# Aquaculture of the Sciaenidae family: main species cultured worldwide and emerging species in Latin America, offering new opportunities for aquaculture diversification

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## Abstract

Sciaenidae is the family of marine fish that has the highest aquaculture growth and production in the world. In this study, the global production, historical characteristics, biological aspects, and aquaculture technologies used for the Sciaenid species with the highest aquaculture production were compiled and analyzed to determine the success factors and bottlenecks that favored these species aquaculture development. This study also presents the state of technological aquaculture development in Sciaenid species in Latin America. The principal Sciaenid aquaculture species are large yellow croaker (*Larimichthys crocea*), red drum (*Sciaenops ocellatus*) and meagre (*Argyrosomus regius*), which together contribute 99.9% of the global aquaculture production of Sciaenid species. The aquaculture success of these three species is attributed to their suitable biology for aquaculture, high consumer demand, good market prices, government support, and prior empirical and/or scientific knowledge with other species that was transferrable to Sciaenidae, however, the aquaculture development of these species has not been free of errors. Principal bottlenecks in development include poorly planned marine spatial planning, the introduction of exotic species, the excessive use of fresh seafood-based feeds (especially in China), and inadequate genetic selection programs. In Latin America, eleven Sciaenidae species with biological attributes similar to the three established aquaculture species are being investigated. The technologies for the totoaba (*Totoaba macdonaldi*) and the Chilean croaker (*Cilus giberti*) are the most advanced. The technology developed and the positive and negative experiences of the Sciaenid aquaculture

industry identified in this review should be considered to assist government decision-making for research and development of aquaculture in the family Sciaenidae.

**Keywords:** Sciaenidae aquaculture, emerging species, reproduction and larviculture, success factors and bottlenecks, world production.

## Introduction

Oceans are estimated to have more than 11,400,000 km$^2$ of capacity to produce up to 15 billion tonnes of finfish per year through aquaculture, more than 100 times the global consumption of sea products (Gentry et al. 2017), nevertheless, of the 57.5 million tonnes of finfish produced from aquaculture for human consumption in 2020, only 8.3 million tonnes came from marine fish farming (FAO 2022). The low marine participation was reflected in the top ten fish farmed in the world in 2020, as the only fish farmed in the marine environment was the anadromous Atlantic salmon (*Salmo salar*), with a production of 2.91 million tonnes (8th position) compared to the 5.9 million tonnes reported for the freshwater grass carp (*Ctenopharyngodon idellus*), which is the species with the highest global production (FAO 2023).

Nonetheless, several marine fish species have gradually reached important levels of production since the end of the 20th century, such as the gilthead seabream (*Sparus aurata*) (319,214 tonnes) and the European seabass (*Dicentrarchus labrax*) (299,809 tonnes) in Europe, and the large yellow croaker (*Larimichthys crocea*) (254,224 tonnes) and the snubnose pompano (*Trachinotus blochii*) (243,908 tonnnes) in China (FAO 2023). The consolidation of these species in aquaculture has been driven by the stagnation or decline in fisheries resources, the increase in the human population, and the increase in fish consumption per capita (20.5 kg per person in 2020). These global demands for fish production and the success of these species have led to increasing interest in incorporating other marine fish as new aquaculture species in regions where marine fish farming has not seen significant development, such as Latin America (FAO 2022).

Among the small group of successful marine aquaculture species, the species of the Sciaenidae family stand out because of their global distribution and favorable performance in captive farming environments (Liu and De Mitcheson 2008; Cárdenas 2012; Duncan et al. 2013; Juarez et al. 2016; Chen et al. 2018; Drawbridge et al. 2021). Generally, Sciaenidae species are eurythermal, euryhaline, adapt well to farming conditions, have high growth rates, low feed conversion rates, and high market value (Cárdenas 2012). Reproductive control in captivity among Sciaenid species has been achieved; some species spawn naturally, while others present reproductive dysfunctions that can be resolved with hormonal therapies to induce oocyte maturation and spawning (Cárdenas 2012; Duncan et al. 2012; Fernandez-Palacios et al. 2014; Ibarra-Castro et al. 2015; Pastor et al. 2015; Soares et al. 2015). Further, larval rearing using established marine fish larval rearing techniques adapted to these species is considered relatively easy compared to that of other marine species (Papadakis et al. 2009, 2013, 2018; Vallés 2013; Vallés and Estévez 2013; Campoverde et al. 2017; Campoverde and Estévez 2017; Chen et al. 2018; Saavedra et al. 2018; Martins et al. 2019). These characteristics of some established and emerging Sciaenidae species in aquaculture indicate that other Sciaenid species may have similar potential for aquaculture. In this context, there is a need to bring together and recapitulate the available information on worldwide farmed Sciaenidae species to demonstrate the advantages of these species and synthesize advances in their production that can be applied to energize the research and development of emerging Sciaenids, especially in regions such as Latin America, where there is interest in culturing more than ten Sciaenidae species (González-Félix et al. 2015; Ibarra-Castro et al. 2015; Boza-

Abarca et al. 2016; López et al. 2016; Minjarez-Osorio et al. 2016; Bolasina and Benedetti 2017; Zapata and Vieyra 2018; Espinales et al. 2019; Madrid et al. 2019). Consequently, the main biological, zootechnical, and technological developments of the species in the Sciaenidae family with the highest global production were compiled and analyzed, with the aim of identifying the major factors that contribute to farming success, the major problems that the industry has encountered during the process of acclimation and domestication of wild fish, and the farming bottlenecks that need to be addressed to improve intensive production. In addition, the review aimed to analyze the state of the art of the technological development of farming new and emerging Sciaenid species in Latin America, a region with aquaculture potential for this group of fast-growing fish species.

## Major biological aspects related to successful Sciaenid aquaculture

According to the Food and Agriculture Organization of the United Nations (FAO 2023), six species of the Sciaenidae family register constant production worldwide: the large yellow croaker, the red drum (*Sciaenops ocellatus*), the meagre *(Argyrosomus regius)*, the shi drum (*Umbrina cirrosa*), the Japanese meagre (*Argyrosomus japonicus*), and the brown croaker (*Miichthys miiuy*). Based on their success in aquaculture, the biological characteristics of these species can be used as a reference for the selection of emerging species. Sciaenidae are predominantly a group of subtropical fish species, although they can also be found in tropical and temperate zones (Table 1). All these species are demersal benthopelagics that move near the bottom over the benthos and are oceanodromes; depending on the time of year, they migrate from open waters to areas near the coast, such as estuaries and river mouths. This behavior depends on the season, the time of reproduction, feeding, or the life cycle stage (larvae, juveniles, or adults) (Chao and Trewavas 1990; Riede 2004). Although Sciaenidae may be found in open marine waters far from the coast, they are predominantly coastal species inhabiting estuaries, coastal lagoons, and river deltas on sandy, muddy, and rocky bottoms. Some species can reach 300 m depth, but they tend to inhabit depths of less than 100 m (Table 1).

Several species of the family Sciaenidae adapt physiologically and metabolically well to low salinities between 4 and 6.5 up to high salinities between 32 and 40. The red drum has an even wider range of adaptation and can live for long periods in freshwater at 0 and resist higher salinities up to 66 (Table 1). The possibility of living in wide ranges of salinities and temperatures enables the culture of these species in various marine and coastal environments, using different farming systems (*i.e.*, cages and ponds).

Sciaenid species are characterized as large species with very good growth rates (Table 1), however, the large yellow croaker, the Sciaenid with the highest world production, is a small species, which suggests that size is not a limitation for production in this family; the productive success of this species could also be attributed to non-biological factors such as aquaculture practices and the large market in China.

Sciaenidae are iteroparous and gonochoric with asynchronous gonadal development (Barbaro et al. 1996; Stipa and Angelini 2009; Grier 2012; IFAPA 2014; Gao et al. 2019). Spawning usually occurs in the brackish waters of estuaries (Su et al. 2004; Stipa and Angelini 2009; Cárdenas 2012; Grier 2012; Froese and Pauly 2022) during spring and summer (Table 1). In agreement with their asynchronous gonadal development, Sciaenidae have multiple reproductive cycles during the year and throughout their lives, which is advantageous for domestication and intensive farming; however, the seasonality of spawning implies the need to control their annual reproductive development to potentially extend spawning periods. They reach sexual maturity at ages between 2 and 6 years depending on the species, with an average of approximately 3 years. Smaller species, such as large yellow croaker, can mature at 2 years, which is a logistical advantage for the culture of this species. Sciaenids are carnivorous species, with a high tendency to consume crustaceans and other invertebrates as juveniles and fish as adults. Carnivorous food preferences suggest that Sciaenidae culture has high dietary fish meal and oil requirements, which indicates that a research effort is required to develop sustainable feeds and feeding practices with reduced fish meal and fish oil content (Table 1). In this sense, researchers have found that plant products can effectively replace fish meal and oil in the diets of meagre (Estevez et al. 2011; Kotzamanis et al. 2018; Suehs et al. 2022).

**Table 1.** Relevant aspects of the biology of the six species of the Sciaenidae family.

| | Large yellow c. | Red drum | Meagre | Shi drum | Brown croaker | Japanese meagre |
|---|---|---|---|---|---|---|
| Natural Distribution | 38°N-13°N<br>106°E-141°E[a] | 43°N-0°S[a] | 65°N-6°S<br>23°W-36°E[a] | 50°N-30°N<br>18°W-42°E[a] | 43°N - 21°N<br>116°E - 146°E[a] | 40°N - 39°S<br>18°E - 155°E[a] |
| Prevailing ecology | Subtropical[b] | Subtropical[b] | Subtropical[b] | Subtropical[b] | Subtropical[b] | Tropical[b] |
| Habitat | Estuaries, lagoons, brackish, coastal waters[c] | Estuaries, lagoons, brackish, coastal waters[h] | Estuaries, lagoons, brackish, coastal waters[p] | Estuaries, found over rocky and sandy bottoms, coastal waters[a] | Estuaries, mud to sandy, mud bottoms, coastal waters[cc] | Estuaries, rocky reefs, bays, continental shelf, coastal waters[a] |
| Max. depth (m) | 120[d] | - | 300[q] | 100[w] | 100[dd] | 100[jj] |
| Natural salinity | 6.5-34[e] | 0-66[i] | 5-39[r] | > 4-40[x] | 4-32[ee] | 5-35[kk] |
| Natural temperature (°C) | 8-32[e] | 2-38[j] | 2-38[s] | 13.3-21[y] | 13-24.8[y] | 15-30[ll] |
| Natural max. weight (kg) | 3.8[e] | 45[k] | 50[t] | 11[z] | 25[ff] | 75[mm] |
| Natural max. length (cm) | 80[f] | 155[l] | 200[t] | 104[z] | 100[ff] | 200[nn] |
| Maximum age (years) | 29[g] | 50m | 40[u] | 18[z] | 13[ff] | 42[oo] |
| First maturity (years) | 2-4[g] | 3-6[n] | 4-5[u] | - | 3[ff] | 2-3(M) 4-5(F)[nn]<br>5(M) 6(F)[jj] |
| First maturity size (cm) | 17.5-25[g] | 60-75[n] | 61,6 (M)<br>70-110 (F)[s] | - | 54,8 (F)<br>49,0 (M)[gg] | 51 (M)<br>68 (F)[nn] |
| Breeding weather season | Spring-fall (China)[g] | Summer-Fall (U.S) [j] | Spring-Summer (Spain) [u] | Spring-Summer (Turkey)[aa] | Autumn (China)[hh]<br>Summer (Korea)[gg] | Spring-Summer (Australia)[pp]<br>Summer (Soud Africa)[qq] |
| Natural food habits | Crustaceans, fishes[c] | Crustaceans, molluscs, fishes[k] | Fishes, crustaceans[a] Cephalopods[v] | Crustaceans, molluscs, other invertebrates[bb] | Fishes and crustacean decapods[ii] | Fishes, squids, crustaceans[qq] |

