Latin American Journal of Aquatic Research, 51(2): 282-294, 2023
DOI: 10.3856/vol51-issue2-fulltext-2999

*Research Article*

# Bioeconomic model for the evaluation of a backyard aquaculture system for tilapia (*Oreochromis niloticus*)

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**ABSTRACT.** Backyard aquaculture is gaining importance as a source of food and economic input for rural families in Mexico. The profitability of this system needs to be determined. Bioeconomic tools allow for making profit projections of any production system. A bioeconomic model composed of biological, production, and economic sub-models was developed to evaluate a low-cost backyard aquaculture system (BAS) appropriate for rural communities, considering theoretical productive parameters at certain environmental conditions. The BAS consisted of a 2800 L water reservoir stocked with 168 masculinized 1 g fingerlings of tilapia (*Oreochromis niloticus*) at 60 ind $m^{-3}$ density and aerated with two ventury-type submerged pumps of 0.046 hp at a rate of 1400 L $h^{-1}$ each. Two culture cycles of 25 weeks each were analysed. The initial investment was USD 1200 (USD 775 equipment + USD 425 operation cost $yr^{-1}$). Results from the model indicate the production of 303 fishes of 614 g, equivalent to 186 kg $yr^{-1}$, considering 10% mortality. Selling at USD 3.62 $kg^{-1}$, net profits varied from USD 184 to 16 at 0 and 25% self-consumption. The payback period was three and four years at 0 and 10% self-consumption but was longer than five years at 25%. A response surface plot of profitability indicators (cost-benefit, net present value, and internal rate of return) was constructed at different self-consumption percentages, sale prices, and temperatures. In conclusion, BAS is a viable self-sustainable alternative for tilapia production at a low scale in rural areas of Mexico and other Latin American countries.

**Keywords:** *Oreochromis niloticus*; tilapia; backyard aquaculture; bioeconomic model; profitability indicators; self-consumption; Mexico

## INTRODUCTION

Backyard systems are considered agroecosystems in which domestic groups produce various species of animals and plants in a homemade way for food self-sufficiency and economic savings (González-Ortiz et al. 2014). These promote social and family coexistence and integration to improve food security and contribute to poverty reduction (Fideicomiso de Riesgo Compartido; FIRCO 2017). Labor and land cost savings are the key elements for backyard systems' economic viability.

Aquaculture is a productive activity with a growth of 46.8% in 10 years (2010-2019), reaching a production of 85.3 million t and USD 259 million in 2019 (Table 1). Food and Agriculture Organization (FAO 2021) estimations indicate that aquaculture will provide more than 50% of fish for human consumption in 2030 (FAO 2003, Pomeroy et al. 2008). From all aquaculture species, the group of tilapia ranked second among the finfish species, highlighting the production of Nile tilapia (*Oreochromis niloticus*), which, in 2018, was the third most produced species in the world (FAO 2020). Tilapia is well suited for culture as a food fish for several reasons. The fish tolerate very poor water quality conditions and will survive oxygen depletions that would kill most other fish, so they could be stocked in very small ponds at high densities and still thrive (Williams 2020).

Corresponding editor: Fernando Vega

Tilapia will produce acceptable weight gains on various inexpensive low-quality feeds, reducing production costs. Tilapia also is resistant to most diseases commonly associated with fish culture. For all this, tilapia participates with 5.29% of world production, with 4.5 million t and USD 9.1 million in 2019 (Table 2) (FAO 2021). In 2019, the demand for tilapia in Mexico was nearly 300,000 t, of which 168,000 t were produced locally, and the rest (127,981 t) were imported from Asia. Apart from being Mexico the second importer of tilapia in the world after the USA, local demand is growing at an annual rate of 9% (CONAPESCA 2018); therefore, aquaculture production needs to be increased.

Martínez-Cordero et al. (2021) mention that micro farms producing less than 500 kg $yr^{-1}$ may represent up to 50% of tilapia farmers in Mexican rural areas. They are family operations where the mother and children take care of the daily management (feeding, pond maintenance) and sales. The father usually works in the agriculture field or the construction business, yet he is still the head of the fish farming business. The impulse of backyard aquaculture could contribute to covering this demand. There are several technologies widely used in tilapia aquaculture. The cost of the technology employed increases with the density at which the organisms are cultured. For instance, water exchange is limited in the recirculation aquaculture system (RAS), and biofiltration is required to reduce ammonia toxicity (Timmons & Ebeling 2013). In this system, Fimbres-Acedo et al. (2019) produced 100 kg $m^{-3}$ of tilapia.

Biofloc technology (BFT) is emerging as an alternative where recycling and reusing waste nutrients such as fish food is employed. The principal approach of BFT is to culture suitable microorganisms along with aquatic species (fish or shellfish) to produce a sustainable system, benefited by the minimum or zero water exchange. In this system, tilapia is normally cultured at densities of 20-30 kg $m^{-3}$ (Avnimelech 2015).

However, tilapia can be cultured at a lower cost in fertilized water, with no aeration, and at low density (0.15-0.2 kg $m^{-3}$) (Vega-Villasante et al. 2009, 2010). He proposed a small-scale aquaculture system for rural and peri-urban communities of the Pacific coast of Mexico, in which the fish are cultured at a density of 3-4 ind $m^{-3}$. Similar systems are widely used in backyard aquaculture because they are simple to operate and only require water exchange with no aeration and feeding the fish with domestic waste or balanced feeds. Earthen ponds or concrete ponds/tanks are the most common containers because they are self-built, but recently, plastic tanks have become increasingly popular.

