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REVIEW

REVIEWS IN Aquaculture

Bioeconomic modelling in tilapia aquaculture: A review

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Abstract

The global production of aquatic resources is increasing at the rate of 3.3 million tons per year, main thanks to aquaculture. However, this industry is considered by financial institutions as high risk due to failures caused by epizootics, natural disasters and poor planning and monitoring. Bioeconomic modelling is a progressive branch of social science that seeks to integrate the disciplines of economics and biology to create theories that better explain economic events using a biological basis and vice versa. This should be used in aquaculture to plan, monitor, and determine cost-effectiveness and risk, to reduce uncertainty and increase profits of ongoing or new projects. A meta-analysis of the literature on bioeconomic modelling in aquaculture during 26 years (1994—2020) was performed, using four search engines. Sixty-eight articles were published in 23 journals, on 25 groups of species or species. The most studied were shrimp, tilapia, seabream, salmon and carp. From these, 12 articles dealt with tilapia models that shared similar biological, management and economic sub-models. In the 26-year analysis, the global scientific productivity in this field is low (2.6 articles/year) in relation to the growth of world aquaculture. Bioeconomic modelling peaked during the decade from 2004 to 2014 with 5.6 papers/year, but then declined to only 0.83 articles/year from 2015 to 2020. This is possibly due to the low diffusion among producers, planners and financial institutions of the advantages of the models and the difficulty to use them if friendly and readily available software is lacking.

KEYWORDS
bioeconomy, cost-effective aquaculture, fish production models, literature review, mathematical models, risk assessment

1 | INTRODUCTION

Bioeconomic models are mathematical tools that make it possible to estimate the success of a production project or to evaluate projects to produce organisms in progress, in order to optimize their production and increase their profitability. These facilitate the representation of the production process considering biological, environmental and economic factors, and allow the simulation of different production scenarios and then the application of different optimization methodologies. Estimations, evaluations or optimizations are utilities that can be obtained from the use of bioeconomic models. The bioeconomy can be defined as 'The efficient administration of biological resources'.[1] This is born from the link between two scientific disciplines that are strongly related in aquaculture: biology and economics. Biology is responsible for the study of living beings and the processes associated with them, while economics studies the efficient administration and distribution of resources.[2] It has its foundations in the Theory of Systems Dynamics and is mainly made up of a biological sub-model and an economic sub-model, which evaluate the behaviour of the systems of a production line. This includes the development of a living organism at any stage and considering exogenous and endogenous variables.[3–6]

As a basis bioeconomic models not only use the biological and technological information and the conditions that affect the productive parameters of the species (i.e., environmental variables, growth of organisms, survival, technology, management) but also the economic conditions where the project is developed, including costs of production, the market with its fluctuations in prices in the short, medium and long term and socioeconomic conditions. In addition, they allow quantifying the production process and weighing the importance of the various components (technological, physical–chemical, biological, economic, zootechnical, risk) that intervene, directly and indirectly, in each of the links of the chain of production, distribution and marketing. They answer questions related to economic feasibility, use of time and movements, optimization of resources and operational areas. They use descriptive analytics to transform data into information, and allow mathematical estimation of the uncertainty that the project will face. Therefore, they are essential for decision making. The models are species-specific,[7–9] and are increasingly complex because additional parameters and variables have gradually been added to offer greater precision.

Bioeconomic modelling in aquaculture began in the 1980s with the work of Karp et al.,[10] Bjørndal,[11] Leung and Shang,[12] focused on shrimp and fish farming. These authors worked on the optimization of the harvest and storage time of the produced resources, driven by the growing demand in the markets for aquaculture products.[6] In addition, it was necessary to find alternatives to improve diets, which were rich in protein and low in fat but at a lower cost, which represented the first biological and technical challenges of aquaculture. These scenarios led to the need to economically evaluate the processes to obtain greater economic benefits to compensate for low production levels and their limitations in installed capacity.[13]

In the 1990s, the aquaculture production industry faced new challenges, since production processes began to be standardized, making the most of resources and installed capacity. As there was a greater supply of products in the market, prices began to decrease and therefore profit margins, so economic aspects were of vital importance for the sustainable development of the activity without leaving aside technical and economic aspects.[13] In that decade, works on bioeconomic modelling emerged,[14–18] who developed bioeconomic models based on the work by Bjørndal.[11] One of the problems that these authors faced was the high difficulty in obtaining empirical production data, so the models developed were theoretical.[6] In recent years, aquaculture production systems have become more complex and bioeconomic modelling has had to evolve, allowing numerous simulations to be carried out quickly with data obtained in situ or theoretically. As a result, scenarios were built that allowed validating or discarding hypotheses or management strategies that were useful for the companies' decision making.[8]

In the 2000s, given the growing need for companies and productive entities to obtain information for decision-making applied to aquaculture production processes, empirical bioeconomic models stand out from theoretical ones, having only a few authors, such as Yu et al. 2009[19] who modelled the optimum harvest time, partial and continuous, respectively, in aquaculture production.