a Froese and Pauly 2022; b Riede 2004; c Masuda et al. 1984; d Nakabo 2002; e Liu 2013; f Robins 1991; g Liu and De Michelson 2008; h Robins and Ray 1986; i Ern and Esbaugh 2018; j Reagan 1985; k Frimodt 1995; l Chao 1995; m Ross et al. 1995; n Waggy et al. 2006; p Caverivière and Andriamirado 1997; q Schneider 1990; r Ruiz-Jarabo et al. 2018; s González-Quirós et al. 2011; t Stipa and Angelini 2009; u García-Pacheco and Bruzón 2009; v, Hubans et al. 2017; w Chao and Trewavas 1990; x Mylonas et al. 2009; y Kaschner et al. 2016; z Aydin 2020; aa Basaran et al. 2009; bb Froglia and

Gramitto 1998; cc Chan et al. 1974; dd Yamada et al. 1995; ee Shan et al. 2009; ff Peng et al. 2020; gg Lee et al. 2017; hh Li et al. 2005; ii Jeong et al. 2019; jj Griffiths 1996; kk Doroudi et al. 2006; ll PIRSA 2001; mm Griffiths and Heemstra 1995, nn Silberschneider et al. 2009; oo Griffiths and Attwood 2005; pp Battaglene and Talbot 1994; qq Silberschneider and Gray 2008.

## Global production and economic value

The world production of species in the Sciaenidae family has been dominated by fishery captures since before 1950, reaching a maximum catch in 2012 (1,940,285 tonnes), but over the next nine years, their catch declined by 27.1% (525,822 tonnes) to 1,414,463 tonnes in 2021 (Figure 1) (FAO 2023).

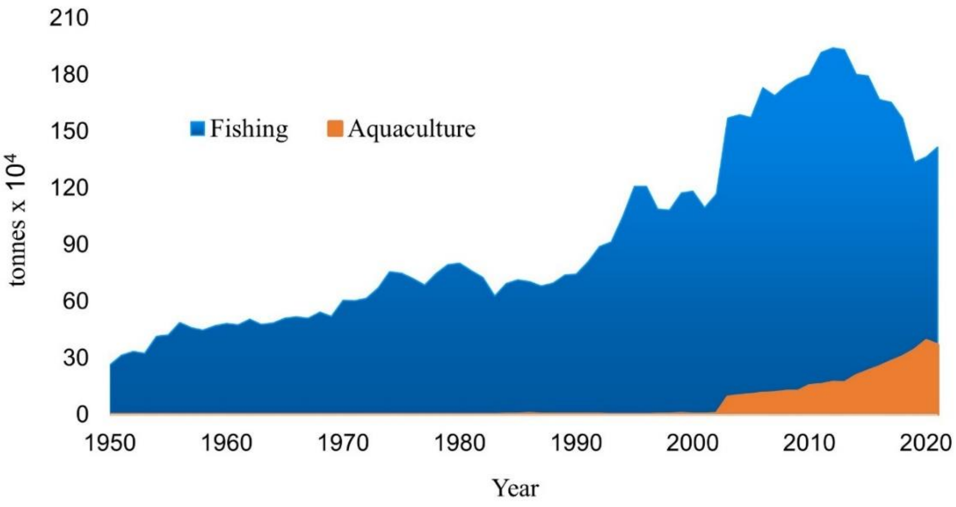


**Figure 1** Global production (not cumulative) of the family Sciaenidae by fisheries and aquaculture according to FAO statistics (1950-2020).

Several factors have been identified as responsible for the decline of natural populations and fishery captures of Sciaenids: i) Anthropic pollution in estuaries; ii) reduced river discharge; iii) climate change; iv) overfishing; v) illegal trade of their valuable swim bladder; and vi) the capture of many adults before spawning due to the ease of locating large mature fish by courtship sound production (Sadovy and Cheung 2003; Fernández Carvajal 2013; Moreno-Díaz and Alfaro 2018; Bolgan et al. 2020). In contrast to their decline in fisheries, aquaculture production of the Sciaenidae family has increased and partially replaced the decrease in fisheries, with a production of 367,578.4 tonnes in 2021, which had a value of US$ 939 million (Figure 1) (FAO 2023).

The three principal Sciaenid aquaculture species, large yellow croaker, red drum, and meagre (hereafter abbreviated to LRM), with the greatest progress in aquaculture produced a total of 367,318 tonnes (99.9%) in 2021. The large yellow croaker is produced on the Pacific Northwest coast of China; the red drum is cultured in eight countries in various areas of the Pacific, Atlantic and Indian Oceans and in the Mediterranean and Red Sea (production in the Mediterranean and Red Sea area is land-based due to restrictions to culture exotic species); and the meagre is produced by twelve countries in the Mediterranean and Black Sea, Northeast Atlantic and the Western Indian Ocean (Table 2) (FAO 2023). In 2021, the combined aquaculture production of LRM exceeded LRM fishery production by 323,390 tonnes, a trend that is expected to be similar for other species in the coming years (FAO 2023).

Between 2018 and 2021, the highest aquaculture production was recorded in Asia, mainly in China (large yellow croaker and red drum), followed by Africa (Egypt) and Europe, where meagre was produced. Three Sciaenid species made minor contributions to aquaculture production of less than 0.1% during the 2018-2021 period, with a total production of 260 tonnes registered in 2021. The shi drum was cultured in the Mediterranean and Black Seas; the Japanese meagre was cultured in three African countries in the Western Indian and Southeast Atlantic; and the brown croaker was cultured in the Republic of Korea and Taiwan (Table 2) (FAO 2023).

**Table 2.** World Sciaenidae aquaculture production in metric tons and value in $US by specie, country, and continent between 2018 and 2021 (FAO 2023).

| Species | Country | *2018*<br>Tons. | *2019*<br>Tons. | *2020*<br>Tons. | *2021*<br>Tons. | value $U.S. (2021) | % production 2018-2021 |
|---|---|---:|---:|---:|---:|---:|---:|
| L. yellow croaker | China | *197,980.0* | *225,549.0* | *254,062.0* | *254,224.0* | *552,174,530.0* | *66,31* |
| Red drum | China | 68,253.0 | 70,187.0 | 77,408.0 | 63,895.0 | 138,779,940.0 | 19.91 |
| | U.S. | 3,245.0 | 3,244,6 | 3,244.6 | 3,244.6 | 19,448,000.0 | 0.92 |
| | Mauricio | 1,948.0 | 3,132.0 | 3,224.0 | 2,216.3 | 13,731,944.0 | 0.75 |
| | Israel | 150.0 | 450.0 | 430.0 | 375.0 | 2,723,510.0 | 0.10 |
| | Guadalupe | 20.0 | 20.0 | 40.0 | 45.0 | 479,000.0 | 0.01 |
| | Martinique | 40.0 | 35.0 | 35.0 | 35.0 | 248,380.0 | 0.01 |
| | Mayotte | 20.0 | 15.0 | 15.0 | 15.0 | 124,190.0 | 0.00 |
| | México | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 |
| | *Subtotal* | *73,676.8* | *77,083.6* | *84,396.6* | *69,825.9* | *175,534,964.0* | *21.7* |
| Meagre | Egypt | 25,130.0 | 25,320.0 | 36,184.0 | 27,688.0 | 115,038,310.0 | 8.14 |
| | Turkey | 1,486.0 | 3,375.0 | 7,428.0 | 5,913.0 | 34,701,360.0 | 1.30 |
| | Spain | 3,929.2 | 4,534.9 | 4,414.7 | 2,788.3 | 14,968,820.0 | 1.11 |
| | Grecce | 1,638.9 | 2,414.9 | 3,426.6 | 4,200.6 | 26,182,510.0 | 0.83 |
| | Croatia | 807.9 | 724.7 | 618.1 | 999.2 | 7,281,810.0 | 0.22 |
| | France | 251.3 | 669.4 | 501.0 | 720.0 | 5,296,780.0 | 0.15 |
| | Tunisia | 10.0 | 330.0 | 641.0 | 713.3 | 3,829,020.0 | 0.12 |
| | Italy | 75.4 | 75.0 | 105.5 | 123.0 | 1,338,390.0 | 0.03 |
| | Saudi Arabia | 130.0 | 13.0 | 35.2 | 70.0 | 466,670.0 | 0.02 |
| | Dominican Rep. | 20.0 | 40.0 | 40.0 | 40.0 | 150,290.0 | 0.01 |
| | Portugal | 32.7 | 6.8 | ND | ND | 0.0 | 0.00 |
| | Cyprus | 1.1 | ND | ND | 12.8 | 110,210.0 | 0.00 |
| | *Subtotal* | *33,512.5* | *37,503.7* | *53,394.2* | *43,268.2* | *209,364,170.0* | *11.93* |
| Shi drum | Grecce | 114.9 | 85.6 | ND | 100.0 | 603,200.0 | 0.02 |
| | Turkey | 30.0 | 47.0 | 26.0 | 2.0 | 9,040.0 | 0.01 |
| | *Subtotal* | *144.9* | *132.6* | *26.0* | *102.0* | *612,240.0* | *0.03* |
| Brown croaker | R. of Korea | *70.0* | *47.0* | *57.0* | *92.5* | *1,729,090.0* | *0.02* |
| Japanese meagre | Mauricio | 63.0 | 10.0 | 23.0 | 61.4 | 442,040.0 | 0.01 |
| | South África | 0.0 | 0.0 | 0.0 | 4.4 | 25,080.0 | 0.00 |
| | *Subtotal* | *63.0* | *10.0* | *23.0* | *65.8* | *467,120.0* | *0.01* |
| | *Total* | *305,447.3* | *340,325.9* | *391,958.8* | *367,578.4* | *939,882,114.0* | *100.00* |
| % Country | *2018-2021* | *2018* | *2019* | *2020* | *2021* | *value $U.S 2021* | *Tons. 2018-2021* |
| 1. China | 86,2 | 266,233.0 | 295,736.0 | 331,470.0 | 318,119.0 | 690,954,470.0 | *1,211,558.0* |
| 2. Egypt | 8,1 | 25,130.0 | 25,320.0 | 36,184.0 | 27,688.0 | 115,038,310.0 | *114,322.0* |
| 3. Turkey | 1,3 | 1,486.0 | 3,375.0 | 7,428.0 | 5,913.0 | 34,710,400.0 | *18,202.0* |
| % Continent | *2018-2021* | *2018* | *2020* | *2020* | *2021* | *2021* | *Tons. 2018-2021* |
| 1. Asia | 87,7 | 268,099.0 | 299,668.0 | 339,446.2 | 324,571.5 | 730,584,140.0 | 1,231,784.7 |
| 2. Africa | 9,0 | 27,171.0 | 28,807.0 | 40,087.0 | 30,698.5 | 133,190,584.0 | 126,763.5 |
| 3. Europe | 2,4 | 6,851.4 | 8,511.3 | 9,066.0 | 8,943.9 | 55,781,720.0 | 33,372.6 |
| 4. America | 1,0 | 3,325.8 | 3,339.6 | 3,359.6 | 3,364.6 | 20,325,670.0 | 13,389.6 |
| 5. Oceanía | 0,0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Total | 100,0 | | | | | 939,882,114.0 | 1,405,310.4 |

ND: No data.