Around 30% of tilapia production in Mexico uses this technology for self-consumption, and the remaining is traded among neighbors or local consumers (Martínez-Cordero et al. 2021). These micro-farms are located in warm regions where the water temperature is higher than 28°C year round; there is enough land to place the tanks, and basic services such as water and electricity are readily available. Nevertheless, the production of these farms is low but could be enhanced by increasing density and providing aeration at an optimum level without major investment.

The profitability of backyard aquaculture in different scenarios has yet to be determined. Bioeconomic tools allow profit projections of any production system and have their foundations in the Systems Dynamics Theory and mathematical tools (Allen et al. 1984, Leung 1994). Bioeconomic models are made up of a biological, a production, and an economic sub-model, which evaluate the behavior of a system in which the development of a living organism is integrated at certain exogenous and endogenous variables typical of the production system and the market (Ponce-Marbán et al. 2006, Pomeroy et al. 2008, Llorente & Luna 2014, 2016).

In this work, a bioeconomic model composed of a biological, production, and an economic sub-model was developed to evaluate the low-cost backyard aquaculture system (BAS) appropriate for rural communities in Mexico, at different sale prices, at certain water temperature conditions, and self-consumption levels.

## MATERIALS AND METHODS

### Backyard aquaculture system (BAS)

The BAS was designed as a closed-flow system that was easy to operate, to which partial water exchanges were done depending on the ammonium concentrations, which consists of a 2800 L plastic water tank (1.86 m diameter × 1.18 m height) to which venturi-type submersible pumps of 0.046 hp are fitted to recirculate the water at 1400 L $h^{-1}$ and oxygenate the water at a rate of 1.2-2.4 kg $O_2$ kW $h^{-1}$ (Fig. 1). This type of pump was selected according to Boyd & Pillai (1985) because of their high range of oxygen transfer capacity with low energy consumption. The number of pumps was calculated as described below. Depending on the $O_2$ demand of the existing biomass under culture and on the oxygen transfer capacity of the pumps. For the model, the biological and culture parameters (Table 3) were those which, in practice, have been demonstrated to be appropriate for tilapia *O. niloticus* cultivation

**Table 1.** World production and value of aquaculture during the period 2010-2019 (FAO 2021).

| Year | Aquaculture production in volume | Aquaculture production in value | Annual variation in volume | Annual variation in value |
|---|---|---|---|---|
| | t × $10^3$ | USD × $10^3$ | % | % |
| 2010 | 57,744 | 131,222 | 0 | 0 |
| 2011 | 59,789 | 154,793 | 4 | 18 |
| 2012 | 63,480 | 169,771 | 6 | 10 |
| 2013 | 66,952 | 191,919 | 5 | 13 |
| 2014 | 70,506 | 210,890 | 5 | 10 |
| 2015 | 72,776 | 206,741 | 3 | -2 |
| 2016 | 76,474 | 223,784 | 5 | 8 |
| 2017 | 79,497 | 238,697 | 4 | 7 |
| 2018 | 82,304 | 248,669 | 4 | 4 |
| 2019 | 85,335 | 259,547 | 4 | 4 |
| Total | 714,857 | 2,036,033 | | |

**Table 2.** World production in volume and value of Nile tilapia from 2010-2019 (FAO 2021).

| Year | Production in volume | Production in value | Annual variation of production in volume | Annual variation of production in volume |
|---|---|---|---|---|
| | t × $10^3$ | USD × $10^3$ | % | % |
| 2010 | 2502 | 4343 | 0 | 0 |
| 2011 | 2917 | 5677 | 17 | 31 |
| 2012 | 3342 | 6702 | 15 | 18 |
| 2013 | 3484 | 7261 | 4 | 8 |
| 2014 | 3758 | 7908 | 8 | 9 |
| 2015 | 4050 | 8075 | 8 | 2 |
| 2016 | 4168 | 8375 | 3 | 4 |
| 2017 | 4446 | 8411 | 7 | 0 |
| 2018 | 4526 | 8652 | 2 | 3 |
| 2019 | 4590 | 9179 | 1 | 6 |
| Total | 37,783 | 74,583 | | |

(DOF 2021). The tank will be stocked at a density of 60 ind $m^{-3}$, with 168 masculinized 1 g fingerlings, and will be cultured in cycles of 25 weeks (5.8 months). Fish will be fed daily at a rate of 5 to 1% body biomass in 10 to 4 daily rations, following the tables recommended by the feed manufacturer. The types of balanced feed will be initiation (0.8-1.5 mm), intermediate (2.5-3.5mm), and finalization (4.5-7.5 mm), containing 50, 35, and 25% protein, respectively. After stocking, the daily activities include temperature checking with a digital thermometer, ammonium concentration determinations using an Ammonia Test Kit (Salicylate), and chlorine (if municipal water is employed) with a free chlorine test kit. Suppose ammonium concentration is higher than 2.0 mg $L^{-1}$. In that case, 30% (840 L) of the water will be replaced with clean water to reduce nitrogenous elements, organic matter, and food residues as well as to maintain an average optimal temperature for the development of organisms close to 28°C (Vega-Villasante et al. 2009, 2010). A mortality rate of 10% will be expected, giving a final density of 54 ind $m^{-3}$ and a harvest of 151 fish per cycle. Production will depend on the fish's final weight, which the model will calculate. The sale price was USD 3.62 $kg^{-1}$ = USD 1.64 $lb^{-1}$ at an exchange rate of 1 USD = 20 MXN. Reference price was obtained from the official records reported for whole tilapia by the Sistema Nacional de Información e Integración de Mercados (SNIIM 2021).

