Universidad Técnica de Manabí
Fundada en 1952

ECA SINERGIA
Revista de Investigaciones en Ciencias Administrativas y Economía

Polyculture of shrimp and tilapia: administrative innovation for sustainable aquaculture in Sinaloa

Policultivo de camarón y tilapia: innovación administrativa para una acuicultura sustentable en Sinaloa

Autores

[1]* Jesús Alberto Somoza Ríos
[1] Rosa Penélope Mares Galindo
[2] Rosa del Carmen Lizárraga Bernal
[2] Gilberto Niebla Lizárraga
[3] Kenia Inzunza Duarte

[1] Universidad Autónoma de Sinaloa, Department of Research and Postgraduate Studies, School of Economic and Administrative Sciences of Mazatlan. Sinaloa, México.
[2] Universidad Autónoma de Sinaloa, Department of Research and Postgraduate Studies, School of Economic and Administrative Sciences of Mazatlan. Sinaloa, Mexico.
[3] Universidad Autónoma de Sinaloa, School of Economic and Administrative Sciences of Mazatlan. Sinaloa, Mexico.

* Autor para correspondencia.

Código JEL: Q22; E23; C61.

Citacion sugerida: Somoza Ríos, J. A., Mares Galindo, R. P., Lizarraga Bernal, R. C., Niebla Lizarraga, G., Inzunza Duarte, K. (2024). Polyculture of shrimp and tilapia: administrative innovation for sustainable aquaculture in Sinaloa. *Revista ECA Sinergia, 15*(3), 99-109. https://doi.org/10.33936/ecasinergia.v15i3.6675

Recibido: 06/05/2024
Aceptado: 29/08/2024
Publicado: 05/09/2024

Abstract

Shrimp consumption and production is fundamental for food security, especially for vulnerable sectors. Simulations were conducted using software such as Stella.9 and R to evaluate polyculture shrimp production. The results suggest that this approach can improve operational efficiency and sustainability in the aquaculture industry. The conclusions indicate that polyculture of shrimp and tilapia is viable and can be replicated in various regions, contributing to the Sustainable Development Goals by promoting more sustainable and environmentally responsible practices.

Keywords: Aquaculture Industry; Production Modes; Simulation; Stella Software; R Software; Polyculture.

Resumen

El consumo y producción de camarón es fundamental para la seguridad alimentaria, especialmente para sectores vulnerables. Se realizaron simulaciones utilizando software como Stella.9 y R para evaluar la producción de camarón en policultivo. Los resultados sugieren que este enfoque puede mejorar la eficiencia operativa y la sustentabilidad en la industria acuícola. Las conclusiones indican que el policultivo de camarón y tilapia es viable y puede replicarse en diversas regiones, contribuyendo a los Objetivos de Desarrollo Sostenible al promover prácticas más sustentables y responsables con el medio ambiente.

Palabras clave: Industria acuícola; Modos de producción; Simulación; Software Stella; Software R; Policultivo.

INTRODUCTION

This research focuses on the development of an administrative management model for polyculture shrimp production, using mathematical simulations to visualize the operational and environmental benefits of this practice. The global context of food production requires more sustainable methods, and this study proposes a viable alternative to improve efficiency in aquaculture, aligning with the UN Sustainable Development Goals.

Aquaculture production has faced increasing challenges due to the need for more sustainable practices that minimize environmental impact without sacrificing production efficiency. Polyculture, in particular, is presented as a promising solution to optimize resources and improve sustainability in shrimp production. This approach, which has been explored in various regions such as the Philippines, Ecuador and Mexico, allows better management of water resources and greater resilience to environmental fluctuations. The present study is framed within this global context, seeking to evaluate the operational and environmental advantages of polyculture in Sinaloa aquaculture, with a view to replicating these results in other regions and contributing to the fulfillment of the Sustainable Development Goals (SDGs), specifically with regard to responsible production and consumption (SDG 12) and climate action (SDG 13).