## Aquaculture production status and characteristics

### *Large yellow croaker*

The large yellow croaker is distributed in the Northwest Pacific, from central Vietnam to South Korea and Japan, including the Yellow and East China seas (Froese and Pauly 2022). Aquaculture production is mainly limited to the coastal waters of continental East Asia, particularly China (Liu and De Mitcheson 2008). Statistics indicate an increase in production of 22.1% between 2018 and 2021, with an annual average increase of 5.5% during this period (FAO 2023). Artificial fertilization and fry rearing were first conducted in 1985 in Fujian Province, Southeast China. Since 2000, a total of 500 hatcheries have been constructed nationwide, producing approximately 1.5 billion fry annually, with Fujian Province alone accounting for around 1.3 billion fry in 430 hatcheries (Chen et al. 2018). Grow-out of the large yellow croaker to produce market-sized fish began in 1995 in small-scale floating cages, which remains the main culture system, accounting for over 95% of this species total production. As of 2013, there were approximately 420,000 floating sea cages used for large yellow croaker aquaculture in China, while pond production remained relatively low (Chen et al. 2018). Expansion into large-scale culture has been constrained by limited coastal space and disease problems in established growing areas. These limitations have led to an interest in recirculation aquaculture systems (RAS), with studies confirming the feasibility of culturing large yellow croaker in RAS (Li et al. 2012). Cage farming remains the principal production method (Wang et al. 2017).

The large yellow croaker can reach 0.3 kg within the first year under temperatures ranging from 20 to 28°C (Liu 2013) (Table 3). The main feed used is trash fish (Chen et al. 2018) because large yellow croaker fed trash fish grow faster compared to those fed artificial diets, despite concerns of food safety, feed quality, nutritional standardization, and environmental impact. Research on juvenile dietary requirements has identified crude protein requirements between 45% and 50%, with 12% crude lipids (Sun et al. 2013). Floating cage cultures typically use commercial feeds containing at least 49.0% crude protein and 5.0% crude fat (Chen et al. 2020).

This species is among the aquaculture species with the largest demand by Chinese consumers, in addition to the yellow croaker (Larimichthys polyactis), largehead hairtail (Trichiurus lepturus), and spineless cuttlefish (Sepiella maindroni). These highly demanded species are sold in free markets and supermarkets as fresh, salted, pickled, dried, or frozen products that are valued at approximately price US$ 6 per kg. The swim bladder is not marketed because farmed fish are too small to provide swim bladders for the market (W. Hong, pers. comm. 2021). In addition to the Chinese market, large yellow croaker is among the eight most exported aquatic products from China, with annual export values exceeding US$ 100 million (Chen et al. 2018).

### ***Red drum***

The red drum is distributed in the Western Atlantic, from Massachusetts in the USA to northern Mexico, including southern Florida, USA (Robins and Ray 1986). Aquaculture of the red drum began in the USA during the 1970s with production in Texas, Florida, Louisiana, and Alabama. Its high aquaculture potential led to its introduction as an aquaculture species in various countries, including China, Israel, Mexico, Ecuador, Taiwan, Singapore, the United Arab Emirates, Martinique, Mauritius and Mayotte (Diamant, 1998; Jirsa et al. 1997; Turano et al. 2002; Jiménez et al. 2005; Cárdenas 2012; Rossi et al. 2015; González-Félix et al. 2018a; Chary et al. 2019; Wang et al. 2020). Production increased by 12.7% between 2018 and 2020, with an annual average increase of 3.17% during this period, but decreased by 17.3% in 2021 compared to 2020, possibly due to the COVID-19 pandemic (FAO 2023). China is the largest global producer of red drum, where the species was introduced in 1991 as juveniles (8 mm in size) from the USA. Since 1996, red drum production has been conducted in earthen ponds and floating marine cages in coastal provinces (Chen and Zhang 2012), primarily around Hainan Island, which has an average annual water temperature of 19-30°C suitable for red drum aquaculture (Editorial Board of Ocean and Fisheries 2015). The Red drum tolerates different environments, and consequently, escaped individuals have established wild populations in all types of marine environments where cage culture is practiced (Zhao et al. 2006).

In China, red drum can grow to 0.5-1 kg within the first year under temperatures ranging from 18 to 25°C (Yang, 1999; Lu 2003) (Table 3). Research has focused on optimizing balanced feeds for this species, with trash fish supplementation common in Chinese operations despite efforts to develop complete feed formulations (Serrano et al. 1992; Jia et al. 2006; Castillo and Gatlin 2018; Burns and Gatlin 2019; Casu et al. 2019). During grow-out, red drum shows adequate growth, with dietary protein levels between 35% and 50% and lipid levels between 7% and 11% (Lin and Arnold 1983; Serrano et al. 1992b; Thoman et al. 1999; Gatlin 2002).

The red drum is a high-value marine fish (Li et al. 2020) sold whole, filleted, or for sashimi (Hong et al. 2021) in fresh or frozen form, typically priced at approximately US$ 3-5 per kg in Chinese markets. The swim bladder of red drum is not marketed (W. Hong, pers. comm. 2021). In the USA, red drum has been sold whole in wholesale seafood markets and as fillets, with whole gutted fish priced between US$4.32 and US$7.41 per kg, and wholesale fillets without skin at US$10.00 per kg (Lazo et al. 2010). In Texas, aquaculture-produced juveniles are also traded as bait for sport fishing, priced at US$3.00-3.65 per pound (Ropicki and Fuiman 2020).

### *Meagre*

The meagre is distributed in the Eastern Atlantic, from Norway to the Congo, and includes the Black Sea and the Mediterranean Sea, whereas this species has also spread to the Red Sea via the Suez Canal (Froese and Pauly 2022). Meagre is the most cultured Sciaenid species in Europe and Africa and has major growth potential in the Mediterranean aquaculture. Production began in 1997 in France, achieving the first successful captive reproduction (Quémener 2002). Initially, a single French hatchery supplied juveniles for grow-out farms with annual productions below 1,000 tonnes for the French and Italian markets (Pómelie and Paquotte 2000). Production increased rapidly after 2005, as protocols for meagre culture, such as effective spawning induction methods and larviculture procedures were shared between research centers and industry (Duncan et al. 2012; Duncan et al. 2013; Mylonas et al. 2013). Production increased by 37.2% between 2018 and 2020, with an average annual increase of 9.3% during this period, but decreased by 19.0% in 2021 compared to 2020, likely due to the COVID-19 pandemic (FAO 2023). Grow-out occurs almost exclusively in sea cages, with some production in ponds in Egypt, Portugal, and Spain (Zied and Hassouna, 2007; Soares et al. 2012; Vargas-Chacoff et al. 2014).

Can grow to 1.1 kg within the first year, under temperatures ranging from 14 to 26°C (Duncan et al. 2013) (Table 3). Commercial feeds are used during grow-out, with studies confirming successful culture using diets containing approximately 43% protein and 15-20% lipids (Fountoulaki et al. 2017). Juveniles have protein requirements close to 50% and do not seem to require high levels of lipids in their diet (Chatzifotis et al. 2012).

Meagre are marketed as large fish weighing 1-2 kg or more. Initially, meagre entered niche markets in France, Italy, and Portugal, where the species was known locally. It is gradually expanding with various product presentations, such as whole fish, fillets, steaks and smoked products, similar to the Atlantic salmon, reaching high market prices ranging from US$7.14-14.28 per kg (Duncan et al. 2013). The swim bladder of meagre is not marketed (Neil Duncan, pers. comm. 2021).

### ***Shi drum***

The shi drum can be found in the Eastern Atlantic, from the Bay of Biscay to Senegal, the Mediterranean and the Black Seas (Barbaro et al. 1996). Research on the aquaculture of the shi drum began with the grow out of wild-caught juveniles, which were then used to form broodstocks (Mylonas et al. 2000). Its production in Mediterranean countries began in the late 1990s and early 2000s and coincided with the first attempts to induce spawning in captivity using hormonal induction in Italy (Melotti et al. 1995; Barbaro et al. 1996, 2002), Cyprus (Mylonas et al. 2000), Greece (Mylonas et al. 2004), and Spain (Arizcun et al. 2009). This species has been cultured in ponds (Henry and Fountoulaki 2014; Grigorakis et al. 2016) because its benthic behavior makes it unsuitable for cage culture; it is commonly found on rocky and sandy bottoms (Koumoundouros et al. 2005).

This species obtained its highest production in 2011, with 1,057 tonnes (FAO 2023), but despite several technological advances (Arizcun et al. 2014; Grigorakis et al. 2016; Gürkan et al. 2017; Hidalgo et al. 2017; Neofytou et al. 2017; Chaves-Pozo et al. 2019; Ayala et al. 2020), its production decreased by 42.0% between 2018 and 2021, averaging a 10.5% annual decrease during this period (FAO 2023). This decline in production may be related to the high susceptibility of shi drum to nodavirus, one of the most pathogenic viruses causing severe mortalities (Katharios et al. 2010; Chaves-Pozo et al. 2021). Consequently, there has been a shift in investment preference towards the culture of meagre, a similar species with more attractive aquaculture characteristics that shares the same geographic region.

