change in IRR was 60% in the scenario of 32 tanks with a sale price reduction. Although there was minimal difference, the scenario of 64 tanks with a feed cost increase showed a minor percentage change of -22% in IRR (Table 5).

DISCUSSION

This study is the first to evaluate the economic efficiency of tilapia production based on farm size (number of grow-out tanks) and its production capacity. Thus, an economic model that considered profitability indicators and local production information on tilapia aquaculture was developed. The commercial farms chosen for this study operated with different tank numbers, from 4 to 100 or even more production units, representing the surface or volume of the production units. In contrast to previous studies that analyzed the profitability of farm sizes, the production, operating costs, and investment in this study showed a linear trend. These studies analyzed the economic and technical efficiency of different sizes or levels of production, as well as the display of the economies and diseconomies of scale (Roy et al. 2002, Theodorou et al. 2010, Zongli et al. 2017, Kumar et al. 2020, Yuan et al. 2020, Hossain et al. 2022), concluding that correct adequacy of investment, production inputs, and technical management results in an optimal level of production.

Positive production returns resulted throughout five years from seven tanks with an NPV of US$ 8,373.57, showing a linear increase in higher scales until reaching 100 tanks with the highest recorded values (US$

1,952,678.02). Additionally, the IRR indicator showed favorable values for farms of size larger than seven tanks, generating returns above the 5% discount rate. IRR (22%) was higher than MARR (20%) in more than 10 tanks. Castilho-Barros et al. (2020) estimated an IRR of 18.4% for a 10-year basis tilapia production in Brazil, carried out on 3 ha in-land pond rearing system with a lower density (3 fish m^{-3}), larger harvest size (700 g per fish) and a lower sales price (US$ 1.34 kg^{-1}). This indicator tends to decrease as the number of tanks increases, which reveals the existence of profitability limits in tilapia production regarding farm size.

Here, production capacity was considered as a comparative factor; hence IRR results for tilapia production were twice the estimated by Reyes (2012), who reported an IRR of 45% in a cage system of pond rearing with a capacity of 10,500 m^3 (equivalent to 50 tanks), which was slightly higher than the IRR estimated by Dorantes et al. (2017) with 66.72% in a cage system of pond rearing with a capacity of 5900 m^{-3} (equivalent to 28 tanks from our case of study). Moreover, Benítez et al. (2015) estimated a 143% IRR, although their analysis did not consider initial investment in the financial evaluation.

Regarding B/C, the benefits were relatively similar in conditions from 32 to 100 tanks, regardless of the investment made for each operational scale, generating B/C values of 1.70 and 1.74, respectively. On the other hand, ROI showed asymptotic trends when the number of tanks increased from 257% for 32 tanks to 365% for 64 tanks to 418% for a 100-tanks system. These results are similar to the ROI estimated by Benítez et al. (2015) of 360% and NPV of US$ 14,996.80, with the same rearing density and production horizon (five-year basis). This analysis reveals the technical and economic efficiency of investment by scale of production, showing a higher increase in farm sizes with less than 50 tanks. In comparison, a moderate increase of 92% was observed in larger farm sizes from 50 to 100 tanks. Other studies have shown relations that promote lower investment costs under certain operating limits and scales of production, which can contribute to lower production costs and increase farm profitability (González-Romero et al. 2014, Yuan et al. 2020); meaning that the relation of farm size and production technology will influence the production capacity, required investments and production costs. These results offer scenarios with different economic indicators that can be used as a base to help farmers plan production or investment decisions.