1. Aquaponics.vThis system combines fish farming and soil-less plant cultivation. Basically, aquaponics is a mixture of aquaculture (raising aquatic organisms such as fish and crustaceans) and hydroponics (growing plants in water instead of soil). In this system, the ammonia produced by the fish is converted into nutrients for the plants, which reduces the toxicity of the water and, at the same time, feeds the plants naturally. This makes aquaponics an interesting option to manage water use efficiently (Rakocy, 2012, Somerville et al., 2022). According to Hernández et al. (2009):

“Aquaculture is defined as the cultivation of aquatic organisms, including fish, mollusks, crustaceans and plants. The farming activity involves human intervention in the rearing process to increase production in operations such as seeding, feeding, protection from predators, etc.”

While hydroponics (Del Pilar Longar Blanco et al., 2013), is the science of growing plants in a soil-less medium. So aquaponics is the integration of the two food production techniques in a single system (Beristain, 2018).

2. Filtration of wastewater by sedimentation and filtration with oysters. Filtration of wastewater by sedimentation and filtration with oysters. In many shrimp farms, shrimp larvae waste is discharged directly into the sea, rivers or estuaries without any treatment. To improve the quality of the water that is returned to nature, an oyster filtration system can be used. These oysters help remove waste through a two-stage process: sedimentation and filtration. A treatment of at least 24 hours with this system can significantly improve the quality of water released into natural ecosystems (Ramos et al., 2008).

3. Polyculture. This technique involves growing two or more aquatic species in the same pond, which helps reduce water consumption. For example, in a pond shared by tilapia and shrimp, the tilapia filter feed at the top of the water, which helps prevent the growth of harmful algae, while the shrimp remain at the bottom. Although polyculture has been studied mainly for combining different fish species, such as cachama, silver mojarra and mirror carp, its application to the joint culture of white shrimp and red tilapia in Mexico is still limited (Valenti et al., 2018, Silva et al., 2017, Ramos *et al*., 2008).

The above reflects sustainable on-farm production, being an issue of vital importance for the future of the planet. It is about finding ways to produce food that are environmentally friendly without compromising natural resources for generations to come (Trejo-Téllez, 2018). From a sustainable perspective Uniamikogbo and Amos (2016), describe the triple bottom line (TBL) as the interrelationship of three elements:

- Economic or financial considerations (financial)

- Environmental stewardship and protection (environmental)

- Human and community well-being (society)

Adjusting works to solve challenges in one of the elements of the TBL can generate long-term benefits in the economy and social quality of life, while limiting impacts on the environment in accordance with the long-term carrying capacity of nature.

Reinforcing the previous position, according to García López (2015), the term “Triple bottom line” dates back to the mid-

1990s. However, it was not until the publication in 1998 of John Elkington's book "Cannibals with forks: the triple bottom line of 21st century business" that this concept began to gain momentum.

One of the main considerations of TBL is the possibility of quantitatively measuring the impact of certain actions of the organization, both from an economic and social and/or environmental point of view. In addition, the TBL concept establishes the paradigm that its main lines (economic, social and environmental) are not static or stable, but are considered to be in constant movement due to social, political and economic pressures, changes in the economic cycle and the influence of certain events such as conflicts of a warlike nature. Therefore, each of the lines or elements of the TBL should be considered as a continental shelf in itself, so that it often moves independently of the others, and can be located above, below, next to and even friction can occur between them (García López, 2015), (Shaffer, 2018).

In this sense, Bertalanffy proposes the General Systems Theory (GST) (Bertalanffy, 1989), which shows a systematic and scientific way of approaching and representing reality.

The objectives of TGS are as follows Pouvreau, (2013).

1. To promote the development of a general terminology to describe systemic characteristics, functions and behaviors.

2. To develop a set of laws applicable to all these behaviors and finally,

3. To promote a (mathematical) formalization of these laws.

It is important to highlight Aragon's position according to his publication:

...the issue was raised by Ansah and Frimpong as follows: "If the growth of organisms under cultivation is overestimated, it may result in unexpected losses of commercial revenue, while underestimating growth could result in poor crop planning with respect to labor allocation, optimal feeding and harvesting time" (Aragon-Noriega, 2016).