### The bioeconomic model

As already mentioned, the bioeconomic model was composed of three sub-models (i.e. biological, production, and economic) (Fig. 2). These sub-models

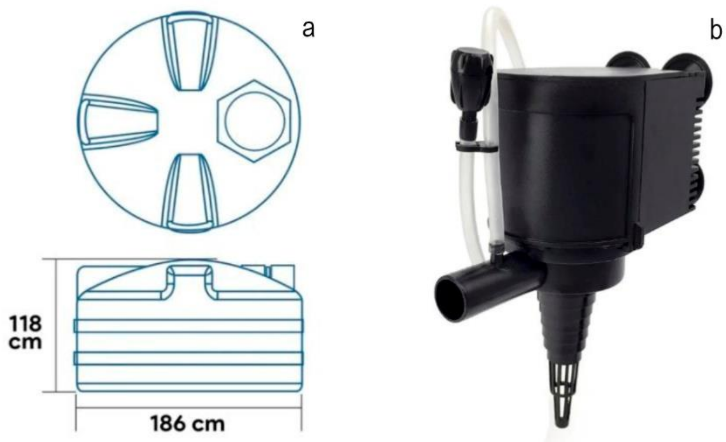


**Figure 1.** Main components of the backyard aquaculture system. a) Dimensions of the plastic tank of 2800 L capacity, b) venturi-type pump of 120 V, 0.046 hp, and 1400 L $h^{-1}$ capacity.

**Table 3.** Parameters for the grow-out of Nile tilapia in the backyard aquaculture system.

| Parameter | Qty | Units |
|---|---|---|
| Number of tanks | 1 | pieces |
| Tank capacity | 2.8 | $m^3$ |
| Cycle duration | 25 | weeks |
| Cycles per year | 2 | |
| Initial density | 60 | ind $m^{-3}$ |
| Fingerlings per tank per cycle | 168 | ind |
| Fingerlings per year | 336 | ind |
| Fingerling individual weight | 1 | g |
| Mortality | 10 | % |
| Final density | 54 | ind $m^{-3}$ |
| Number of fish harvested per cycle | 151 | ind |
| Number of fish harvested per year | 303 | ind |
| Individual weight at harvest | 614 | g |
| Food conversion factor | 1:1.2 | |

work independently from each other, receiving input information from the others to be processed with mathematical equations to generate output information that feeds the next sub-model finally.

**Biological sub-model**

The biological sub-model comprised the dependent and independent variables directly influencing growth: biomass, oxygen requirements, temperature, and expected mortality.

Biomass is the weight of all the organisms under culture, which varies along the culture period. It was calculated through the following equation:

$$B_t = N_t \times Wp_t$$

where: $B_t$: biomass at time $t$ of the culture, $N_t$: number of organisms at time $t$ of the culture, and $Wp_t$: average weight at time $t$ of cultivation.

Determining the oxygen demand by the organisms in the tank along the culture period is vital since an oxygen limitation will negatively affect weight gain and feed conversion and even produce the death of the fish. For the model, the following equation by Valbuena-Villareal & Cruz-Casallas (2006) was used:

$$O_2Dt = (1kg \times O_2C_0) / B_t$$

where: $O_2Dt$: oxygen demand at time $t$ of the culture, $O_2C_0$: rate of oxygen consumption at a given biomass (0.000508 $kgO_2$ $kg^{-1}$ $h^{-1}$), and $B_t$: biomass at time $t$ of cultivation.

Tilapia is a poikilothermic organism; therefore, growth depends on the existing temperature in the water (Jover-Cerdá 2000). For this sub-model, the mathematical model developed by Cho & Bureau (1998) modified by Atwood et al. (2003) was selected because it allowed predicting the growth rate of fish at different stages of development, depending on the average temperature in the water during the culture cycle. It uses a thermal growth coefficient (TGC), which was calculated with the following equation using data from a real experiment by Espinosa-Chaurand et al. (2019):

$$TGC = (W_f^{\frac{1}{3}} - W_i^{\frac{1}{3}})/(\Delta°T \times t)$$

where: $TGC$: thermal growth coefficient, $W_f$: observed final weight, $W_i$: observed initial weight, $\Delta°T$: effective growth temperature: mean water temperature during the cycle - minimum developmental temperature (15.5°C according to Atwood et al. 2003), and $t$: culture time.