The shi drum is characterized by a medium growth rate, with average weights of 650 g reported in less than 24 months (Mylonas et al. 2004). After 4 months of culture in 4.5 $m^3$ tanks, juveniles (60 g) grew to 375.6 g at temperatures between 19 and 30°C (Segato et al. 2005). The shi drum is fed commercial feed, and studies on juveniles indicate a need for more than 47% crude protein and suggest crude lipid levels below 10% (Kokou et al. 2019). This species has high market value throughout the Mediterranean region (Chaves-Pozo et al. 2019). In Turkey, shi drum are sold at US$10 per kg (Aydin 2020), and it is notable that otoliths are marketed for kidney pain treatments with an approximate price between US$0.5 and 1.2 (Daily Sabah 2023). Like the meagre, no records were found regarding the commercialization of the swim bladder in this species.

### *Brown croaker*

The brown croaker is distributed in the Northeast Pacific Ocean, including eastern China, the western coast of Korea, and the western Japan Sea (Froese and Pauly 2022), where it inhabits muddy and sandy coastal waters (Chan et al. 1974). Experiments in artificial breeding and farming were conducted during the late 1990s in the coastal areas of Fujian, Zhejiang, and Guangdong in China. Early work in artificial breeding used broodstock weighing ≥2 kg, obtained from the open sea using drift netting or longline fishing methods (Lou 2004). Since 2006, brown croaker farming technologies have been developed in South Korea to complete the life cycle in captivity, including reproductive control, captive spawning, egg incubation, and larval and juvenile rearing (An et al. 2012). Production increased by 24.0% between 2018 and 2021, with an annual average increase of 6.0% during this period, however, global production was just 92.5 tons in the Republic of Korea in 2021 (FAO 2023). The low production of brown croaker has been related to bottlenecks in juvenile production caused by high mortality and low growth during the larval stage in captivity, which need to be overcome (Shan et al. 2009). It is possible that this species has a higher production than officially registered (Hong, personal comm. 2022) as it widely cultured for human consumption in China (Hong and Zhang 2003; Lou 2004). Adequate growth has been achieved in floating cages; after 18 months of farming, fingerlings grew to an average weight of 3 kg at temperatures between 10.5 and 30°C (Wang 2008).

The brown croaker is a carnivorous fish, and in China, juveniles are reared on diets that contain 48.5% and 5.1% crude protein and lipid, respectively (Song et al. 2006). Most brown croakers are sold on the market as chilled and frozen products. The most valuable product is the swim bladder, which is sold for more than 1,000 US$ per kg, as traditional Chinese medicine considers the swim bladder of the brown croaker to have beneficial effects on human health (Tang 1987).

### ***Japanese meagre***

The Japanese meagre inhabits a wide range of coastal habitats in four regions of Indian and Pacific Oceans, extending from the southeastern coast of Africa to Pakistan, the Chinese coast from Hong Kong to southern Korea and Japan, and the entire coast of Australia, including the southern coast (Trewavas 1977; Kailola et al. 1993; Griffiths and Heemstra, 1995). It is considered a candidate species for mariculture in Australia and South Africa (Kaiser et al. 2011). Captive breeding of this species began in New South Wales, Australia, in 1992 (Jiménez et al. 2013) and later spread to African countries such as Mozambique and

South Africa (FAO 2023). The Port Stephens Research Center was the first hatchery to artificially produce Japanese meagre (Battaglene and Talbot 1994) using intensive rearing techniques developed for the Australian seabass (*Macquaria novemaculeata*) and the snapper (*Pagrus auratus*) (Fielder and Bardsley 1999). Advances in reproduction and juvenile production have enabled Australia to develop floating cage culture, both for human consumption and wild stock enhancement (Fielder and Bardsley 1999; Taylor et al. 2005; Hayward et al. 2007). In the following years, no production statistics have been recorded in Australia (FAO 2023), although research reports suggest that the species has been produced locally in ponds in subtropical areas at temperatures between 25 and 30°C (Guy 2016).

Global production of Japanese meagre reached a peak in 2014, with 312 tonnes produced in South Africa and Mozambique, but decreased to 65,8 tonnes in 2021. There was a 4.2% increase in production between 2018 and 2021, with an annual average increase of 1.0% during this period, but production remained low at just 65.8 tons in 2021 (FAO 2023) (Table 2). The statistics do not show consistent production, which fluctuates with a downward trend. There may be unregistered production in South Africa; for instance, in 2017, no production was registered (FAO 2023), but harvests of 21,255 kg were reported between June and July 2017 (Viljoen 2019).

Adequate growth has been achieved in floating cages; after 23 months, fingerlings grew to an average weight of 1-1.5 kg at temperatures between 19 and 28°C (Viljoen 2019). In this same study, juveniles in their first two months of culture were fed a commercial diet with crude protein and lipid levels of 50% and 10%, respectively, while feed with 44% protein and 11% lipids was supplied to older fish (Viljoen 2019).

The Japanese meagre has high-quality flesh and a good market demand in South Africa. Local sales, including gilled and gutted, and completely cleaned with heads on, are reported at prices between US$3.8 and 5.6 kg per kg, while low prices were reported for fish caught in Namibia (Collett 2007; Viljoen 2019). There were no data on the marketing of the swim bladder. Despite early interest in the production of Japanese meagre, the breeding programs for this species are in an early phase, and wild-caught adults are used as broodstock to produce F1 offspring by mass-spawning in communal tanks. The low production may be related to bottlenecks in the production of juveniles (Mirimin and Roodt-Wilding 2015).

## Technology used for industrial Sciaenidae aquaculture.

The aquaculture of LRM has achieved significant technological advancements since 1975 for red drum (Yang 2000), 1985 for large yellow croaker (Chen et al. 2018), and 1997 for meagre (Quémener 2002). These advancements cover all stages, including reproduction, incubation, larval culture and grow out, which are summarized as follows.

### *Reproduction*

The definition and control of the main environmental parameters that enable maturation in captivity for LRM have been established (Table 3). Suitable body weight for reproduction ensure greater reproductive performance and efficiency in terms of both the quantity and quality of eggs necessary for the industry. Each of the three species spawn at different sizes (Arnold 1991; Ma et al. 2005; Fakriadis et al. 2020). For instance, large yellow croaker (1-2 kg) are smaller compared to red drum and meagre (>6 and >8 kg, respectively), but does not limit their reproductive performance. In fact, smaller broodfish have shorter generation times and are easier to handle in captivity.

For conditioning and maturation, tanks with a volume >10 m$^3$ and a water column height of >1 m are frequently used. Better results are obtained with tanks of at least 50 m$^3$ and heights ≥1.5 m, characteristics that provide a better environment for maturation and an adequate depth for courtship (Duncan et al. 2013). In China, floating cages are used to maintain large yellow croaker broodstocks (Hong and Zhang 2003), and when the reproductive season begins, these broodstocks are moved to rectangular concrete tanks and stimulated with one or several doses of hormones to induce spawning (Danjun et al. 1991). Broodstock density ranges from 1 to 11 kg m$^{-3}$. For example, red drum broodstock are kept at high densities of 11 kg m$^{-3}$ in 16 m$^3$ tanks with 60–100% daily water turnover and pelleted feed (Biomar Ecolife 16 no. 12) provided *ad libitum* (Gardes et al. 2000), while meagre broodstock are kept at lower densities of less than 1.7 kg m$^{-3}$ in 250 m$^3$ concrete ponds and fed fish/shellfish until apparent satiety (Pastor et al. 2013). The sex ratio (M:F) in broodstocks varies according to the site, from 2:1 to 1:2, with 1:1 being the most common (Table 3). Meagre reproduces in captivity in temperate waters, while large yellow croaker and red drum do so in subtropical waters, however, red drum can reproduce at tropical temperatures close to 29°C (Table 3). Broodstock nutrition is based on natural diet items (fish, squid, or shrimp), especially in China, and/or formulated feeds or vitamin and mineral supplements. Reproduction has been controlled naturally in red drum or with low doses of hormones in large yellow croaker and meagre, as reproductive dysfunctions are considered mild. Periods of 180 days under a photoperiod of 12 h to 13 h of light and temperatures of 24 to 28°C enable natural spawning in red drum (Arnold 1988; Lazo et al. 2010). All three species have high fecundity (>200,000 eggs kg$^{-1}$) and high egg production (0.8-1.0 mm diameter) per spawning (500,000-1,500,000 eggs) (Table 3).

**Table 3.** Relevant technical aspects for the captive reproduction of large yellow croaker, red drum and meagre (LRM)

| Reproduction | Large yellow croaker | Red drum | Meagre |
|---|---|---|---|
| Broodstock (kg) | 1-2 [a] | 8-18 [f] | > 8 (wild) > 6 (breeder) [n] |
| Tank volumen (m$^3$) | 57 [b] | 10-17 [g] | ≥ 50 [n] |
| Tank height (m) | 1.2 [b] | 1.5 [g,f] | > 1 m [n] |
| Density (kg/m$^3$) | 1.5-2 [a] | 11 [h] | ≤ 5 [n], 1-3 [o], 1.7 [p] |
| Sexual ratio (M:F) | 1:2 [b] | 1:1 [g, f ,i] | 1:1.1 [q] |
| Temperature (°C) | 24 [b] | 24-26 [j], 21-28.8 [i] | 15-18.1 [n] |
| Salinity | 24 [c] | 25-27 [i] | 18-40 [p] |
| Oxygen (mg/L$^{-1}$) | > 5 [a] | > 6 [i] | > 5 [o] |
| Feeding | Minced fresh mackerels mixed with complex vitamins and minerals additives,<br>(5% of body mass/day$^{-1}$) [b] | Fish, squid, shrimp and/or pelleted feeds [f]<br>Pelleted feeds 1.1% body weight/day$^{-1}$) [i] | Sardine, squid and pelleted feeds. (1.6% body weight/week$^{-1}$) [n] |
| Reproductive Control | Low doses of hormones [a] | High doses of hormones and natural spawning [k] | Low doses of hormones and some natural spawning [n] |
| Efficient dose of hormone | GnRHa 3-10 μg/kg$^{-1}$ [a] | GnRHa (LHRHa3) 100-160 μg/kg$^{-1}$ + HCG 5 mg/kg$^{-1}$ [k]<br>HCG 500-600 IU/kg$^{-1}$ [l] | GnRHa 15 μg/kg$^{-1}$ [n] |
| Eggs production per spawn | 500,000-1,000,000 [d] | 1,540,000[m], > 1,000,000 [f] | ≈ 1,000,000 [o] |
| Fecundity (eggs/kg$^{-1}$) | 390,000-901,000 [e] | 361,410 [i] | ≈ 200,000 [o] |
| Egg diameter (mm) | 1.0 [c] | 0.80 to 0.98 [j], 0,98 ± 0,04 [f] | 0.99±0.02 [n], 0,83-0,95 [o] |

a Liu 2013; b Yu et al. 2017; c Fang et al. 2003; d Su et al. 2004; e Science and Technology Department of Fujian Province 2004); f FAO 2009; g Lazo et al. 2010; h Gardes et al. 2000; i Lastilla et al. 2015; j Reagan 1985; k Deng 1999; l Jiang 2002; m Wilson and Nieland 1994; n Duncan et al. 2013; o IFAPA 2014; p Pastor et al. 2015; q Mylonas et al. 2013.