One of the first documented polyculture systems was developed on Negros Island in the Philippines (Puricelli et al., 2002), the system employed 95 ha of ponds on Negros Island in 2002 and was further extended in 2003 to other nearby islands, while by 2008 more than 60% of shrimp farms in the Philippines were using polyculture between tilapia and shrimp (Fitzsimmons and Shahkar, 2017). Another use in the Philippines, apart from the production of two species, was to maintain water quality and conditions by means of cages located inside the shrimp fattening ponds, with tilapia consuming most of the waste generated by shrimp (Fitzsimmons and Shahkar, 2017).

Currently, in Ecuador there are several farms that have adopted polyculture systems, most use systems where they store red tilapia to maintain the conditions of the pond where the shrimp are fattened, the city that has built an important international trade with tilapia produced in polyculture ponds with giant shrimp is Guayaquil (Fitzsimmons and Shahkar, 2017).

One of the species to be cultivated in polyculture is the red tilapia (Oreochromis mossambicus), which was introduced in Mexico in 1964 and is of great importance in the production of animal protein in tropical and subtropical waters around the world, particularly in developing countries, where it is also known as mojarra. Tilapia farming is one of the most profitable in aquaculture, as it is highly productive due to the species' attributes, such as rapid growth, disease resistance, high productivity, tolerance to high density conditions, ability to survive low oxygen concentrations and different salinities, as well as acceptance of a wide range of natural and artificial feeds. Aquaculture accounts for 91% of tilapia production in Mexico and is grown in 31 Mexican states, with the largest producers being Chiapas, Tabasco, Guerrero, Estado de México, and Veracruz. In Baja California Sur, cultivation is reported for self-consumption, and Baja California's production in 2010 was less than one ton (Aquacultura| Tilapia | Instituto Nacional de Pesca | Gobierno | Gob.Mx, n.d.).

The other species that will produce in polyculture is the white shrimp, Litopenaeus vannamei. It began in Mexico at the Monterrey Technological Institute, Campus Guaymas, where research was carried out by the University of Sonora in the early 1970s until the second half of the 1980s, when commercial cultivation began. Since then, production volume has increased significantly, as has installed capacity, mainly in Sinaloa, Sonora, and Nayarit. However, shrimp farming is affected by various infectious agents, which is why the industry adopts "Good Management Practices" (GMP), and in some cases uses semi-intensive farming systems (Santos et al., 2021). These practices are carried out mainly in the northwestern states of Mexico, where the activity has the highest production; in 2008 alone it exceeded 60% of total national shrimp production (fishery and aquaculture), white shrimp production is normally carried out in semi-intensive ponds (Santos *et al.*, 2021)

The objective is to develop an administrative management model for shrimp production through a mathematical simulation, using polyculture. This approach is aligned with the UN Sustainable Development Goals (SDGs), specifically SDG 12: Responsible Production and Consumption, by proposing an efficient use of aquatic resources and reducing the environmental impact of shrimp production. The research focuses on the contexts of the Philippines, Ecuador and Mexico, where polyculture practices have been implemented to assess their viability and sustainability in aquaculture. The results obtained in these countries highlight the potential of polyculture not only to improve operational efficiency, but also to mitigate negative environmental effects, suggesting that this approach could be replicated in other regions and countries. In the analysis of the results and conclusions of the study, the importance of adapting this model to different geographical and cultural contexts is highlighted, thus maximizing its contribution to the achievement of the SDGs at a global level.

MATERIALS AND METHODS EMPLOYED

Three softwares were used, the first one was the Sankey Diagram Generator, which is freely available on the internet, this was used to graphically represent the amount of brackish water needed to produce shrimp. The second was Stella.v9 where a simulation of a shrimp production was made, where the amount of oxygen demanded in the pond was identified according to the increase in size and the third was the R Studio software where a production of two aquaculture species at the same time was simulated by means of a mathematical equation.

To simulate the polyculture scenario, the mathematical formula of Karl Ludwing Von Bertalanffy was used, which is written as follows:

$$lt = l\infty[1 - e^{-K(t-t0)}] \quad (1)$$

Where the parameters of the growth model are:

lt = defines the expected size

l∞ = defines the maximum size - asymptotic (cm)

k = growth rate towards the maximum (1/y)

t0 = initial condition parameter (y), shifts the growth curve on the x-axis to allow for a negative length at age zero.