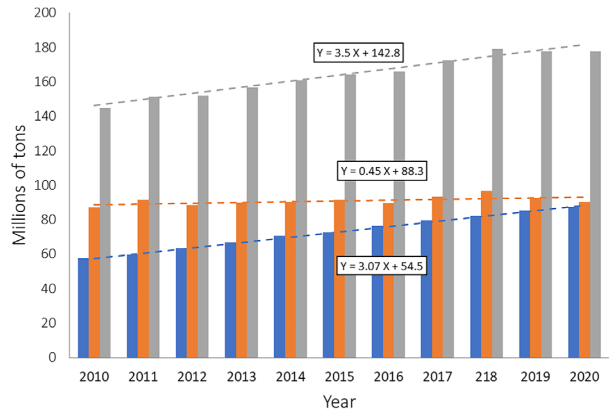

FIGURE 1 Evolution of the global production of aquatic organisms, from fisheries and aquaculture during the period of 2010–2020 (FAO, 2021). ▬: Aquaculture, ▬: Fisheries, ▬: Total production, - - -: Lineal (aquaculture), - - -: Lineal (fisheries), - - -: Lineal (total production).

During the 2010–2020 decade, the global production of aquatic resources increased linearly at a rate of 3.5 million tons per year (Figure 1), going from 144.8 million tons in 2010 to 177.8 million tons in 2020.[20] However, this increase was almost exclusively due to aquaculture since fisheries only increased linearly at a rate of 0.45 million tons per year, from 87.1 to 90.3 million tons, while aquaculture increased linearly by 3.07 million tons per year, that is, five times more than the fisheries, going from 57.7 to 87.5 million tons in those 10 years.[20] In 2020, the contribution of aquaculture still did not exceed that of fisheries, since it only contributed 49.2% of the world's production of aquatic resources, but if this trend continues, in a few years it will be the most important activity as a world producer of aquatic resources.

The Food and Agriculture Organization of the United Nations estimates that aquaculture will produce more than 50% of fish production for human consumption in 2030.[4,21] Aquaculture is considered a fast-growing industry, producing high-value and market-accepted species, such as carp, shrimp and tilapias. Table 1 shows the evolution of global aquaculture and tilapia production in the same decade (2010–2020), both in volume and value. As already mentioned, aquaculture production went from 57.7 to 87.5 million tons in just 10 years, of which tilapia contributed 5.02%, going from 2.5 to 4.4 million tons. Regarding its value, global production almost doubled in those 10 years, going from 131.2 to 273.3 million US dollars.[20,21] The value contributed by tilapia production also increased from 4.3 to 8.7 million dollars, but this value only contributed to 3.1% of the value of global production. However, the growth of tilapia production in this decade (2010–2020) was higher (43%) than the growth of world aquaculture (34%), respectively, (Table 1), indicating that tilapia aquaculture is increasing at a faster rate than other species. Tilapia species already occupy a second place within the

TABLE 1 Evolution of global and tilapia aquaculture production in biomass and value from 2010 to 2020, including annual percentage increases. Data from FAO (2020).

Year	Global aquaculture production tons × 10^3	Tilapia aquaculture production tons × 10^3	Value of global aquaculture production US × 10^3	Value of tilapia aquaculture production US × 10^3	Annual increment of global aquaculture production %	Annual increment of tilapia aquaculture production %	Annual increment in value of global aquaculture %	Annual increment in value of tilapia aquaculture %
2010	57,744	2,502	131,222	4,343	0	0	0	0
2011	59,789	2,917	154,793	5,677	4	17	18	31
2012	63,480	3,342	169,771	6,702	6	15	10	18
2013	66,952	3,484	191,919	7,261	5	4	13	8
2014	70,506	3,758	210,890	7,908	5	8	10	9
2015	72,776	4,050	206,741	8,075	3	8	−2	2
2016	76,474	4,168	223,784	8,375	5	3	8	4
2017	79,497	4,446	238,697	8,411	4	7	7	0
2018	82,304	4,526	248,669	8,652	4	2	4	3
2019	85,335	4590	259,547	9179	4	1	4	6
2020	87,500	4407	273,332	8752	3	−4	5	−5
Total	802,357	42,190	2,309,365	83,335	34	43	52	50
Mean					4.3	6.1	7.7	7.6
Tilapia versus global		5.3		3.6		126		96

group of farmed finfish and within them, the Nile tilapia (*Oreochromis niloticus*) is the fifth most farmed aquatic species in the world, reaching 27 million tons with a value of 52 billion dollars during the last decade.[21]

Despite this progress, financial institutions aquaculture is a high-risk economic activity.[22] High losses have occurred due to shrimp pandemics such as yellow head, tail and white spot disease, Taura syndrome, etc.[23] In salmon the (infectious salmon anaemia) virus appeared in the region of Los Lagos in Chile in August 2007,[24] and in tilapia the TiLV virus, the etiological agent of the lake tilapia disease discovered in Israel 2014.[25] Additionally, there are environmental variables, such as hurricanes, floods and periods with atypical temperatures, which have seriously affected some projects.[26] For this reason, effective tools, such as bioeconomy models, are required to increase the certainty of projects.