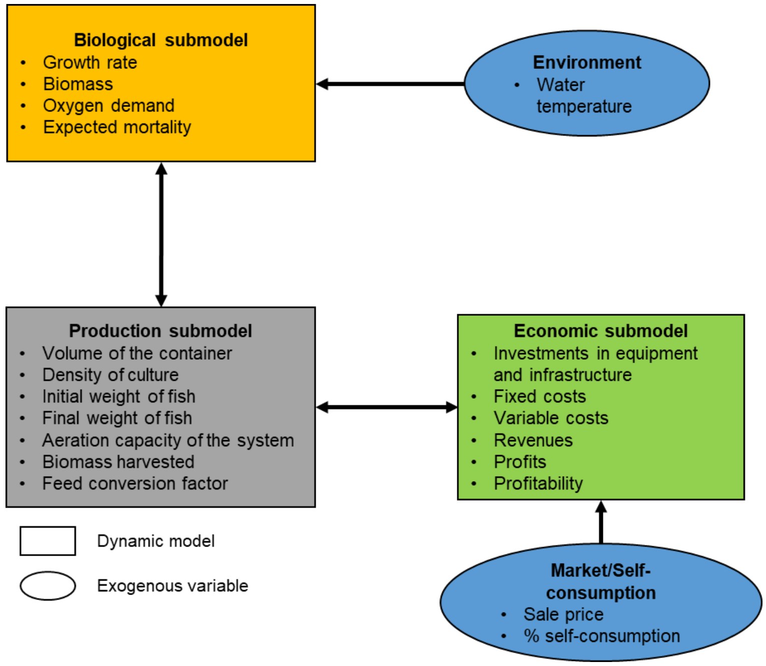


**Figure 2.** Schematic representation of the bioeconomic model developed to evaluate the backyard aquaculture system.

Once the TGC was obtained, the forecasted weight of the fish at harvest was obtained with the following equation:

$$W_f = (W_i^{\frac{1}{3}} + (TGC \times \Delta°T \times t))^3$$

where: $W_f$: forecasted final weight, $W_i$: predetermined initial weight, *TGC*: thermal growth coefficient, $\Delta°T$: predetermined effective growth temperature = predetermined mean water temperature during the cycle - minimum developmental temperature (15.5°C according to Atwood et al. 2003), and *t*: predetermined culture time.

Mortality is a phenomenon that occurs in all cultures due to various factors such as diseases, environmental variables, and predation (Pulido 2012). A 3 to 10% mortality is generally found during the grow-out stage of tilapia (Vega-Villasante et al. 2009, 2010). In this work, we considered 10% mortality and determined the number of organisms at the time of harvest with the following equation:

$$N_f = N_i - (N_i \times M_{exp})$$

where: $N_f$: number of fish at harvest, $N_i$: initial number of fish, and $M_{exp}$ expected mortality at the end of the culture.

## Production sub-model

In the production sub-model, the volume of the container, the culture density, the initial and final weights of fish, the capacity of the aeration system, the biomass harvested, and the food conversion factor were variables to be considered. All of them were predetermined values except the capacity of the aeration system to meet the demand of the fish and the feed conversion factor (FCF), which were both dynamic, depending on the biomass under culture. The number of venturi pumps required to meet the $O_2$ demand by the fish will depend on the biomass in the tank at harvest and on the minimum $O_2$ diffusion capacity of a single pump (1.2 kg $O_2$ kW $h^{-1}$). The number of pumps required was calculated using the equation:

$$N_{pumps} = O_2Dt\,/\,(kW\,h \times O_2D)$$

where: $O_2Dt$: dissolved oxygen demand at time *t* of the culture, *kW h*: energy consumption of pump (0.034 kW $h^{-1}$, and $O_2D$: minimum oxygen diffusion by a venturi pump (1.2 kg $O_2$ kW $h^{-1}$).

The FCF was calculated with the equation (Arce-Vega 2014):

$$FCF = TF/B_h$$

where: *FCF*: feed conversion factor, *TF:* food given during cultivation time, and $B_h$: biomass harvested.

## Economic sub-model

This sub-model included input data such as expenses and revenues and output data such as profits and profitability indicators; expenses included investment costs in equipment and infrastructure and variable and fixed costs. These costs allowed us to calculate the cost per kilogram. The revenues were the income funds from sales of biomass harvested and allowed to calculate the gross income (GI) at a given sales price. The output data from the model were net profit (NP), net profit margin (NPM), price margin rate (PMR), and the profitability indicators such as cost-benefit, net present value (NPV), and the internal rate of return (IRR). The latter two indicators were contrasted against the discount rate based on the Certificates of the Treasury of the Federation (CETES) at one year (8.3%) (SHCP 2021). Finally, the payback period (PP) was calculated.

Variable costs are the direct costs that have to do with production. The higher the production, the higher the variable costs. Fixed costs do not depend on the amount of product generated; only the maintenance costs of the production system were considered. This work's variable costs included fry, balanced feed, electricity, and water.

The following equation calculated the cost per kilogram produced:

$$C/kg = TC/B_t$$

where: *C/kg*: cost per kilogram produced, *TC*: total costs, and *Bt*: total biomass at time *t*.

GI is the amount of money obtained from the sale of the biomass produced at the market price before any expenses such as taxes, deductions, or reinvestments to continue producing.

GI was calculated with the equation (Ponce-Marbán et al. 2006):

$$GI = B_t \times P_t$$

where: *GI*: gross income, $B_t$: biomass at time *t*, and $P_t$: sale price (USD $kg^{-1}$).

NP is the income from sales but discounting not only production expenses but also distribution, logistics, operating expenses, taxes, and obligations. NP were calculated from the difference of the income from sales minus the sum of all the expenses incurred, with the equation (Ponce-Marbán et al. 2006):

$$NP = GI - TC$$

where: *NP*: net profit, *GI*: gross income, and *TC*: total costs.