Prior to the final simulation in the R software with the equation described above, first of all, a field investigation was carried out to learn about the process involved in shrimp production from the shrimp postlarvae laboratories to harvesting in the shrimp farms, collecting information in a follow-up log, as a second step, a Sankey diagram was made, Based on the information collected in the logs, which allowed us to know the amount of brackish water needed to produce one ton of shrimp, being this amount our frame of reference, after that, a simulation was made in the Stella software highlighting the need for pre-harvest, finally, based on the above, a mathematical simulation of a representation of a polyculture between tilapia and shrimp was made to make the latter a sustainable proposal in the current modes of production.

RESULTS AND DISCUSSIONS

In accordance with the objective of this research, we will start from the information obtained in the logbooks, as a result of the field research on shrimp production from the cradle to the door stage; however, it is important to point out at this point that this analysis was carried out based on the production of 1 ton of shrimp (1,000 kg). It is necessary to conceive that for this process to be carried out and harvest 1 ton of white shrimp with a weight of 10 grams per shrimp, 100,000 shrimp will be obtained at the end.

Our shrimp input and output inventory is based on knowing the quantities of each unit process, determining the amount of brackish water needed (liters), electrical energy for pumping brackish water (kWh), electrical energy for the motors that oxygenate the ponds (kWh), and the feed needed from cradle to gate to produce 1 ton of shrimp.

In order to obtain data with a higher degree of reliability, it would be necessary to carry out an in-depth investigation; however, for the sake of convenience, the percentages of survival that were used in the field study were taken.

To produce the amount of shrimp mentioned above with 100,000 shrimp with a weight of 10 grams as the final product, a pond that houses 94 shrimp with 180 days of maturation is needed in its initial stage, 55% will be females and the remaining 45% will be males, according to what was investigated with the producer, a percentage of copulation or pregnant females of 10% is obtained, resulting in 5 females ready to spawn.

Of the 5 females mentioned in the previous paragraph will produce a total of 2, 083,333 eggs, of which only 60% will hatch, resulting in 1, 250,000 nauplii. After this, the care and production process begins in the PL production laboratory, of which for the next stage with 50% we will obtain 625,000 zoeae and with the same percentage of survival only 312,500 mysis arrive, which according to the following and even better management increases to 80% survival to reach a PL stage with 17 days of maturation with 250,000 PL17, so that later in the farm with the care of the biologist, 45% of survival is obtained after 3 months of culture with 1,000 kg of shrimp. The above is shown in Table 1 of the Life Cycle Analysis (LCA) inventory. The table shows the inventory for the product in its cradle-to-gate analysis, and the Sankey diagram shows graphically the aforementioned Figure 1.

The Sankey Diagram Generator software was used to create the Sankey diagram and perform the LCA of 1 ton of shrimp, working in conjunction with the Excel administrative tool, generating a book with the data in Table 1, mentioning the input and output processes and their respective quantities, resulting in an amount of 29,016 liters needed to produce shrimp and a total wastewater of the same amount.

To better understand the shrimp production part, a simulation of population growth scenarios in biological subjects, such as population increase of shrimp and tilapia under different growth variables, for example, was carried out with Stella version 9 software:

- Decrease in the amount of oxygen “O”.

- Increased levels of ammonium “NH3”.

- Deaths.

- Days of growth.

These four variables were used to create a scenario. The maximum growth period was 30 days, a semi-intensive polyculture system with 2,000 organisms in a pond (half shrimp and half tilapia).

This scenario had 4 elements or building blocks (Cervantes, Chiappa and Dias, 2009):

- Stock: Used to accumulate or consume resources.

- Flow: The rate of change of the stock.

- Connector: Used to take input data and manipulate it to convert that input into some output signal.

- Converter: An arrow that allows information to pass between: converters; stocks and converters; stocks, flows and converters.

As a result, we had that during the growth graph it would be necessary to perform pre-harvests so that the levels of the variables mentioned above are maintained, this is only representative and so that the reader can have an idea of the increase/decrease of the levels, for example, higher growth, lower amount of oxygen, PH, and consequently increase in the levels of ammonium, these are some needs that are required in the polyculture system.