In this work, a meta-analysis of the literature on bioeconomic modelling in aquaculture, covering a period of 26 years (1994–2020) is presented, to know the actual status of bioeconomic modelling in aquaculture and particularly in tilapia, published in scientific journals worldwide. A meta-analysis is a quantitative statistical analysis in order to test the pooled data of several separate but similar studies to test the effectiveness of the results.[27] This research was made investigating in different search engines, including the authors, the year of publication, the journal where it was published, the species studied, and the location of the research groups, the purpose for which the model was developed, the technology used, and its application (theoretical or commercial). Finally, this analysis was focused specifically on bioeconomic modelling in tilapia because of the growing interest in the species worldwide.

2 | MATERIALS AND METHODS

The data of the present study were obtained by searching published scientific content, using several search engines. The first engines consulted were Scopus, ScienceDirect and Springer Link using their advanced search engines following this process: In Scopus, title-abs-key (bioeconomic AND modelling AND PUBYEAR >1999 AND PUBYEAR <2021). Subsequently, the search was refined to works focused on the aquaculture production of tilapia. In ScienceDirect, ‘bioeconomic AND modeling AND tilapia, and in Springer Link, “bioeconomic AND modeling AND tilapia”’. The selection criteria were those of Llorente and Luna[6] and Ruiz-Campo and Zuniga-Jara,[28] which consists of the selection of the works in which a mathematical model is developed or used that considers the biological, environmental and economic elements. In addition, the literature review works by Pomeroy et al.[4] and Llorente and Luna[6] and other search engines, such as Google Scholar, were consulted. Only peer-reviewed works were considered. Each search engine with its own algorithm looks for the selected words within the title, abstract and keywords of the article or searching the entire text.[28] Another search engine was the Web of Science (WoS), searching for the categories of Agricultural Engineering and Fisheries since aquaculture category is lacking in WoS.[28] Abbreviated tags were used to facilitate searches by subject (S), title (TI), author (AU), editor (ED) and ST (searched topic) were used.

Once the results of each engine were obtained, the articles that included keywords in the title such as analysis, bioeconomic modelling, bioeconomy, tilapia, aquaculture or a mixture of these were selected. No article was discarded before without careful review.

The selected articles were then classified into 11 dimensions: authors, year of publication, search engine, journal name, species used, experiment location, main application, type of production system, final purpose, data analysis stage and use of data.

The models of those papers dealing with tilapia bioeconomy were reviewed in detail to know the approaches followed by the authors and to identify potential aspects for their improvement.

3 | RESULTS

A total of 68 articles were selected out of 260 found in the search, containing bioeconomic modelling in aquaculture (Figure 2). These were selected if a mathematical model was developed or employed that considers biological, environmental and economic elements.[4,6,28] The engine that generated the most articles was Scopus with 152 articles, followed by ScienceDirect (43), other engines (39), Springer Link (16) and WoS (10). These articles were written in 19 different countries or regions (Figure 3), with Mexico being the country with the highest number of published articles (20), followed by the United States and Vietnam (7), Spain (5), Australia (4), Israel and Chile (3), Canada, the Mediterranean and Norway (2), Italy, Taiwan, Korea, Malawi, Germany, Europe, Greece, Oceania and Ecuador (1). These focused on 25 aquatic species (Table 2), including 12 molluscs, 3 crustaceans, 8 marine fish and 2 freshwater fish. Shrimps were the group of species with more articles (15), followed by tilapias (12), sea bream (11), salmon and carp with 3 articles each, and the rest of the species with two or one publication (Figure 4). Fifty-six articles were published from 2004 to 2014, in 23 scientific journals (Table 3): Aquaculture Economics and Management (15), Aquaculture (10), Aquaculture Research (6), Aquaculture International (5), Aquacultural Engineering and Ecological Modelling (4), Journal of the World Aquaculture Society (3), and the rest (17) in other journals with two or one publications (Table 3).

The characteristics of the 12 bioeconomic models published on tilapia are presented in Table 4. Here it can be seen that 11 of them were theoretical models adjusted with data obtained from commercial farms, while one of them presents an empirical model developed through data obtained through previous experiments. These models deal with four tilapia species (*Oreochromis niloticus*, *O. shiranus*, tilapia not specified and red tilapia), and were classified in the categories of (a) management and (b) economic viability, depending on the objective for which they were used. Management papers (9) were published between 1996 and 2020, six of them in Mexico, one in Malawi, one in the United States, and one in Germany. These dealt with optimization of harvest times,[79,80] optimal feed rations,[84,87] diet evaluation,[82] effects of size heterogeneity,[83,88] and the integration of aquaculture with aquaponic tomato production.[89] Table 4 also shows the type of production system used and the final purpose of the model, either for process optimization or to simulate scenarios. The remaining three articles on economic viability were published from 2006 to 2014, two of which were written in Mexico and the most recent in Ecuador. These models seek to determine, through simulations, the economic viability of tilapia growing out in semi-intensive systems. They evaluate the economic impact of tilapia production in monocultures,[88] and polycultures,[3] as well as the impact of replacing standard feeds for feeds with plant ingredients.[84]