NPM is an analytical metric to assess a company's financial health. A positive margin denotes that sales revenue is above all expenses the company accrued, fixed and variable, to produce and market a good or service (Branch & Klaehn 2003). A quick way to quantify this concept is through a percentage rate determining what percentage the net profits represent compared to the gross income. The NPM was calculated with the following equation:

$$NPM = \frac{NI}{GI} \times 100$$

where: *NPM*: net profit margin rate, *NI*: net income, and *GI*: gross income.

The PMR is the difference between the price at which a good or service is sold and the total estimated cost (Branch & Klaehn 2003). The PMR was calculated with the equation:

$$PMR = \frac{SP}{TPC} \times 100$$

where: *PMR*: price margin rate, *SP*: sale price, and *TPC*: total production costs.

Cost-Benefit is a profit indicator that compares costs *vs.* the economic benefits generated by the project during its execution time. Values equal to or greater than 1 indicate economic benefits that exceed the costs incurred by the project, so it can be interpreted as a profitable project in which sufficient income is generated to subsidize costs and generate profits for the investor (Aguilera 2017). The equation employed to estimate cost-benefit was:

$$Cost - Benefit = \frac{UGI}{UTC}$$

where: *UGI*: updated gross income, and *UTC*: updated total costs.

NPV is a profitable indicator used to determine the current value of all future cash flows generated by the project, including the initial capital investment. A discount rate is used to determine the current value of these cash flows, which can be determined by a percentage of the investment yield of a banking institution or by a percentage higher than the weighted rate for annual inflation, which allows recovering the investment made (Mete 2014). NPV was calculated with the equation Mete (2014):

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+i)^t}$$

where: *NPV* : net present value, $CF_t$ : cash flows in the period *t*, $I_0$ : initial investment made at the initial moment (*t* = 0), n : number of individual cash flows during project evaluation (= 5 years) and *k* = discount rate (= 8.3 %).

The IRR represents the discount rate (cost of capital) that equals the present value of income with the present value of expenses; in other words, it is the annual growth rate that an investment is expected to generate. The IRR was calculated with the following equation (Mete 2014):

$$IRR = NPV = 0$$

where: *IRR* = internal rate of return, and *NPV* = net present value.

Finally, the PP is the time needed before recovering the investment. The PP was calculated with the equation:

$$PP = -I_0 + \sum_{t=1}^{n} CF_t = 0$$

where: *PP*: payback period, $I_0$: initial investment (t = 0), $CF_t$: cash flow in period *t*, and *n*: number of individual cash flows during project evaluation (= 5 years).

These sub-models with their respective variables were loaded in an Excel template to calculate profitability at different self-consumption percentages, sale prices, and temperatures. A response surface plot was drawn using MatLab 2019b software to show the scenarios.

## RESULTS

The temperature growth coefficient (TGC) calculated with data from Espinosa-Chaurand et al. (2019) was 0.02400 (Table 4), allowed to build the growth rate curve of Figure 3 and to find the final weight of 614 g in the 25 week-cycle. Considering this individual weight and 10% mortality, 186 kg $yr^{-1}$ of fresh tilapia will be harvested. Five kilograms of initiation, 89 kg of intermediate, and 129 kg of finalization feeds will be employed, giving 223 kg of balanced feed per year, resulting in a 1:1.2 feed conversion factor.

The dissolved oxygen demand of fish during the culture time is shown in Table 5. Considering the oxygen transfer capacity of 1.2 kg $O_2$ kW $h^{-1}$ of the venturi pump, two pumps will be required to meet the $O_2$ demand until the end of the culture.

Considering the final weight of the fish, the quantity of feed required, and the number of pumps, the total investment required to build and operate the BAS for one year will be USD 1200 (Table 6), including USD 775 of investment (equipment) and USD 425 of productions costs. The equipment list includes scales for biometrics, nets for handling the fish, cleaning tools, a digital thermometer, and a spare venturi pump. The operation costs include fry, feed, cleaning reagents, electricity, ammonium and chlorine kits, water, and maintenance.

The costs and financial and profitability indicators calculated by the model at 0, 10, and 25% self-consumption are shown in Table 7. Total costs per year will be USD 425.26, giving a cost per kg of USD 2.29, considering an annual production of 186 kg. Selling

**Table 4.** The thermal growth coefficient (TGC) and the effective growth temperature (Δ°T) as calculated with observed values from an actual grow-out experiment of Nile tilapia. *Espinosa-Chaurand et al. (2019), **Atwood et al. 2003.

| Parameter | Observed values from a grow-out experiment* |
|---|---|
| Initial weight (g) | 3.06 |
| Final weight (g) | 512.32 |
| Time (weeks) | 18 |
| Mean temperature (°C) | 30.7 |
| Minimum maintenance temperature (°C)** | 15.5 |
| Δ°T (°C) | 15.16 |
| TGC | 0.02400 |

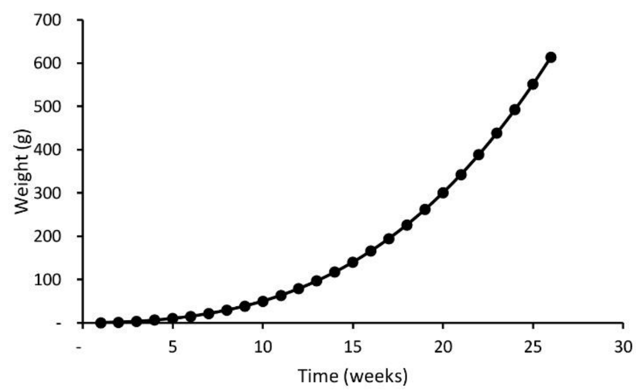


**Figure 3.** The calculated growth rate of Nile tilapia, cultured in the backyard aquaculture system during 25 weeks, at 28°C mean temperature and with a thermal growth coefficient of 0.02400.