Simulating a scenario as close to reality as possible will help investors to visualize results, without having to risk production ponds for their crop, since models help in decision making and simulations can give an approximate idea of what can happen. This point will be addressed and explained in detail about what Ludwig Von Bertalanffy proposes in his mathematical equation of growth, which is why we used the administrative tool, the “R studio” software, where the parameters needed were introduced and a representation of a culture with two species at the same time, red tilapia and white shrimp, was made.

In accordance with the above, the model of Karl Ludwig Von Bertalanffy, who developed a model of growth as a function of life span, which is an exponential type model for individual growth and is applied to the great majority of fish. The model to describe this equation on an individual basis is shown in Figure 2.

Complementing the above, k is a constant defined by a growth curve for different commercial aquaculture species, as shown in Figure 3.

The simulation of a polyculture will serve to show a scenario on the viability of the cultivation of two species, with the firm idea of having a positive impact on the care of the environment and breaking a paradigm in the current modes of production, which is why it was proposed to carry out a polyculture of white shrimp and red tilapia, which will help to reduce production costs, the amount of water used and consequently increase profits.

With this clear, we proceeded to introduce the values for each of the species, in the case of tilapia they were taken according to the research of Ortega Salas et al, (2013), K=0.4618 (monthly), L∞= 249.32 and T0= 0.12, while for shrimp they were taken according to the research of Andrade de Pasquier and Perez E. (2004), K=3.24 (annual), L∞= 20.0 and T0= -0.2927, Figures 4 and 5 will show the evidence of what was described respectively.

For the equation in Figure 4, we used a maximum growth time of 6 months (one production cycle) and a maximum growth size of 249.32 mm, while for Figure 5, we used the same maximum growth time of 0. 5 (half a year) and a maximum size of 20 cm, this according to the studies of tilapia and shrimp culture respectively mentioned above, comparing both graphs we can see that for month 3 will be maintained in a sustained growth for both species, while after that the growth will not be so pronounced, according to the fishbase database (Population Length/Weight - Detail, n. d.) on the length/weight relationship for red tilapia we can determine that according to the growth graph in Figure 4 it will reach an average weight of 398.95gr, while according to the Ramos Cruz (2000) database the shrimp will reach an average weight of 27.5gr.

The results obtained in this research on polyculture of shrimp and tilapia are consistent with previous studies that highlight the advantages of this practice in terms of sustainability and efficiency. Fitzsimmons and Shahkar (2017) found that polyculture of tilapia and shrimp in the Philippines not only improved water quality, but also optimized resource use, resulting in more sustainable and profitable production (Zhang et al., 2020). Similarly, Ortega-Salas et al. (2013) documented that in Ecuador, the implementation of polyculture systems resulted in a significant increase in tilapia production while maintaining adequate conditions for shrimp growth. These studies support the findings presented in this research, which demonstrate that polyculture is not only a viable strategy to increase production, but also offers environmental benefits by reducing the ecological impact of aquaculture. However, it is important to note that, as mentioned by Valenti et al. (2018), effective implementation of polycultures requires complex logistics and specialized management, which may represent a barrier to their large-scale adoption. The results obtained in the life cycle inventory (LCA) analysis indicate that polyculture has a significant impact on oxygen levels in white shrimp ponds, which translates into a survival rate of 45% after three months, in the absence of pre-harvest. However, this negative effect can be mitigated by constant monitoring by the responsible personnel and the application of preventive measures that reduce the risk of diseases, which increases the survival rate. Compared to traditional monoculture, polyculture is notably more productive and more resistant to environmental fluctuations, adapting better to the biodiversity of the environment. This positions polyculture as a superior sustainable option for shrimp production. However, its implementation faces challenges, mainly due to the logistical complexity involved, such as species coordination, personnel training and additional infrastructure and management costs.