All tilapia bioeconomics models found, share a common structure composed by biological, management and economic sub-models (Table 5). The biological sub-model aims for the estimation of the growth, either in weight or in size of the organisms according to the environmental conditions provided by the production system. The most used equations to quantify growth in weight (Equations 1–3) and size (Equation 4) along a period, using initial weight, asymptotic weight of the organism, anabolism, catabolism and temperature as input parameters were:

$$W(t)=W_{\infty}*\left(1-e^{-(c+b*\varphi(t))^{3}*(t-t_{0})}\right)^{3}, \quad (1)$$

$$W(t)=\eta W(t)^{\frac{2}{3}}-\kappa W(t), \quad (2)$$

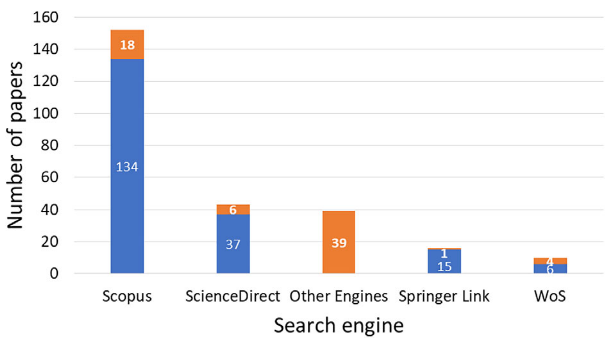

FIGURE 2 Results of searches for bioeconomic modelling papers in different search engines for the period of 1994–2020. ■: General bioeconomic, ■: Aquaculture bioeconomy modelling.

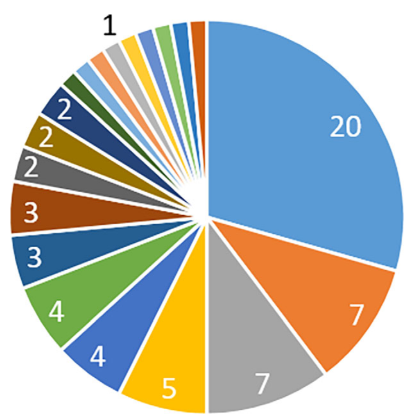

FIGURE 3 Geographical location of research groups that publish papers on aquaculture bioeconomy. Figures are number of papers published from 1994 to 2020. ■: Mexico, ■: USA, ■: Vietnam, ■: Spain, ■: Not specified, ■: Australia, ■: Israel, ■: Chile, ■: Canada, ■: Mediterranean, ■: Norway, ■: Italy, ■: Taiwan, ■: Korea, ■: Malawi, ■: Germany, ■: Europe, ■: Greece, ■: Oceania, ■: Ecuador.

TABLE 2 Species selected as study subjects in 68 aquaculture bioecomic modelling papers for the period of 1994–2020.

Common name	Scientific name	Number of papers	References
Molluscs (12 references)			
Cham scallop	*Patinopecten yessoensis*	1	29
Catarina scallop	*Argopecten ventricosus*	1	30
Sea scallop	*Placopecten magellanicus*	1	31
Giant clam	*Tridacna gigas*	1	32
Manila clam	*Tapes philippinarum*	1	33
American oyster	*Crassostrea virginica*	1	34
Penshell	*Atrina maura*	1	35
Mussel	*Mytilus galloprovincialis*	1	36
Blacklip abalone	*Haliotis rubra*	1	37
Greenlip abalone	*Haliotis laevigata*	1	38
Red abalone	*Haliotis rufescens*	1	39
Japanese abalone	*Haliotis discus hannai*	1	40
Crustaceans (18 references)			
Shrimp	*Penaeus sp.*	15	19,41–54
Mud crab	*Scylla paramamosain*	2	55,56
Lobster	*Panulirus ornatus*	1	57
Marine fish (21 references)			
Seabream	*Sparus aurata*	11	5,58–67
Salmon	*Salmo salar*	3	68–70
Bluefin tuna	*Thunnus thynnus*	2	71,72
Striped bass	*Morone saxatilis*	1	73
Asian sea bass	*Lates calcarifer*	1	74
Cod	*Gadus morhua*	1	75
Cobia	*Rachycentron canadum*	1	76
Mero malabar	*Epinephelus malabaricus*	1	77
Freshwater fish (15 references)			
Tilapia	*Oreochromis sp.*	12	3,78–88
Carps	*Cyprinus carpio*	3	89–91
Not specified (2 references)			
Not specified		2	92,93

$$W(t) = \alpha * L_t^3, \tag{3}$$

where $W(t)$ = weight at time t, W_∞ = asymptotic weight under culture conditions, t_0 = theoretical age when $W_T = 0$, t = time, $\varphi(t)$ = estimated mean temperature, c and b = constant parameters, φ_t = water temperature during the day, η y κ = anabolism and catabolism coefficients, respectively, α = constant and L_t = length at time t.