### *Egg incubation and larviculture*

Incubation is generally carried out in conical tanks with a volume between 0.4 and 2 m$^3$, using stocking densities of 200 to 1000 eggs L$^{-1}$, depending on the exchange capacity and quality of the water in the tanks. The optimal temperature range is 20 to 28°C, and salinities higher than 20 depending on the species, as detailed in Table 4. Hatching times range from 18 to 56 hours post fertilization (hpf), depending on the temperature. For meagre, fertilization and hatching percentages of 83-99% have been reported, which are the highest among the three species (Table 4).

Hatched larvae have an initial total length between 2.4 and 3.2 mm. According to the conditions of water exchange and the quality of the water, initial larval stocking densities range from 10 to 50 larvae L$^{-1}$ in tanks with volumes from 2 to 50 m$^3$, depending on the objectives of the larval culture (i.e., research, mass production). In China, rectangular concrete tanks, such as 8×4×1.5 m tanks with a water column height of 1.3 m, are commonly used (Ma et al 2005).

Larviculture for all three species is recommended with a photoperiod of LD 12:12 (hours light: dark) and low light intensities of 500 lux in warm waters at approximately 25°C. Salinities should be 25 for large yellow croaker and red drum, and 32-39 for meagre (Table 4). Larvae of all three species open their mouths at 3 days post-hatching (dph) at 25°C, initiating exogenous feeding. A relevant physiological process for proper larval development is the inflation of the swim bladder. During this time, the water surface must be kept clean so that larvae rise and fill their bladders with an air bubble. In meagre, the swim bladder inflation period occurs between 4 and 8 dph at 28°C (Duncan et al. 2013). Larviculture of LRM involves the use of microalgae, rotifers, and brine shrimp. *Chlorella sp*., *Nannochloris occulata* and *Isochrysis galbana* are the most commonly used microalgae in larval culture. In China, the high survival rates of larval cultures of large yellow croaker and red drum are attributed to the use of live copepods captured from the sea, although frozen copepods (30-40 dph) are also used (Mai et al 2005). High larval survival rates are achieved with densities of 5 to 20 rotifers mL$^{-1}$ (3-20 dph), 0.5-4 *Artemia* nauplii mL$^{-1}$ (6-30 dph), and copepods between 9 and 15 dph. Live food can be replaced with microdiets for red drum larvae (Lazo et al. 2000, 2002) (Table 4).

**Table 4.** Relevant zootechnical aspects for the incubation and larviculture of large yellow croaker, red drum and meagre (LRM)

| Incubation | Large yellow croaker | Red drum | Meagre |
|---|---|---|---|
| Tank volumen (m$^3$) | 1 [a] | 0.5-2 [h] | 0.4 [r] |
| Temperature (°C) | 24 [a] | 24-28 [h] | 18-20 [s] |

| | | | |
|---|---|---|---|
| Salinity | 29.0±3.0 [b] | 27 [i] | 37 [r] |
| Density (eggs/L$^{-1}$) | 200-300 [c] | 200-500 [h] | 1.000 [t] |
| Hatching time (h) | 25 [a] | 18-25 [h] | 44-56 [s] |
| Fertilization (%) | 41.4±2.3 [a] | 30-80 [i] | 99.3±1.0 [u] |
| Hatching (%) | 61.5±8.7 [a] | - | > 80 [t] |
| *Larviculture* | | | |
| Tank volumen (m$^3$) | 2 [d], 76.8 [b] | 5-15 [h] | 1.2 [r], 40[w] |
| Large initial LT (mm) | 2.76 [g], 3.2±0.1 [b] | 2.37 [j], 2.2 [h], 2.40±0,33 [i] | 2.82±0.37 [t] |
| Density (larvae/L$^{-1}$) | 10 [e] | 20-30 [i] | ≤ 50 [r,t] |
| Temperature (°C) | 20-24 [e] | 25-30 [h] | 20 a 24 [t], 19-23 [rw] |
| Salinity | 21-25 [e] | 25-30 [h] | 32-39 [t] |
| Luminous intensity | 500 lux [d] | 677±20 pE m$^{-2}$ s$^{-1}$ [k] | 500 lux [v], 1,000-5,000[w] |
| Photoperiod (hL: hD) | 10:14 [d], 12:12 [b] | 12:12 [l] | 12:12 [u], 24-0[w] |
| Mouth opening (dph) | 3 [b] | 3 [i] | 3 [u] |
| Larval nutrition | Constant availability of natural medium copepods [c, f] | Rotifer, copepods, artificial microparticle diets [j] | Microalgae, rotifers, a*rtemia* and microdiets [u,w] |
| Microalgae (cells/mL$^{-1}$) | *Chlorella sp*.: 2-5×10$^6$ [d] | (*Nannochloris occulata, Isochrysis galbana*): 40 000 - 100 000 [h] | (*Nannochloropsis sp., Isochrysis galbana*) 250,000 [u] |
| Microalgae (dph) | 4-15 [e] | - | 2-27[w] |
| Rotifer/mL$^{-1}$ | 5-15 [e], 5-20 [d] | 5-10 [h,i] | 5-10 [u], 2-3[w] |
| Rotifer (dph) | 3-8 [e], 4-6 [d] | 3-10 [h], 3-11 [i] | 3-8[w] |
| Nauplii artemia/mL$^{-1}$ | 1-1.5 [e], 15-20 [d] | 0.5-2 [i,m] | 1-4 [t], 0,04-0,35[w] |
| Nauplii artemia (dph) | 6-11[e], 7-8 [d] | 11-15 [h] | 8-30 [t], 7-30[w] |
| Copepods (dph) | 10-14[e], 9-15 [d] | 21 [n] | 0,01-0,08[w] |
| Microdiets + live food (dph) | 10-14 [e] | 14 [o] | 23-30 [t], 14-30[w] |
| Only microdiets (dph) | > 15 [d, e] | > 15 [h] | > 30 [t], 30-44[w] |
| Growth rate (mm/day$^{-1}$) | 0.7 within 40 dph [c] | 0.73 within 26 dph [p], 0.378 within 40 dph [i] | - |
| Survival rate (%) | 30-40 [c] | 72-75 [q] | 7.7-25.7 [u], 12-41(60 dph) [t] |

a Yu et al. 2017; b Mai et al. 2005; c Liu 2013; d; Chen et al. 2021; e Feng et al. 2017; f Wang et al. 2012; g Su et al. 2004; h FAO 2009; i Lastilla et al. 2015; j Wang and Ji 1996; k Holt 1993; l Lazo et al. 2000; m Gatlin 2002; n Xue and Quan 2002; o Zhang and Jiang 2002; p Lu 2003; q Zhang et al. 2002; r Pastor et al. 2015; s Duncan et al. 2018; t IFAPA 2014; u Duncan et al. 2013; v Vallés and Estévez 2013, w Papadakis et al. 2018.

## Grow-out

Fingerlings are either stocked directly into cages, culture ponds or kept in tanks during a pre-grow-out phase. For example, in red drum, a pre-grow-out phase has been reported, with growth from 3.8 to 49.2 g in 80 days, a specific growth rate (SGR) of 3.32, a feed conversion ratio (FCR) of 1.14-1.40, and a survival rate of 61% (Alo 2008).

The grow-out of these species begins at densities between 20 and 50 juveniles per m$^3$, depending on the quality of the water and initial size. Growth rates vary depending on the species; the highest rates exceed 2 g day$^{-1,}$ while the lowest range from 1.5-2 g day$^{-1}$. The feeding of small trash fish has sustained commercial production in China and other Asian countries but involves consuming large amounts of small fish due to the high FCR (4.2-10) and the high environmental impact of such feeding practices. In contrast, diets based on balanced feed are more efficient (FCR: 0.9-1.9), especially for meagre, which has achieved an FCR close to 1. Both red drum and meagre reach a body weight (BW) of *ca*. 1 kg in the first year of culture, while large yellow croaker BW does not exceed 500 g (Table 5). The growth performance of LRM is adequate at temperatures close to 25°C and with oxygen concentrations greater than 5 mg $L^{-1}$, however, they show large differences in salinity preferences: meagre requires high salinity, large yellow croaker needs intermediate values, while red drum tolerates a wide range of salinities (Table 5). Survival rates may vary depending on culture conditions. For example, meagre cultured in adequate water quality at appropriate densities and with a diet based on high-quality commercial feed achieves survival rates close to 90% (Table 5).

**Table 5**. Relevant zootechnical aspects for the grow out of large yellow croaker, red drum and meagre (LRM)

| Culture | Large yellow croaker | Red drum | Meagre |
|---|---|---|---|
| Density juvenile (fish/$m^3$) | 20-40 [a] | - | 50 [k] |
| Type of food | Trash fish 90%, pellets 10% [b] | Trash fish and pellets [f,g] | Pellets 100% [m, l] |
| Growth rate (g/$day^{-1}$) | 1.46-1.97 [c] | - | 2.74 [n] |
| FCR (trash fishes) | Small trash fishes: 5-10 [d] | 5.7 [f], 4.2 [g] | not apply |
| FCR (compound diets) | 1.4-1.9 [b] | 1.6-1.8 [h] | 0.9-1.2 [n] |
| Average weight $year^{-1}$ (g) | 268 [e] | 500-1,000 [i] | 1,100 [n] |
| Temperature (°C) | 20-28 [e], 15-25 [c] | 18-25 [j] | 14-26 [n] |
| Salinity | 24.5-30 [e] | Fresh-brackish-sea waters [j] | 33-35 [n] |
| Oxygen (mg/$L^{-1}$) | > 5 [c] | > 4 [f] | 6.8±0.4 [k] |
| Survival rate (%) | 60.8-80.1 [e] | 67 [h] | ≥90 [n] |

a Science and Technology Department of Fujian Province, 2004; b Liu and De Mitcheson 2008; c Cai et al. 2016; d Hu 2015; e Liu 2013; f Shen 2009; g Zhang et al. 2002; h Houel et al. 1996; i Lu 2003; j Tang 2000; k Ghozlan et al. 2018; l Chatzifotis et al. 2010; m Chatzifotis et al. 2012; n Duncan et al. 2013.