Finally, an inverse relationship has been detected between species growth and oxygen levels, i.e., as growth increases, available oxygen levels decrease; a similar phenomenon occurs with water pH. For this reason, it is crucial that growers pre-harvest to maintain these levels within optimal ranges. The models presented in this research provide growers with tools to avoid contingencies, improve crop efficiency and optimize decision-making.

revistasinergia@utm.edu.ec Vol. 15, Núm. 3 (99-109): Septiembre-Diciembre, 2024 DOI: 10.33936/ecasinergia.v15i3.6675

Table 1.

LCA Inventory to produce 1 ton of shrimp.

Finished product:		**Amount:**		**Weight:**		
White shrimp 10 gr		**100,000 shrimps**		**1 tonne**		
Inputs	**Amount**	**Unit**	**Process used**	**Unit**	**Amount**	**Outputs**
Pumping electricity	51.45	kWh	Shrimp broodstock pond			
Males and females	24	piezas	Shrimp broodstock pond			
Food	20	kg	Shrimp broodstock pond			
Brackish water	1,004.21	m^3	Shrimp broodstock pond			
Electricity for blowers	282.24	kWh	Shrimp broodstock pond			
			Shrimp broodstock pond	m^3	1,004.21	Sewage
Pumping electricity	51.45	kWh	Female spawning			
Food	0	kg	Female spawning			
Brackish water	1,004.21	m3	Female spawning			
Electricity for blowers	141.12	Kwh	Female spawning			
			Female spawning	m^3	1,004.21	Sewage
Pumping electricity	102.9	kWh	Nauplii, zoeae and mysis production			
Food	0	Kg	Nauplii, zoeae and mysis production			
Brackish water	2,008.41	m^3	Nauplii, zoeae and mysis production			
Electricity for blowers	846.72	kwh	Nauplii, zoeae and mysis production			
			Nauplii, zoeae and mysis production	m^3	2,008.41	Sewage
Fuel	1,500	l	Transport of postlarvae to the aquaculture farm			
			Transport of postlarvae to the aquaculture farm	kg	3,900	CO2
Pumping electricity	102.9	kWh	Postlarvae seeding			
Food	200	kg	Postlarvae seeding			
Brackish water	253,605.12	m^3	Postlarvae seeding			
Electricity for blowers	0	kWh	Postlarvae seeding			
			Postlarvae seeding	m^3	0	Sewage
Pumping electricity	1,763	kwh	Harvest of 1 ton of shrimp			
Food	20	kg	Harvest of 1 ton of shrimp			
Brackish water	0	m^3	Harvest of 1 ton of shrimp			
Electricity for blowers	0	kwh	Harvest of 1 ton of shrimp			
			Harvest of 1 ton of shrimp	m^3	253,605.12	Sewage
Fuel	1,500	l	Commercialization			
			Commercialization	kg	3,900	CO2

e-ISSN 2528-7869

Figure 1.

Sankey diagram to produce 1 ton of shrimp.