The equation to calculate growth in size was:

$$\frac{\partial L_t}{\partial t} = g * (L_\infty - L_t), \tag{4}$$

where g = daily growth rate and L_∞ = theoretical asymptotic length.

The management sub-model aims for the evaluation of the production process over time, to estimate total biomass (Equation 5) and weight dispersion (variation coefficient) (Equation 6), survival rate (Equation 7), feeding rate (Equation 8) and the expected food conversion factor (Equation 9), at a given projected food ration (Equation 10), total ammoniacal nitrogen concentration (Equation 11), and culture density in a number of individuals (Equation 12) and biomass density (Equation 13)

$$B(t) = N(t) * W(t), \tag{5}$$

where $B(t)$ = biomass at time t (kg/m^3), $N(t)$ = existing population at time t (ind/m^3) and $W(t)$ = average weight at time t

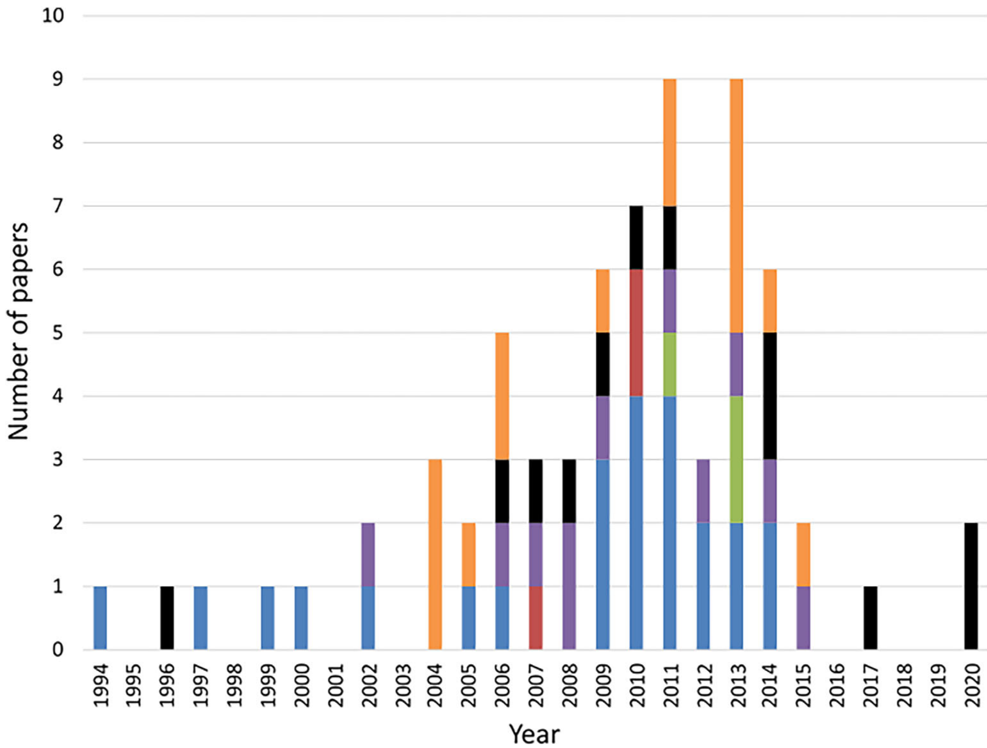

FIGURE 4 Scientific literature on aquaculture bioeconomic modelling of different species for the period 1994–2020. ■: Shrimp, ■: Tilapia, ■: Sea bream, ■: Salmon, ■: Carp, ■: Others.

$$\mathrm{WD} = \frac{\sigma}{W(t)} * 100, \tag{6}$$

where WD = weight dispersion, σ = standard deviation and $W(t)$ = average weight at time t

$$N(t) = N_0 * \mathrm{e}^{-Z^t}, \tag{7}$$

where $N(t)$ = survival rate, N_0 = initial population (ind/m^3) and Z = constant mortality rate (%/day)

$$\mathrm{FR}_t = \frac{F_t}{W(t)} * 100, \tag{8}$$

where FR_t = feeding rate at time t, F_t = food granted at time t and $W(t)$ = average weight at time t

$$\mathrm{FCF}_t = F_t / B(t), \tag{9}$$

where FCF_t = food conversion factor at time t, $\mathrm{Food}_{\mathrm{cons}\,(t)}$ = consumed food at time t and $B(t)$ = biomass at time t (kg/m^3)

$$\frac{dx}{dt} = g(x, r), \tag{10}$$

where dx/dt = food ration, x = size of the individual at time t and r = normalized ration size at time t

$$\mathrm{TAN} = \xi_1 * \xi_2, \tag{11}$$

where TAN = total ammoniacal nitrogen, ξ_1 = % of protein in the food given and ξ_2 = standardized constant. ξ_2 is obtained from the percentages of food ingested and ammonium excreted by various species, taking into account that 16% of protein is nitrogen, only 80% of ingested nitrogen is assimilated, 80% of assimilated nitrogen is excreted and 90% of excreted nitrogen is in the form of TAN. $\xi_2 = 0.16 * 0.8 * 0.8 * 0.9 = 0.092$.

$$D_{N(t)=} \frac{N(t)}{v}, \tag{12}$$

$$D_{B(t)=} \frac{B(t)}{v}, \tag{13}$$

where $D_{N(t)}$ = density of individuals at time t, $D_{B(t)}$ = biomass density at time t and v = volume in the pond.