Economies of scale have been described in several fish farming studies, showing that average cost decrease as the farm size rises, for example, rearing of gilthead bream (*Sparus aurata*) by Gasca-Leyva et al. (2002), García-García et al. (2005), De Benito et al. (2012), Cang et al. (2018), and Rahman et al. (2019). In this study, a substantial effect on the economy of scale was observed with increasing yields in the first 30 tanks followed by a low increase with a tendency to be constant as the number of tanks increased (Fig. 1). This behavior is because variable production cost increases according to the increase in the units produced (kg of tilapia). However, fixed costs and the initial investment cost increase in a staged manner according to the adjustments of labor, technology, and required infrastructure for each farm size. This behavior is not in agreement with the classical investment analysis in fish aquaculture, such as the gilthead bream (rearing in floating cages) (Gasca-Leyva et al. 2002, De Benito et al. 2012), sturgeon (Logan et al. 1995), white shrimp (Tian et al. 2000, González-Romero et al. 2014), or tilapia (Yuan et al. 2017, 2020). Nonetheless, the observed trend in the study can be attributed to the effect of the equipment indivisibility and the required infrastructure for each scale of production, as indicated by Allen et al. (1984), Edwards & Starr (1987), and Salvanes (1989).

Results of this analysis establish that tilapia aquaculture in rearing farms developed in Yucatán is favorable as long as the scales of operation, the adequate number of tanks, and the required investment are considered (González-Romero et al. 2014, Yuan et al. 2020). However, similar to the results obtained by Mussa et al. (2020) from aquaculture in Malawi, the production of tilapia is carried out under decreasing scale returns since most farms have more equipment than the required, such as paddle aerators, motor pumps, and even tanks in disuse or an inoperative state due to lack of maintenance. This situation is observed in many local farms that invested without planning in the adequacy of the equipment, infrastructure, and production capacities (farm size or number of tanks), which can increase operating costs.

The unit cost of investment and the average cost of production resulted in an increasing scale return in the first 30 tanks. After these, returns were constant to scale (Fig. 2). A relative decrease is observed since a higher number of tanks in combination with fixed costs and investment costs do not result in a proportional effect.

The average cost to operate a tilapia production system with 31 tanks is US$ 1.55 $kg^{-1,}$ which reduces to US$ 1.50 kg^{-1} for a system with 80 to 100 tanks. This outcome suggests that required investment and operating costs for farm sizes over 80 tanks do not compensate for the effects of economies of scale. Therefore, for a sale price of US\$ 2.62 kg^{-1}, there is a profit margin between US\$ 1.12 and 2.07. This result is similar to those reported by Castilho-Barros et al. (2020), applying economies of scale to the farm size of tilapia in-land pond rearing system in Brazil, where the higher average cost of production was US\$ 1.44 kg^{-1} for 1 ha operation, decreasing to US\$ 1.21 kg^{-1} for a 5-ha system. As in the present study, lower operating costs resulted when farm size increased, although, as the scale of production increases, the rate of change tends to decrease.

The behavior of the marginal cost concerning the average cost showed efficiency and inefficiency outcomes of tilapia production regarding the number of tanks. The variation of profitability regarding higher number of tanks demonstrates points of technical efficiency (greater profitability) due to the adjustment of the indivisibility factor in equipment and infrastructure within the scales of production (Fig. 2). It is essential to mention that the inefficient use of inputs and production assets can result in an economic deficit, and thus generate an increase in the cost and opportunity value, including long-term production competitiveness as referred by several authors (Gasca-Leyva et al. 2002, Zongli et al. 2017). This situation can result in a long-term dynamic effect with critical adverse consequences in balance and discontinuity to the production's profitability.

Proportional adjustments must be installed over fixed and variable factors associated with the facilities, equipment to establish a long-term optimal production size or level, and available labor force to reduce average costs (Gasca-Leyva et al. 2002, Cang et al. 2018). According to the results of this study, farm sizes of 32, 48, 64, and 80 tanks are suggested as the optimal strategies of choice, as the costs of the different production and investment factors contribute to offering higher profitability by increasing the efficiency in the use of equipment and farm facilities.