the fish at USD 3.62 $kg^{-1}$, the GI will vary from USD 673 to 503 at 0 and 25% self-consumption, resulting in positive NP and NPM, which indicates breakeven values at 25% self-consumption since above this percentage, NP become negative. However, profitability indicators at 25% self-consumption are negative because of the deduction of the discount rate of 8.3% per year. With these indicators, the PP will be three and four years for 0 and 10% self-consumption and longer than five years for 25% self-consumption.

Different scenarios of profitability indicators (cost-benefit, NPV and IRR) at different self-consumption percentages and different prices and temperatures are shown in the surface response plot of Figure 4. It is evident that indicators are higher at 0% self-consumption, at highest tempe-rature tested (32°C) and at the higher sale price.

The annual production of tilapia in terms of the number of fish and weight harvested available for self-

**Table 5.** Venturi-type pumps required to meet $O_2$ demand by Nile tilapia during a 25-week cycle.

| Time weeks | Fish weight g | Number of fish ind | Biomass kg | $O_2$ demand kg $O_2$ kg$^{-1}$ h$^{-1}$ | Pumps required |
|---|---|---|---|---|---|
| 4 | 11 | 168 | 1.8 | 0.001 | 0.02 |
| 8 | 39 | 165 | 6.5 | 0.003 | 0.08 |
| 12 | 97 | 162 | 15.8 | 0.008 | 0.20 |
| 16 | 195 | 160 | 31.1 | 0.016 | 0.39 |
| 20 | 343 | 157 | 53.8 | 0.027 | 0.67 |
| 25 | 614 | 154 | 94.61 | 0.048 | 1.18 |

**Table 6.** Required investment for building and operating the backyard aquaculture system during the first year. *One spare venturi pump was included in case of failure

| Quantity | Unit | Concept | USD |
|---|---|---|---|
| 1 | Piece | Plastic tank (2800 L) | 500.00 |
| 3* | Piece | Venturi pump (1400 L h$^{-1}$) | 120.00 |
| 1 | Piece | Portable scale (0.01-200 g) | 25.00 |
| 1 | Piece | Commercial scale (40 kg) | 50.00 |
| 2 | Piece | Fish nets | 50.00 |
| 1 | Lot | Cleaning tools | 15.00 |
| 1 | Piece | Digital thermometer | 15.00 |
| | | Equipment cost | 775.00 |
| 336 | ind | Fry | 19.00 |
| 5 | kg | Initiation feed | 9.00 |
| 89 | kg | Intermediate feed | 111.00 |
| 129 | kg | Finalization feed | 96.00 |
| 1 | Lot | Reagents and medicines | 30.00 |
| 297 | kw | Electricity | 31.00 |
| 10 | Piece | Ammonium and chlorine kits | 15.00 |
| 108 | m$^3$ | Water | 99.00 |
| 1 | Lot | Maintenance | 15.00 |
| | | Production costs yr$^{-1}$ | 425.00 |
| | | Total investment yr$^{-1}$ | 1200.00 |

consumption and sales at different self-consumption percentages is shown (Table 8). At 0% self-consumption, 303 fish and 186 kg will be available for sale.

However, if 10% of production is destined for self-consumption, 31 fish of 614g and 19 kg will be available to feed the family and will have revenues of USD 605 by selling 272 fish and 167 kg. At 25% self-consumption, 75 fish and 46 kg will be available for feeding the family, equivalent to 1.4 fish and 0.88 kg per week. The financial self-sustainability will be reached at this self-consumption since the revenues will be enough to cover the production costs.

## DISCUSSION

In this work, evaluating the BAS with the bioeconomic model resulted in a viable self-sustainable alternative for tilapia production at a low scale in rural areas of Mexico and other Latin American countries. With a low investment of USD 1200, the BAS could produce high-quality food, contributing to food security and poverty reduction, providing extra income for the family. Regardless of the low-scale production system, BAS is profitable because labor and land have no cost. At 10% self-consumption, a family of five members could consume 3.8 kg of fish yr$^{-1}$, a figure which is above the average per capita apparent tilapia consumption in Mexico (3.08 kg ind$^{-1}$) and in the world (0.9 kg ind$^{-1}$) (Martínez-Cordero et al. 2021). At this percentage, there will be a NP of USD 117, which could contribute to the family's economy. The harvest of fish for self-consumption or sales could be anticipated several weeks before reaching week 25 since not all fish attain the same size simultaneously. So, partial harvests of the larger fish could be done, bringing the advantage of gradually reducing the culture density and availability of food and revenues for the family.