Finally, with regard to the economic sub-models, all the authors seek to determine economic viability of the project, starting from quantifying total costs (Equation 14) from fixed costs (Equation 15), variable costs (Equation 16), gross income (Equation 17) and net profits (Equation 18). These economic parameters allow calculating cash flows and profitability through parameters such as the net present value (NPV) (Equation 19), internal rate of return (IRR) (Equation 20), and cost-benefit (Equation 21) during the life of the project.

TABLE 3 Preferred journals for publication of aquaculture bioeconomic modelling.

Scientific journals	Number of Articles
Aquaculture, Economics and Management	15
Aquaculture	10
Aquaculture Research	6
Aquaculture International	5
Aquacultural Engineering	4
Ecological Modelling	4
Journal of the World Aquaculture Society	3
European Journal of Operational Research	2
Marine Resource Economics	2
Reviews in Aquaculture	2
Others	2
Journal of Shellfish Research	1
Agricultural and Resource Economics Review	1
Agricultural Systems	1
Applied Economics	1
Ecological Economics	1
Ecology and Society	1
Fish and Fisheries	1
International Journal of Production Economics	1
International Transactions in Operational Research	1
Journal of Environmental Management	1
Latin American Journal of Aquatic Research	1
Mathematics and Computers in Simulation	1
Natural Resource Modelling	1
Total	68

$$\mathrm{TC}(t) = \mathrm{FC}(t) + \mathrm{VC}(t) \tag{14}$$

where TC(t) = total costs at time t, FC(t) = fixed costs at time t, VC(t) = variable costs at time t

$$\mathrm{FC}(t) = \mathrm{LC}(t) + \mathrm{EC}(t) + \mathrm{DP}(t), \tag{15}$$

where TC(t) = total costs at time t, FC(t) = fixed costs at time t, VC(t) = variable costs at time t

$$\mathrm{VC}(t) = \mathrm{AC}(t) + \mathrm{RC}(t) + \mathrm{OVC}(t), \tag{16}$$

where VC(t) = variable costs at time t, AC(t) = fry cost ($/ind), RC($t$) = cost of food ration at time t, OVC(t) = other variable costs (= 0.05*AC(t) + RC(t))

$$\mathrm{GI}(t) = \mathrm{BV}(t) * P_w, \tag{17}$$

where GI = gross income, BV(t) = biomass value at time t and P_w = sale price per weight

$$\mathrm{NP} = \mathrm{GI}(t) - \mathrm{TC}(t), \tag{18}$$

where NP = net profits, GI(t) = gross income at time t and TC(t) = total costs at time t

$$\mathrm{NPV} = \sum_{t=1}^{n} \left[\frac{\mathrm{CF}_t}{(1+i)^t} \right], \tag{19}$$

where NPV = net present value, CF_t = cash flow at time t and i = discount rate

$$\mathrm{IRR} = \sum_{t=0}^{n} \left[\frac{\mathrm{CF}_t}{(1+i)^t} \right] = 0, \tag{20}$$

where IRR = internal rate of return CF_t = cash flow at time t and i = discount rate

$$\mathrm{C/B} = \frac{\mathrm{GI}}{\mathrm{TC}}, \tag{21}$$

where C/B = cost–benefit, GI = gross income and TC = total costs.

In all cases, the three sub-models worked independently but received input information from the others to be processed with mathematical models, to finally generate output information that feeds the next sub-model.

4 | DISCUSSION AND CONCLUSIONS

In this work, it has been pointed out that at a global level, there is a sustained trend towards an increase in the production of aquatic resources, and that this trend is supported only in aquaculture since fisheries have reached their maximum sustainable level. However, the main problem facing aquaculture is that being an economic activity, profit margins are frequently narrow and sometimes nil.[97] This is possibly due to poor planning, control and monitoring of production and the occurrence of external factors that are difficult to control but are feasible to measure, analyse and learn from them. Like protected agriculture, it would be ideal for aquaculture to evolve towards the modernisation of production systems to produce more and in less volume, with fewer risks, with control of variables, such as water temperature, which greatly influences growth and survival of organisms and disease control. However, much of the world's aquaculture is carried out in a rustic way, without control of environmental variables and with little knowledge of production costs.[97]

In this work, the 68 articles found are of high quality since they were published in prestigious specialised journals, which can be found with the criteria described in this work in the four search engines used. However, if the time of the analysis (26 years) is taken into account, the scientific productivity in this field was low (2.6 articles/year) in relation to the growth of world aquaculture (Figure 4). Possibly this is due to a low diffusion of the advantages of having bioeconomic models and the complexity with which scientists present their

TABLE 4 Bioeconomic models on management and economic viability of tilapia aquaculture during the period of 1994–2020.