Analyzing more than one optimal farm size allows for consideration of production alternatives for investments with variable payment capacity, as this may be true for producers in the study area or conservative investors. Based on these results (Table 3), the cost of the required investment to increase the production appears not to compensate for the effects of the scale economy (increase of tank numbers), given that economic return will be similar without the risk involved in a higher investment cost. Studies analyzing different systems and species show similar conclusions, where the recommended production scale with the best profitability was given: optimal farm size of 64 grow-out ponds for shrimp production in China (Tian et al. 2000), 48,000 m^3 farm capacity for sea bream cage production (Gasca-Leyva et al. 2002), and 2000 t production for 450 g in the Mediterranean (De Benito et al. 2012), 2 ha ponds recommended for shrimp production in Mexico (González-Romero et al. 2014), and 7.5 ha ponds for tilapia production in China (Yuan et al. 2020).

The importance of evaluating points of technical inefficiency, the combination of factors, production assets, and the capacity and functionality of indivisible equipment can aid in generating better recommendations for investment and optimal operating levels (Salvanes 1989, Engle 2007, Yuan et al. 2017, Zongli et al. 2017, Cang et al. 2018, Rahman et al. 2019). Therefore, farm size determination is crucial in aquaculture to obtain higher profitability since it links the initial investment to the required production capacity, as mentioned by Gasca-Leyva et al. (2002), González-Romero et al. (2014), and Yuan et al. (2020).

The profit sensitivity analysis in this study considered the sale price and the feed cost, the latter having the most significant impact on production costs, as shown in the results. In agreement with other economic studies of short-term analysis, these factors have the most incidence in a farm's optimal management: risk analysis by González-Romero et al. (2014) showed that feed price was one of the main factors affecting the profitability of the system; results by Yuan et al. (2017) shows that commercial tilapia farms smaller than 10 ha suffer a more significant effect from the elasticity in the selling price compared to farms of 10 ha or more; Castilho-Barros et al. (2020) estimated a 42 and 37% increase in IRR by reducing the feed conversion ratio (from 1.5:1 to 1.2:1) and increasing the selling price (from 1.34 to US\$1.47 kg^{-1}) respectively. Our analysis shows an IRR variation concerning the modifications of ±20% of the aforementioned productive scenarios. In adverse scenarios (sale price reduction, feed cost increase), IRR remained above MARR (20%).

This analysis demonstrates that sale price reduction considerably affected profitability, with the farm size of 32 tanks being the most affected. After evaluating the system sensitivity associated with the market effect (feed cost and sale price), the alternative of 48 tanks per system is proposed as the most suitable option when an IRR variation is present, in contrast to the other profitable farm size alternatives mentioned above. This study shares two relevant data to the economic analysis performed by Fernández-Sánchez et al. (2022) in bass production, where the annual volume production or farm scale in fish rearing is the primary constraint to generating better economic results, and the sale price fluctuations have the more significant effect on financial returns of an aquaculture system.

Our results represent, to some extent, the current regional production where the highest profitability is observed in aquaculture systems with around 30 grow-out tanks (with the intent of increasing production). An initial investment in a farm with 32 grow-out tanks that can later be expanded to a production of 48 tanks is recommended to improve the profitability and competitiveness of the system. The infrastructure capacity and the equipment indivisibility should be considered as they could favor an investment decision with positive and conservative results.

It is important to emphasize that to improve aquaculture production, it is necessary to adjust the production requirements, meaning that the use of assets, inputs, and investment levels need to agree with the objective(s) of the farm or producer, as well as ensuring available markets and access to training for efficient use of the resources.

CONCLUSIONS

Scale returns increased with farm size from one to 30 tanks, with a tendency for constant scale profits in farms with more than 30 tanks. In this study, evaluating the economic return of the production and investment of aquaculture farms in Yucatan indicates that a farm with 48 grow-out tanks would be the most suitable alternative for tilapia's investment or production scale. This conclusion is supported by the observed reduction in average costs and higher profitability, combined with market conditions, input, and infrastructure requirements of aquaculture.

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