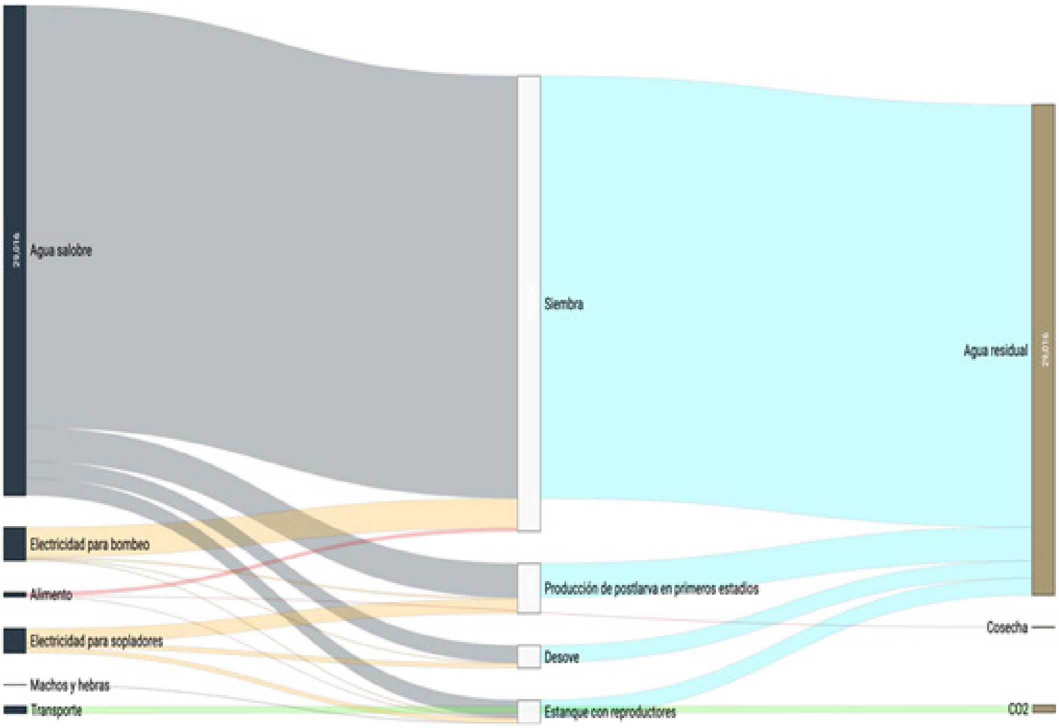

Figure 2.

Aquaculture growth according to the Von Bertalanffy equation.

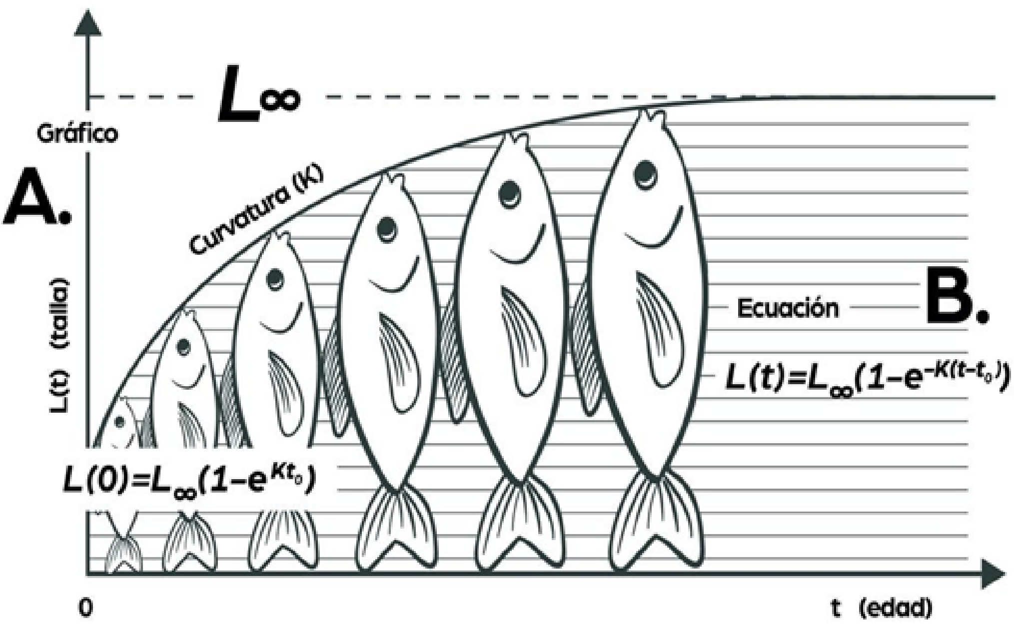

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Figure 3.

Growth curves for different commercial aquaculture species.