**Table 7.** Financial and profitability indicators of the backyard aquaculture system per year, at a sale price of USD 3.62 $kg^{-1}$ and different self-consumption percentages. Profitability indicators were calculated considering the five years duration of the project and at a discount rate of 8.3% $yr^{-1}$.

| Concept | Self-consumption percentage | | |
|---|---|---|---|
| | 0 | 10 | 25 |
| Total costs | 425 | 425 | 425 |
| Cost per kg | 2.29 | 2.29 | 2.29 |
| Gross income (USD) | 673 | 605 | 503 |
| Profits before depreciation (USD) | 248 | 181 | 80 |
| Net profit (USD) | 184 | 117 | 16 |
| Net profit margin (%) | 27.4 | 19.3 | 3.16 |
| Price margin (%) | 58.3 | 58.3 | 58.3 |
| Cost-Benefit | 1.12 | 1.00 | 0.84 |
| Net present value (USD) | 303 | 10 | -$429 |
| Internal rate of return (%) | 21.7 | 8.8 | -15.9 |
| Payback period (years) | 3 | 4 | >5 |

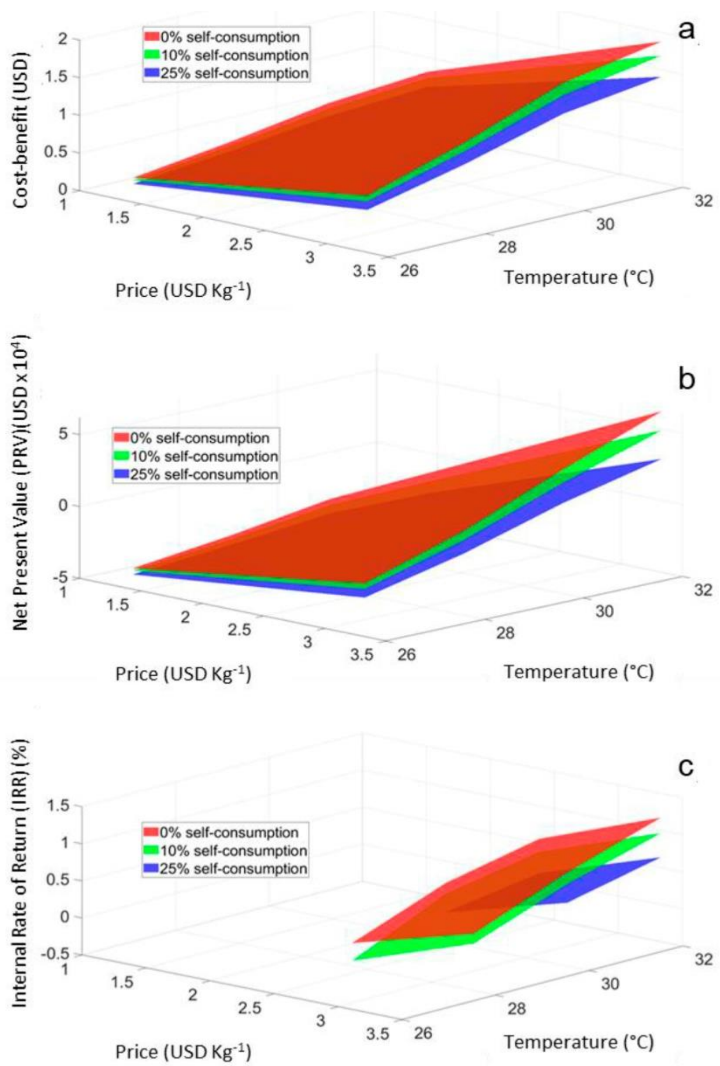


**Figure 4.** Response surface plot of profitability indicators of Nile tilapia produced in the backyard aquaculture system at different self-consumption percentages, prices, and temperatures. a) Cost-benefit, b) net present value and c) internal rate of return.

**Table 8.** Available annual production of Nile tilapia in terms of the number of fish and weight for self-consumption and sales at different self-consumption percentages produced in the backyard aquaculture system. Revenues from sales are shown. The shaded area indicates where the results are profitable. *Individual fish weight = 614g. **At a unit cost of 3.62 USD $kg^{-1}$.

| Self-consumption % | Annual production available for self-consumption | | Annual production available for sales | | Revenues* USD | Total annual production kg |
|---|---|---|---|---|---|---|
| | N° of fish** | kg | N° of fish** | kg | | |
| 0 | 0 | 0 | 303 | 186 | 673 | 186 |
| 5 | 15 | 9 | 287 | 176 | 637 | 186 |
| 10 | 31 | 19 | 272 | 167 | 605 | 186 |
| 15 | 46 | 28 | 257 | 158 | 572 | 186 |
| 20 | 60 | 37 | 243 | 149 | 539 | 186 |
| 25 | 75 | 46 | 226 | 139 | 503 | 186 |
| 30 | 91 | 56 | 212 | 130 | 471 | 186 |
| 35 | 106 | 65 | 197 | 121 | 438 | 186 |
| 40 | 121 | 74 | 181 | 111 | 402 | 186 |
| 45 | 137 | 84 | 166 | 102 | 369 | 186 |
| 50 | 151 | 93 | 151 | 93 | 337 | 186 |
| 55 | 166 | 102 | 137 | 84 | 304 | 186 |
| 60 | 181 | 111 | 121 | 74 | 268 | 186 |
| 65 | 197 | 121 | 106 | 65 | 235 | 186 |
| 70 | 212 | 130 | 91 | 56 | 203 | 186 |
| 75 | 226 | 139 | 75 | 46 | 167 | 186 |
| 80 | 243 | 149 | 60 | 37 | 134 | 186 |
| 85 | 257 | 158 | 46 | 28 | 101 | 186 |
| 90 | 272 | 167 | 31 | 19 | 69 | 186 |
| 95 | 287 | 176 | 15 | 9 | 33 | 186 |
| 100 | 303 | 186 | 0 | 0 | 0 | 186 |