### *Production costs*

Feeding represents the highest percentage of production costs, as with other species of marine fish. For these three species, the costs of feed are estimated to exceed 52% on average. Large yellow croaker has the highest feeding cost, possibly influenced by the use of large quantities of fish and crustaceans, which increase the feed conversion factor (FCR = 5-10). The costs of this feeding strategy are increasing since food is scarce and a regular supply is not guaranteed (Liu and De Michelson 2008). Consequently, Chinese researchers aim to develop balanced feeds for production purposes (Duan et al. 2001; Mu et al. 2018; Li et al. 2021). In contrast, large yellow croaker shows low labor and fingerling production costs, attributed to the use of artisanal farming methodologies where labor is less qualified and less expensive. The low production costs of fingerling can be attributed to the high survival rate (30-40%) and the use of microalgae farming methodologies based on feeding copepods from the natural environment, avoiding the high costs of using *Artemia* nauplii (Table 6).

Red drum farming in China has 23.3% higher production costs for fingerlings than in the USA, although feed costs are 23.6% lower. This indicates that production costs vary according to the culture methodologies and labor costs in each region. The production costs of red drum in the EU and meagre are similar, possibly due to the use of technologies with typical Western characteristics (Table 6).

**Table 6**. Large yellow croaker, red drum and meagre (LRM) production costs

| Production costs | Large yellow croaker | Red drum | Meagre |
|---|---|---|---|
| Feeding costs % | 74-84 [a] | 31.9 [b], 55.5 [c] | 41 [d] |
| Processing cost % | - | - | 18 [d] |
| Labour cost % | 7-12 [a] | 19.1 [b], 14,3 [c] | 13 [d] |
| Fingerling cost % | 4-12 [a] | 42.6 [b], 19.3 [c] | 21 [d] |
| Other expenses % | 2-7 [a] | 6.4 [b], 10.9 [c] | 8 [d] |

a Chen et al. 2018; b Zhang et al. 2002; c FAO 2009; d Duncan et al. 2013.

## Success factors and industry bottlenecks of LRM

The success factors summarized in Table 7 highlight the biological attributes of these species that support their good adaptation, proper development, and fast growth in captivity, however, research and development strategies are required to generate and adapt farming technologies for a particular species of interest. The following success factors have been promoted by researchers and producers: i) *Control of reproduction*, which has been achieved with the development of environmental manipulation for the spontaneous spawning of red drum and hormone-based spawning induction protocols for all three species (Arnold et al. 1977; Gardes et al. 2000; Liu and De Mitcheson 2008; Duncan et al. 2012; Mylonas et al. 2013; Fernandez-Palacios et al. 2014; Soares et al. 2015; Yu et al. 2017). Controlling reproduction has enabled the production of high-quality eggs in the quantities required for aquaculture production. ii) *High survival rates in larval and fingerling culture*: The optimization of zootechnical management and the formulation of adequate diets have led to successful larval culture and juvenile production. For example, the Chinese strategy of using harvested marine copepods for feeding large yellow croaker and red drum larvae has proven efficient. In 2000, the value of copepod production in China exceeded US$16.7 million (Chen et al. 2018). For meagre, optimizing culture husbandry and nutrition of larvae and juveniles through scientific research has been successful (Papadakis et al. 2009, 2013, 2018; Cardeira et al. 2012; Vallés et al. 2015; Vallés and Estévez 2015, Solovyev et al. 2016; Campoverde et al. 2017; Campoverde and Estévez 2017). iii) *Adaptation of consolidated technologies from other species*: In China, knowledge from the production of other marine fish species (i.e., snappers, groupers, etc.) has been adapted to the production of large yellow croaker and red drum (Chen et al. 2018). For meagre, farming technology has been derived from the production of two major Mediterranean marine species, gilthead sea bream and european sea bass (Duncan et al. 2013). For example, larval, juvenile and grow-out cultures of meagre use similar feed and facilities as those for sea bream and sea bass (N. Duncan pers. comm. 2021). This strategy provides an initial basis for technological development and is a strategy that must be applied to emerging species, especially in regions where marine fish farming is incipient, as is the case in Latin America.

**Table 7.** Main success factors in the aquaculture of large yellow croaker, red drum and meagre (LRM)

| Success factors | L. yellow croaker | Red drum | Meagre |
|---|---|---|---|
| Broodstock mature at young age/size | X [a] | - | - |
| High fecundity and multiple spawns per female | X [a] | X [f] | X [q] |
| Controlled reproduction with hormones | X [a] | X [g] | X [q] |
| Natural spawning | - | X [h] | X [r] |
| Controlled larval cultures with high survival rates | X [b] | X [i] | X [q] |
| Constant availability of natural copepods for larval feeding | X [b] | X [j] | - |
| Good growth in the first year of culture | - | X [k] | X [q] |
| Acceptable feed conversion factor | X [c] | X [c] | X [q] |
| Species with capacity for high density cultivation | X [b] | X [l] | X [q] |
| Disease resistance | - | X [n,m] | X [q] |
| Ability to be cultivated in wide ranges of salinity and temperature | X [d,e] | X [o] | X [q] |
| Can be grown in fresh water | - | X [o,p] | - |
| Successful adaptation of culture technologies from other species | X [b] | X [m] | X [q] |
| Adaptive capacity in habitats of different oceans | - | X [m,f] | - |
| High economic profitability | X [b,a] | X [c] | X [q] |
| Promotion and support of local and regional governments | X [b,a] | - | X [q] |
| Scale of production with high employment generation | X [b,a] | - | - |

a Liu and De Mitcheson 2008; b Chen et al. 2018; c W. Hong pers. comm. 2021; d Liu 2013; e Li et al. 2012; f Wilson and Nieland 1994; g Arnold et al. 1977; h Montie et al. 2016; i Lee and Ostrowski 2001; j Hong and Zhang 2003; k Lu 2003; l Editorial Board of Ocean and Fisheries and *Sciaenops ocellatus* 2015; m Zhao et al. 2006; n Sandifer et al. 1993; o Gullian Klanian et al. 2018; p Watson et al. 2014; q Duncan et al. 2013; r Soares et al. 2015.

## Major bottlenecks in the management of the industry

The development of Sciaenidae culture has faced several challenges. One of the most recognized problems has been the massive and disorderly growth of the large yellow croaker industry in China, which has used more than 60% of frozen low-value fish as food since 1990. Frequently, food is stored in inappropriate conditions, resulting in 60% wasted food. These practices contribute to the spread of diseases and an uncontrolled fishery, negatively impacting the environment, lowering supply, increasing prices, and affecting production profitability (Liu and De Mitcheson 2008; Chen et al. 2018). Additionally, inadequate marine spatial planning has led to cage overcrowding in reduced coastal areas causing water eutrophication, infections by nearly 20 diseases, decreased production efficiency, and reduced product quality and safety (Chen et al. 2008).

Another problem is the introduction of the red drum in China. After two decades of cultivation, it has become the most widespread non-native species in the country, and it is common to capture juveniles and mature adults in estuaries and coastal waters of the Bohai Sea, the Yellow Sea, the East China Sea, both sides of the Taiwan Strait, the northern South China Sea and Beibu Bay (Liao et al. 2010; Lin et al. 2020). This predatory species is considered to greatly affect the environment, though its full impact is unknown (Lin 2020).

Additionally, the selection of broodstock for industry development poses a challenge. The high fecundity of breeders enables small numbers of breeders to produce the high numbers of juveniles required for industrial aquaculture, however, a larger number of breeders are necessary to maintain a genetic diversity, avoid inbreeding, and provide a basis for genetic improvement. In China, the formation of F1 broodstock adapted to captivity has facilitated a constant supply of viable eggs in large yellow croaker (Chen et al. 2018). Most farmed croakers originated from a single spawn (i.e., the Guanjingyang and Min-Yuedong stocks) and from hatcheries in Fujian Province, which resulted in a large loss of genetic diversity due to a limited number of broodfish and the retention of lines through several generations. This situation resulted in a decrease in meat quality and growth performance (Liu and De Mitcheson 2008). A similar problem has been detected in meagre broodstocks since they were acquired from a limited number of sources (Duncan et al. 2018). In both cases, research efforts have been made to enrich the genetic diversity of the initial batches from which culture began (Duncan et al. 2013; Yu et al. 2017; Ramos-Júdez et al. 2019; Chen et al. 2020). In Europe, producers have addressed this problem by setting up breeding programs with an adequate genetic base.

## Status of technology in Sciaenid aquaculture in Latin America.

Latin America and the Caribbean hold a prominent position in the global production of aquatic species, with Chile, Brazil, and Ecuador contributing 77% of the regional production. Marine fish farming is still in its early stages, except for Atlantic salmon farming in Chile, which accounts for 27% of the total aquaculture production in the region (Souto Cavalli et al. 2021). Latin America has high potential for the development of marine aquaculture (Gentry et al. 2017). Efforts have focused on producing fast-growing native species such as spotted rose snapper (*Lutjanus guttatus*), longfin yellowtail (*Seriola rivolina*), yellowtail amberjack (*Seriola lalandi*), and eleven species of the Sciaenidae family (Cárdenas, 2012; Dettleff et al. 2020; Ibarra-Castro et al. 2020; Reinoso et al. 2020; Chacón-Guzmán et al. 2021).

In this review, eleven species of the Sciaenidae family, identified as potential for aquaculture in seven countries, are highlighted. Among them, two species are from the Atlantic Ocean and nine from the Pacific Ocean (Figure 2).