Authors	Year	Search engine	Journals	Species	Location	Main application	Type of production system	Final purpose	Stage of development	Data use
Management										
Kazmierczak and Caffey	1996	Others	Others	Not specified	USA	Optimum use of resources in aquaculture recirculation systems	Intensive production in tanks with RAS	Optimization	Growout	T/C
Saiti et al.	2007	Scopus	Aquaculture Research	*Oreochromis shiranus*	Malawi	Optimal harvest time for small-scale crops	Tanks	Optimization	Growout	T/C
Gasca-Leyva et al.	2008	ScienceDirect	Ecological Modelling	Not specified	Mexico	Optimal harvest time for biological assets with size heterogeneity	Tanks	Optimization	Growout	T/C
Poot-López et al.	2010	ScienceDirect/ Scopus	Agricultural Systems	Not specified	Mexico	Integration of agricultural and aquaculture production systems (impact on feeding rates)	Tanks	Optimization	Growout	T/C
Domínguez-May et al.	2011	Scopus	Aquaculture Economics & Management	Not specified	Mexico	Effect of size heterogeneity and ration on time and size of optimal harvest	Tanks	Optimization	Growout	T/C
Poot-López et al.	2014	ScienceDirect/ Scopus/WoS	Aquaculture	*Oreochromis niloticus*	Mexico	Optimal serving size	Tanks	Optimization	Growout	T/C
Karimanzira et al.	2017	Scopus	Aquaculture Economics & Management	Not specified	Germany	Integration of agricultural and aquaculture production systems (tomato-tilapia aquaponic system)	Intensive production in tanks with RAS	Optimization	Growout	C
Domínguez-May et al.	2020	ScienceDirect/ Scopus	Ecological Modelling	Not specified	Mexico	Optimal portion size	Tanks	Optimization	Growout	T/C
Borrego-Kim et al.	2020	Scopus	Journal of Aquatic Research	*Oreochromis niloticus*	Mexico	Effect of size heterogeneity on optimal harvest time	Semi-intensive production in tanks	Optimization	Growout	C
Economic viability										
Ponce-Marbán et al	2006	ScienceDirect/ Scopus/WoS	Aquaculture	*Oreochromis niloticus*	Mexico	Economic viability of Nile Tilapia in a polyculture (Australian Red Lobster-Tilapia)	Semi-intensive production in ponds	Simulation	Growout	T
Poot-López and Gasca-Leyva	2009	Scopus/WoS	Journal of the World Aquaculture Society	*Oreochromis niloticus*	Mexico	Economic evaluation of feed replacement in the tilapia diet	Semi-intensive production in ponds	Simulation	Growout	E
Zuniga-Jara and Goycolea-Homann	2014	Springer Link/WoS	Aquaculture International	Red tilapia	Ecuador	Economic viability of red tilapia farming	Semi-intensive production in ponds	Simulation	Growout	T/C

Abbreviations: C = Commercial; E = Experimental; T = Theoretical.

TABLE 5 Submodels and equations used for the development of bioeconomic models in tilapia production.

Sub-model	Parameter	Equation(s)	References
Biological	Growth in weight	(1)–(3)	3,78,79,81–86
	Growth in size	(4)	85
Management	Biomass and survival	(5)	3,78–87
	Weight dispersion	(6)	88
	Survival rate	(7)	94
	Feeding rate	(8)	85
	Food conversión factor (FCF)	(9)	82,85
	Food ration	(10)	87
	Total ammoniacal nitrogen (TAN)	(11)	84,87
	Density	(12), (13)	85
Economic	Costs	(14)–(16)	3,78–88
	Gross income	(17)	3,78–88
	Net profits	(18)	3,78–88
	Net present value (NPV)	(19)	3,79,84,85
	Internal rate of return	(20)	95
	Cost/Benefit	(21)	96