There are several requirements for the successful application of the BAS. This system is suitable for warm areas of Mexico and Latin America, where average water temperatures above 28°C are registered. Nevertheless, tilapia have been cultured successfully in the Mexican plateau with an average water temperature of 26.2°C (Dorantes 2022) with freezing temperatures during the winter. The temperature in those areas is kept higher than 28°C by isolating the tanks with plastic domes and warming up the water required for water changes; this would imply making further investments and new calculations to determine the project's viability. Water and electricity supply are also indispensable requirements for the operation of the BAS. These may not represent a problem, at least in Mexico, since in 2015, 94.4 and 99.0% of inhabited households had water and electric supply, according to the Instituto Nacional de Estadística y Geografía of Mexico (INEGI 2018, 2019). For the project's success, a reliable source of high-quality fry and feed must be available. There are currently several hatcheries that can supply genetically-improved fry (Martínez-Cordero et al. 2021) and suppliers of feed for aquaculture in Mexico. However, in this country, greater efforts are required to satisfy the future demand derived from the Mexican population's growth in demand for both supplies.

Among the project's risks is the occurrence of diseases caused by bacteria, fungi, and ectoparasites. However, as pointed out before, tilapia is a highly-resistant species to diseases, and its susceptibility diminishes with age and size (Roy et al. 2021). Diseases could be treated with simple methods such as salt baths or the application of several measures (Cedric-Komar 2008). Another risk would be a pump failure and electricity shutdown that could cause $O_2$ depletion and suffocation and mortality of the fish. A spare pump was included in the equipment list, but in case of an electric shutdown, a standard car battery coupled to a 120V AC to 12V DC inverter (not included in the calculations of this work) would keep the pumps running for several hours.

The BAS is environmentally friendly since the water discarded in the water changes is full of nitrogenous compounds which could be employed to grow vegetables. In the case of recovering sediments rich in nutrients, these can go to the compost together with the waste of consumed fish (bones, viscera, and skins).

The results of the project could be enhanced with several actions. The same family could expand its production capacity by reinvesting their profits to increase the number of tanks. They also may increase revenues by selling the fish live since this finished product presentation is highly valued and getting more popular.

The major challenge to overcome is adopting this new activity in the family's daily routine. The routine includes feeding the fish according to the feeding tables, which indicate the quantity and type of feed to be employed according to the fish size, which implies weighing the fish and selecting the correct feed for the developmental stage. It also includes monitoring water temperature, ammonia, and chlorine (if municipal water is employed) and making water changes if needed. The correct administration of funds will be important to pay for supplies and save funds for the next cycle. Qualified extensionists could tackle these cultural aspects with appropriate training and supervision. Although the culture parameters of this work were carefully selected, it would be convenient to corroborate results in an experiment in different locations with temperature regimes. With this experiment, it would be possible to make the necessary adjustments to the model, if needed, for later use as a tool for evaluating existing projects and planning future projects.

In this work, the model selected for growth prediction considered the stages of development and the effect of temperature using the thermal growth coefficient since it was imperative to quantify with high precision the feeding rate and food requirement (Jover-Cerdá 2000). Hernández & Ratkowky (2004) and Dumas et al. (2010) developed models for growth predictions using the Von Bertalanffy (1957) equation which could be biased. According to Lester et al. (2004), the equation presents inaccuracies because it does not contemplate the different stages of development. Other models use the specific growth rate equation to predict growth in *Ictalurus balsanus*, *Oncorhynchus mykiss*, and *O. niloticus* (Jover et al. 1998, Arce & Luna 2003, Morales 2004). These models also disregard the different stages of development of the organisms, do not contemplate the effect of temperature on growth, and consider fish growth to be exponential (Arce-Vega 2014).

In conclusion, the evaluated BAS proved to be a viable self-sustainable alternative for tilapia production at a low scale in rural areas of Mexico and other Latin American countries. A specially designed governmental program is required to promote and finance this activity. Mexico has to try to increase its tilapia production since it has a deficit of nearly 128,000 t $yr^{-1}$ imported from Asia (CONAPESCA 2018), the second-largest international market for tilapia products (Martínez et al. 2021). The BAS system could contribute to diminishing the deficit if families in rural areas of Mexico massively adopt it.

## ACKNOWLEDGMENTS

The first author JCRDO thanks Drs. Juan Carlos Seijo and Mariel Guillian-Klanian for their teachings during his doctorate studies in the Doctorate Program of Fisheries and Aquaculture Bioeconomy at CIBNOR-CICIMAR-UMM. He thanks Consejo Nacional de Ciencia y Tecnología and Programa de Posgrado y Formación de Recursos Humanos del Centro de Investigaciones Biológicas del Noroeste for the financial support during his postgraduate work (grant CONACYT 746664; grant CIBNOR Folio94 id.:1320). He also thanks the scientific and technical staff of the Unidad Nayarit del Centro de Investigaciones Biológicas del Noroeste for their help and advice regarding tilapia aquaculture.

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*Received: October 20, 2022; Accepted: December 23, 2022*