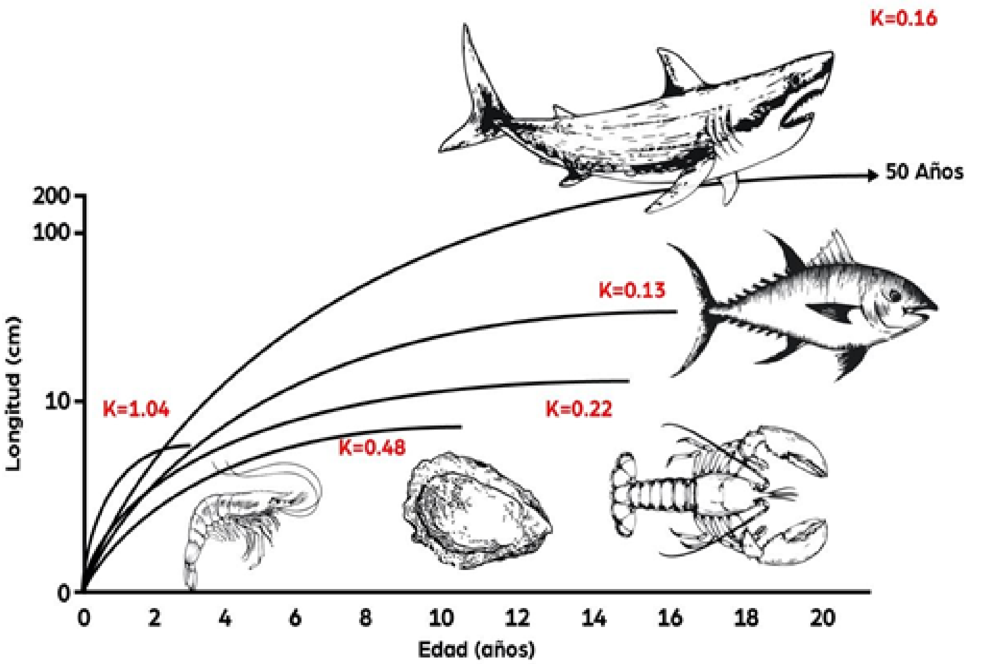
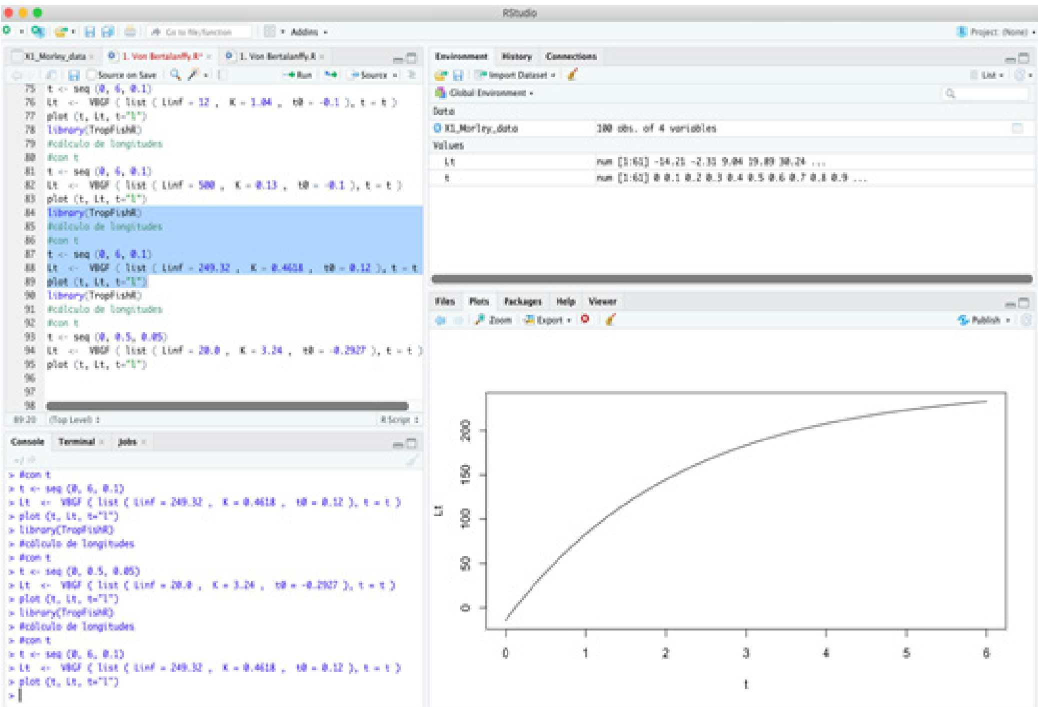


Figure 4.

Growth curve for tilapia according to "R studio" software.



e-ISSN 2528-7869

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