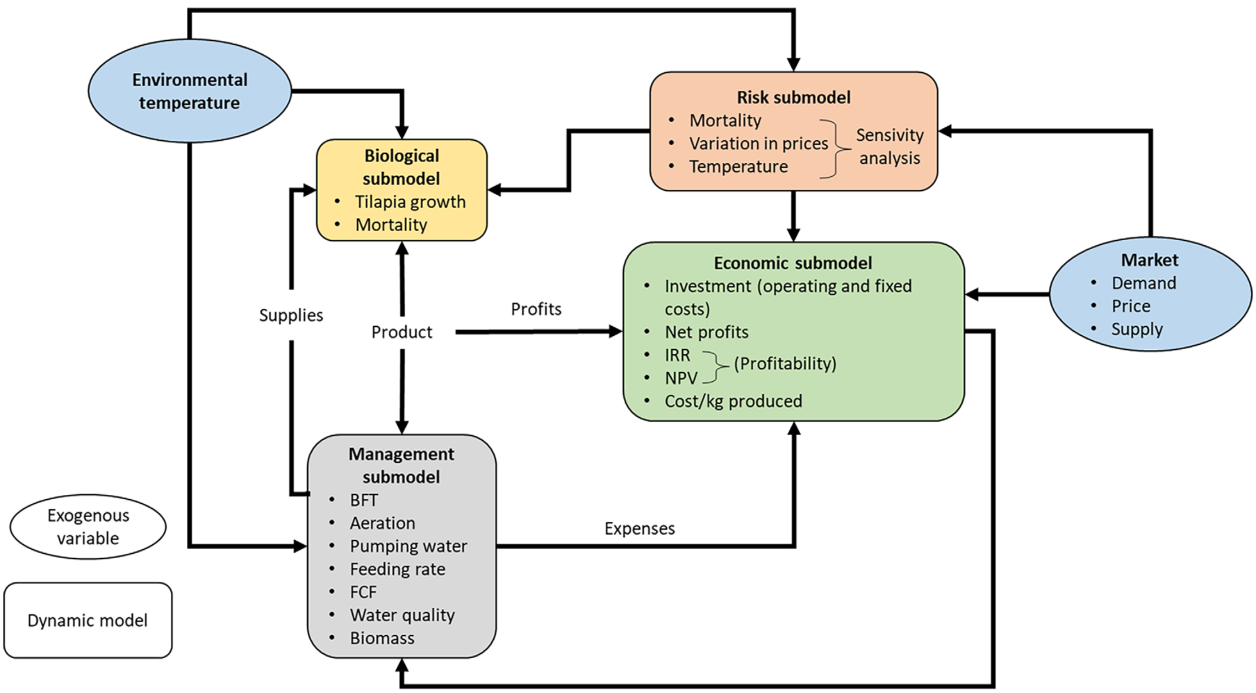

FIGURE 5 Conceptual diagram of the aquaculture bioeconomic model for tilapia.

models to users, generally in the form of scientific articles that are difficult for producers, planners or financial institutions to understand and apply.

The relationship between the degree of use of bioeconomic models and the lack of knowledge among industry professionals to work with mathematical and optimization models, the need for the development of models to be accompanied by the development of decision-making support systems, or the creation of interfaces that make possible for the user to take advantage of these developments, are crucial aspects to understand the current situation and the main future challenges. A large number of endogenous and exogenous factors leads to farmers need decision support systems for operational issues, such as seeding and harvesting dates, or strategic issues, such as site selection. Simulations and optimizations would help farmers reduce uncertainty.

A review of these kind of models/tools nowadays cannot ignore the need to integrate bioeconomic models with computing and data management tools that do not limit capacity for simulation and optimization based on increasingly large volumes of information. There are few user-friendly software programs that allow them to make bioeconomic calculations, run simulations and projections. It was not until recently that technical advice offers based on bioeconomic models have emerged, and particularly for Chilean salmon farming.[98]

The biological sub-model is one of the main ones in this model and it is where the information on the biology of the organism is inserted, including growth rates and natural mortality under environmental conditions that allow its development. The management or production sub-model is made up of those parameters that are proper and inherent to human intervention in a range of optimal and suboptimal environmental conditions. The parameters that make up this sub-model include aeration, water pumping, feed conversion factor (FCF), water quality, biomass, etc. The economic sub-model parameterizes and evaluates the monetary elements to provide information on the profitability and economic viability of the project, which are essential for making timely decisions. With this, it is determined if it is prudent to make an investment or if it is feasible to continue or make adjustments to production under the current established parameters.

The analysis of all sub-models, made possible to create a conceptual diagram of the bioeconomic model for tilapia (Figure 5), based on the System Dynamics Theory in which all independent sub-models interact with the others to produce the profitability information. This is on the logic of the production process, that is, it first focuses on the development of organisms including the effect of temperature that affects their growth, then the management that is given, and then the economic part that depends on biomass and of the costs in the production. However all papers analysed lack of a risk sub-model (Figure 5) to parameterize and understand not only the behaviour of the results under the conditions considered normal, but also to simulate what would happen within the uncertainty of the system. Risk sub-models have been introduced in bioeconomic modelling of other species, such as shrimp,[99] making sensitivity analyses to see to what extent the project could collapse or reach the goals we set for ourselves, or by carrying out more complex analyses, such as the Monte Carlo simulation.[100]

In conclusion, this work provides valuable information that shows that the aquaculture bioeconomy is advancing, but slowly, as a tool to support the development of world aquaculture. Low-cost and easily accessible user-friendly software, such as Excel, is required to apply the existing and future models, which could be improved with a risk sub-model to make sensitivity analysis.

AUTHOR CONTRIBUTIONS

Juan Carlos R. Dorantes-de-la-O: Data curation; investigation; writing – original draft; software. **Alfonso N. Maeda-Martínez:** Conceptualization; writing – original draft; project administration; supervision; resources. **Luis D. Espinosa-Chaurand:** Writing – review and editing. **Rodolfo Garza Torres:** Writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors do not have any conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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