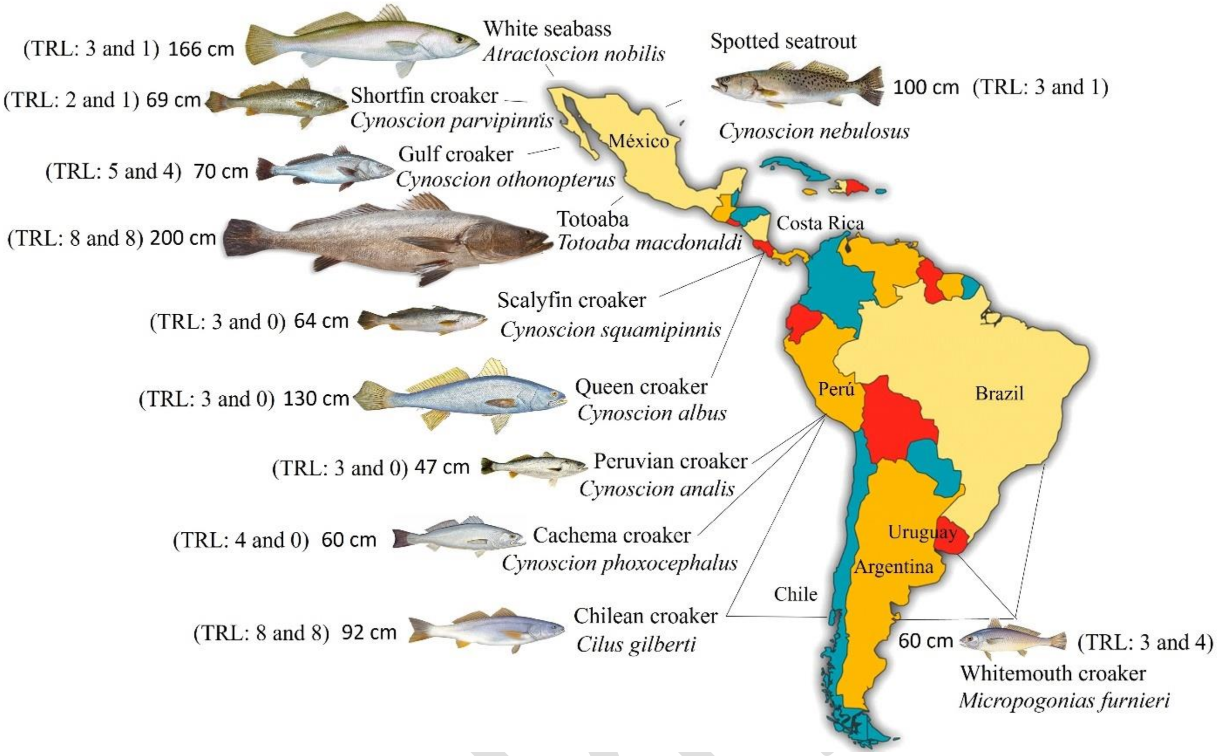


**Figure 2.** Species of the Sciaenidae family investigated and/or cultivated in Latin American countries during recent decades (1990s – 2010s). The maximum reported length is indicated (cm) with the present TRL for fingerling production and grow-out (TRL are explained in Table 9.

Seven of these emerging / new Sciaenid aquaculture species inhabit subtropical regions, while four inhabit tropical zones (Table 8). These species share many similarities with the Sciaenidae species with the highest global production (LRM). They are demersal benthopelagics, moving near the bottom over the benthos, and oceanodromous, migrating from open waters to coastal areas such as estuaries and river mouths depending on the time of the year (Riede 2004; Froese and Pauly 2022). Predominantly coastal, they inhabit estuaries, coastal lagoons, river mouths, and deltas on sandy, muddy, and rocky bottoms.

These species can reach depths of 122 m but tend to inhabit depths less than 100 m (Table 8).

The eleven Latin America Sciaenidae species tolerating a wide range of salinities, and most adapt physiologically and metabolically well to salinities between 1.9 and 11, and to high salinities between 32 and 49.8 (Table 8). They are also eurythermal, inhabiting waters with temperatures between 9 and 29.1°C, depending on the species (Table 8). Similar to species with the highest worldwide production, these characteristics show potential for culturing these species in different marine and coastal environments using different types of cages and ponds.

The eleven Latin America Sciaenidae are iteroparous and gonochoric with asynchronous development (Froese and Pauly 2022). The subtropical species spawn primarily in spring and summer, while the tropical species spawn year-round, generally with two annual spawning peaks, one in the rainy season and another in the dry season (Table 8). These captive breeding and reproductive characteristics shared with LRM enable them to have multiple reproductive cycles during their lifetime, making them suitable for domestication and intensive farming. The species reach first sexual maturity at ages between 2 and 9 years, with an average of approximately 4.5 years. They are carnivorous, predominantly consuming crustaceans and fish (Table 8). Overall, the eleven Latin America Sciaenidae species have biological traits similar to those of other Sciaenid species that are successfully produced worldwide and offer similar high potential for aquaculture development.

**Table 8.** Relevant aspects of the biology of the eleven species of the Sciaenidae family produced and/or investigated in Latin America.

| | Totoaba | Chilean croaker | White seabass | Gulf croaker | Shortfin croaker | Spotted seatrout | Scalyfin croaker | Queen croaker | Peruvian croaker | Cachema croaker | Whitemouth croaker |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distribution | 32°N-17°N[a] | 6°S-37°S 80°W-70°W[a] | 65°N - 22°N[a] | 32°N - 25°N[a] | 34°N - 21°N, 118°W-108°W[a] | 42°N - 15°N, 83°W-70°W[a] | 31°N [a] | 17°N-2°S[a] | 3°S - 8°S, 82°W-8°W[a] | 18°N[a] | 27°N - 36°S, 84°W-34°W[a] |
| Ecology | Subtropical[a] | Tropical[a] | Subtropical[a] | Subtropical[a] | Subtropical[v] | Subtropical[a] | Tropical[a] | Tropical[a] | Subtropical[a] | Tropical[a] | Subtropical[a] |
| Habitat | Coastal waters. In river mouths near rocky coasts[b] | Estuaries, breakers, sandy beaches[i] | Rocky bottom, kelp beds, bays, along sandy beaches[m] | Coastal waters, near river mouths[b] | Shallow inshore sandy areas[b] | Estuaries, coastal waters, sand bottoms, seagrass beds[y] | Coastal waters, along shores and in estuaries[b] | Coastal waters; estuaries, river mouths, shallow bays[b] | Coastal waters, estuaries and shallow bays[b] | Coastal waters and estuaries[b] | Muddy and sandy bottoms in coastal waters and in estuaries[kk] |
| Max. depth (m) | ~70[c] | 40[i] | 122[m] | - | - | - | - | - | - | 60 [a] | - |
| Salinity | 11-40[d] | - | - | 5-35[r] | 2-35[w] | 1.9-49.8[z]<br>0.2-75[aa] | - | - | - | - | - |
| Temperature (°C) | 19.8 - 26.7[a]<br>17-26[c] | 12.1 - 17.1[a] | 9 - 22.9[a] | - | 17.6 - 24.4[x] | 12 - 26.7[x] | 19.9 - 28.4[x] | - | 17.7 - 20.5[x] | 23.4 - 29.1[x] | 16.5 – 28[x] |
| Max. weight (kg) | 135[e] | - | 41[n] | 2.4[s] | 3.2[s] | 7.9[s] | - | - | - | - | - |
| Max. length (cm) | 200[e] | 92[j], 100[k] | 150[n] | 100[t] | 69[s] | 100[s] | 64[b] | 130[ff] | 47[cc] | 60[b] | 60[ll], 74[mm] |
| Max. age (years) | 30[e] | 26[k] | 30[n] | 8[t] | - | 18[bb] | - | - | - | - | 39[ii] |
| First maturity years) | 6 (♂) 7 (F)[f] | 8-9[k] | 3-4[n] | 2 (♂) 2.3 (♀)[t] | - | 1 (♀)[cc] | - | 5[gg] | - | 3-4[ii] | - |
| First maturity (cm) | 120 (♂)[g]<br>130 (♀)[c] | 54.83[i] | 51 (♂)<br>61 (♀)[o] | 26 (♂) 29 (♀)[t] | - | 20 (♂) 25 (♀)[cc] | 29-33[dd] | 55[ee,gg] | 20.2[hh] | 32.7[ee], 33.7[ii] | 33[oo] |
| Breeding weather season | Late winter, early spring[h] | Spring-summer[i] | Spring-summer[p] | Spring[p] | - | Spring-summer[cc] | All year[ee] | All year[ee] | - | All year[ee] | Spring-summer[ii] |
| Natural food habits | Crabs, fish, amphipods, shrimp[f] | Fishes invertebrates[l] | Fishes, squids, crayfish[q] | Crustaceans, mollusks, fishes[u] | Mainly on small fishes[b] | Mainly on crustaceans, fishes[y] | Fishes, shrimps, crustaceans[b] | Shrimps, fishes, cephalopods[b] | Shrimps, fishes[b] | Crustaceans, fishes, mollusks[jj] | Crustaceans, mollusks, fish[kk] |

a Froese and Pauly 2022; b Chao 1995; c Hernández-Tlapale et al. 2020; d Ortíz-Viveros 1999; e Berdegué 1955; f Cisneros-Mata et al. 1995; g Molina-Valdéz et al. 1988; h Hernández-Aguilar et al. 2018; i Calbún and Orlando 2017; j Valle et al. 2020; k Aburto 2005; l Fernández and Oyarzun 2001; m Eschmeyer et al. 1983; n Drawbridge et al. 2021; o Vojkovich and Crooke 2001; p Moser et al. 1983; q Hart 1973; r Perez-Velazquez et al. 2014; s IGFA 2001; t Gherard et al. 2013; u Román-Rodríguez 2000; v Ocean Biogeographic Information System 2006; w González-Félix et al. 2017; x Kaschner et al. 2016; y Frimodt 1995; z Banks et al. 1991; aa Simmons 1957; bb Hugg 1996; cc Nieland et al. 2002; dd Vásquez-Arias 1999; ee Alpízar and Rodríguez 2019; ff Jiménez Prado and Béarez 2004; gg Lai et al. 1992; hh Samamé 1971; ii Carozza et al. 1997; jj Cabrera-Alvarado 2017; kk Isaac 1988; ll Nakamura 1986; mm Haimovici 1997; oo Macchi 1997.

To determine the technological progress of aquaculture for species in the Sciaenidae family in Latin America, a literature review was conducted, and professionals with experience in each species and country were consulted to establish the level of technological maturity of each species. For this purpose, the technology readiness level (TRL) methodology was used (Straub 2015; Beims et al. 2019) (Table 9). The technology readiness level constitute a measurement system that assesses the maturity level of a technology, facilitating its transition to product development and comparing its maturity with other technologies (Graettinger et al. 2002).

For the analysis of each TRL, examples of technological advancements in aquaculture were assigned to carry out the classification:

TRL 1. Collection of scientific information on the species to estimate the idea of its aquaculture potential.

TRL 2. Transfer from ideas to demonstration of good aquaculture potential.

TRL 3. Experiments on reproduction, larval culture, etc., that provide initial data of performance in captivity completed.

TRL 4. Experimental tests of juvenile production and small-scale growth in floating cages developed on a research or laboratory scale.

TRL 5. Pilot tests of juvenile production and medium-scale culture in cages developed.

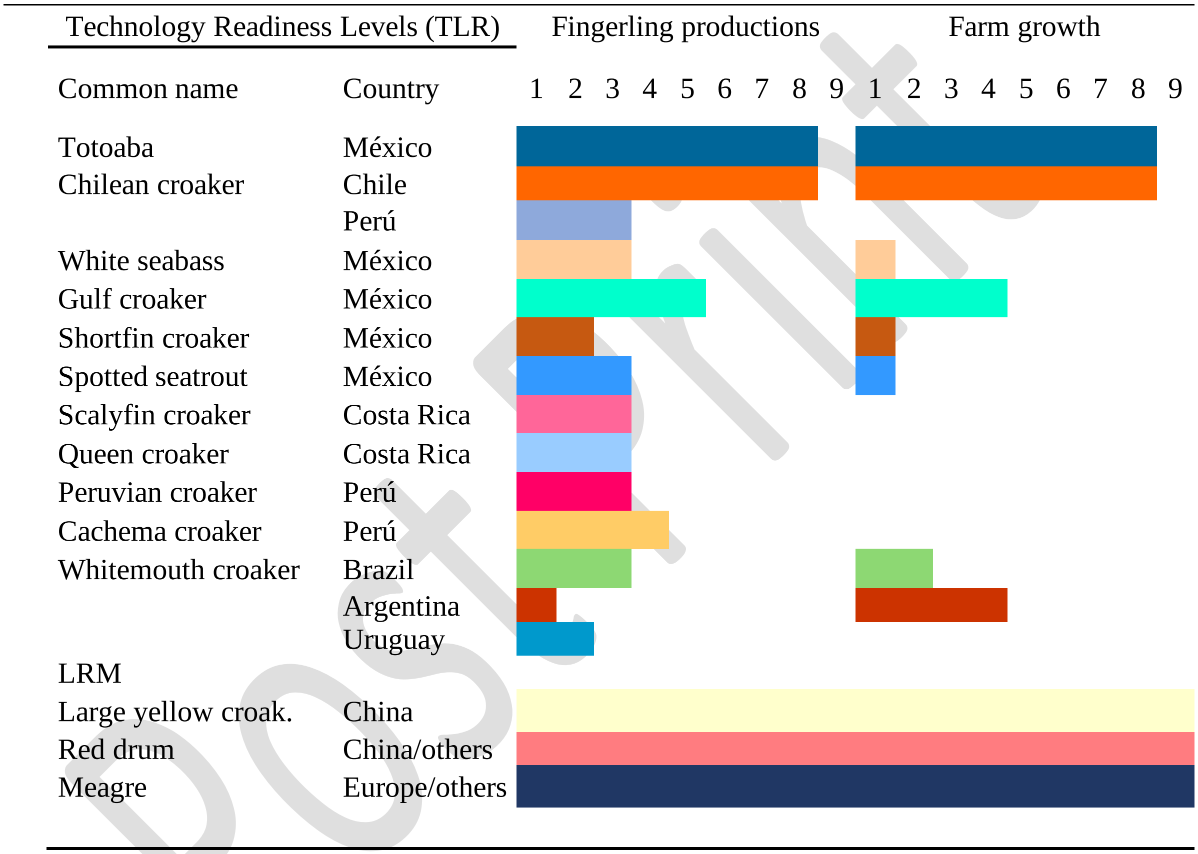
TRL 6. Pilot tests or prototype systems for the mass production of juveniles and pilot harvests generally carried out on large-scale marine farms with private capital.

TRL 7. First commercial productions of juveniles to supply the private farming industry in an operational or industrial environment.

TRL 8. Constant production of juveniles supplies the market and is of good quality. First harvests are produced on a commercial scale, and the product is successfully placed in different markets.

TRL 9. Increased production of juveniles in quality and quantity, with grow-out production expanding geographically. The industry consolidates is robust to negative pressures and there is competition between different companies.

**Table 9** Levels of technological development of emerging species of the family Sciaenidae grown in Latin America. Qualification carried out by means of the adaptation of the Technology Readiness Levels (TRL) (Graettinger et al. 2002), to the processes of research and development (RandD) in production of juveniles in laboratory and cultivation in marine farms.



| Technology Readiness Levels (TLR) | | Fingerling productions | | | | | | | | | Farm growth | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Common name | Country | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Totoaba | México | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| Chilean croaker | Chile | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |
| | Perú | ■ | ■ | ■ | | | | | | | | | | | | | | | |
| White seabass | México | ■ | ■ | ■ | | | | | | | ■ | | | | | | | | |
| Gulf croaker | México | ■ | ■ | ■ | ■ | ■ | | | | | ■ | ■ | ■ | ■ | | | | | |
| Shortfin croaker | México | ■ | ■ | | | | | | | | ■ | | | | | | | | |
| Spotted seatrout | México | ■ | ■ | ■ | | | | | | | ■ | | | | | | | | |
| Scalyfin croaker | Costa Rica | ■ | ■ | ■ | | | | | | | | | | | | | | | |
| Queen croaker | Costa Rica | ■ | ■ | ■ | | | | | | | | | | | | | | | |
| Peruvian croaker | Perú | ■ | ■ | ■ | | | | | | | | | | | | | | | |
| Cachema croaker | Perú | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | |
| Whitemouth croaker | Brazil | ■ | ■ | ■ | | | | | | | ■ | ■ | | | | | | | |
| | Argentina | ■ | | | | | | | | | ■ | ■ | ■ | ■ | | | | | |
| | Uruguay | ■ | ■ | | | | | | | | | | | | | | | | |
| LRM | | | | | | | | | | | | | | | | | | | |
| Large yellow croak. | China | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Red drum | China/others | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Meagre | Europe/others | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

Among the eleven Sciaenid species produced and/or investigated in Latin America, two species, the totoaba in Mexico and the Chilean croaker in Chile, have made the greatest progress in research and development during recent years (Table 8). The totoaba, unlike other Sciaenid species, is highly valued for its swim bladder. In Hong Kong, the prices for 100 g and 500 g of dried totoaba swim bladder may reach between US$2,600 and US$25,000 per unit, respectively. In the Sea of Cortez (Mexico), fishermen are paid between US$3,000 and

US$5,000 per fresh kilogram of swim bladder, leading to considerable poaching and illegal trading (Juarez et al. 2016). Reproduction in captivity has been controlled by means of hormonal induction (100 µg $kg^{-1}$ GnRHa) (True 2012). Larval culture has been progressively controlled, with high survival rates, and juveniles grow rapidly, reaching 2.5 kg in one year and 6 kg in two years. The average FCR is 2.5, and the average weight gain is *ca*. 7.5 g $day^{-1}$ (Juarez et al. 2016). The culture technology for totoaba has been demonstrated on a commercial scale (TRL 8).

In the case of the Chilean croaker, research and development in juvenile production and farming in floating cages have evolved since the early 2000s (Pavéz-Miqueles 2018; Álvarez et al. 2020), with an annual production of 12 tonnes in 2020 (FAO 2023). The culture technology for this species has been demonstrated on a commercial scale for grow-out (TRL 8), and consolidated commercial production is expected in the coming years. Most research on this species in Chile remains unpublished. In Peru, studies on adaptation to captivity, growth at different densities, and diet development indicate an interest in diversifying aquaculture with this species, though this research is in the initial stages with juvenile production (Méndez-Ancca et al. 2017; Espinoza Ramos 2018).

The other Sciaenid species considered for aquaculture in Latin America have TRL of 1 to 5, indicating that initial research to test ideas and concepts has been successful and that proof of concept and validation is being undertaken (Table 3). These species can be divided into two groups: those researched since the 1990s or early 2000s such as gulf croaker (*Cynoscion othonopterus*), shortfin croaker (*Cynoscion parvipinnis*), white seabass (*Atractoscion nobilis*) and whitemouth croaker (*Micropogonias furnieri*), but not yet reaching the technological development of totoaba and Chilean croaker, and those researched in the last decade, such as spotted seatrout (*Cynoscion nebulosus*), scalyfin croaker (*Cynoscion *squamipinnis*), queen croaker (*Cynoscion albus*), Peruvian croaker (*Cynoscion analis*), and cachema croaker (*Cynoscion phoxocephalus*).

In the first group, research on gulf croaker and shortfin croaker was directed toward improving nutritional aspects and reproductive biology, and determining the euryhaline capacity of the species (Contreras Olguín 1994; Perez-Velazquez et al. 2013; González-Félix et al. 2015, 2016, 2017; Minjarez-Osorio et al. 2016). In both species, there has been successful production of juveniles at the experimental scale, but further improvements are required in larval feeding and nutrition, egg production, spawning control with environmental variables and hormones, and balanced feed formulation for weaning, pre-grow-out, and maturation (Pérez et al. 2013). In the case of the white seabass, culture technology was developed at the Hubbs-Sea World Research Institute (San Diego, California, USA), where since 1983, juveniles (up to 80 g) have been produced for restocking (Drawbridge and Kent 2001). Collaborative research with North American centers near the USA-Mexican border has focused on nutrition (López et al. 2006, 2009, 2016; Durazo et al. 2010; Galaviz et al. 2011). The technology has not been adapted for mass juvenile production and grow-out in Mexico. Regarding the whitemouth croaker, even though research on this species dates from the early 1990s (Aristizabal et al. 1992), no major advances have been achieved in its culture and domestication. Research has mainly occurred in Argentina, Uruguay, and Brazil, focusing on experimental spawning, larval development, and experimental culture of juveniles in cages (Berois et al. 2004; García-Alonso and Vizziano 2005; Queiroz Albuquerque et al. 2009; Sampaio et al. 2011).

In the second group, research has aimed to establish technological bases for reproduction control and larval culture. This includes studies on spotted seatrout in Mexico (Ibarra-Castro et al. 2015), scalyfin croaker, and queen croaker in Costa Rica (Boza-Abarca et al. 2016), and Peruvian croaker and cachema croaker in Peru (Palacios et al. 2015; Espinales et al. 2018; Zapata and Vieyra 2018). Continued interest in these species suggests that technological improvements in juvenile production are likely in the coming years.

## Conclusion

This review confirms that the Sciaenidae family comprises some of the marine fish species with the highest aquaculture growth and potential in the world. Sciaenidae species possess biological attributes compatible with aquaculture production, suggesting that the industry will continue to expand as new species are incorporated. The success of the species of the most productive species is multifaceted, relying not only on biological factors but also on cultural, technical, management, and market factors. Sciaenidae species adapt well to different environments, exhibit high fertility, and reproductive dysfunctions have been controlled; adaptation to captivity can lead to spontaneous spawning, especially in generations reared in captivity.

Larval culture is considered viable as the larvae are hardy, exhibit high growth and survival rates, and can be fed on artemia, copepods, and inert feeds. Most species present high growth rates and acceptable feed conversion factors under intensive farming conditions. The industry has been promoted by a market that adequately pays for the product. Aquaculture development has been supported by governments and the academic sector, which integrate development with financial support programs and applied research, respectively.

Latin America has emerged as a region with significant potential for Sciaenidae aquaculture. The eleven species investigated and/or produced have biological attributes similar to those of the Sciaenidae species with the highest worldwide aquaculture production. Studies have revealed similarities in captive adaptation for controlled reproduction, juvenile production, and nutrition, indicating why these species in Latin America can emerge as viable aquaculture species. Technological development in the region is led by the totoaba and Chilean croaker. Other species studied in Latin America are either in the initial stages of research and development or have not shown significant technological advancement beyond initial studies. The technology developed so far in the Sciaenidae family, along with the experiences of major industries identified in this review, should be considered strategic tools to promote the research and development of emerging species in this family.

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