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Review article

Current status of carangid aquaculture and way forward

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Abstract

Importance of the work: Interest in marine fin-fish aquaculture has grown in recent decades in response to the rising demand for seafood.

Objectives: To provide information and knowledge regarding aquaculture of carangid fishes and synthesize common features, followed by recommendations for development of aquaculture.

Materials & Methods: The main literature sources used in this review were from SCOPUS and Google Scholar. Production data were from the Food and Agriculture Organization of the United Nations. All information and data gathered were analyzed and synthesized.

Results: Of the 148 carangid fish species, 13 contribute a substantial proportion of global aquaculture production. The two most valuable species are pompano (*Trachinotus ovatus*), mainly produced by China and Japanese amberjack or yellowtail (*Seriola quinqueradiata*), mainly produced by Japan. This review provided an overview of aquacultural practices for each species and revealed that the following characteristics are common to carangid aquaculture: culture was first established using wild fingerlings; the success of hatchery production of fingerlings requires lengthy rearing of broodstock; availability of commercial artificial feed is another key success factor; diseases and parasites can be devastating and very difficult to control; and market constraints can have major adverse impacts.

Main finding: The following recommendations were made: 1) development of fry production technology is a priority; 2) stocks should be genetically improved to cope with diseases and parasites; 3) cost-effective and environmental-friendly artificial diets should be developed; 4) cost-effective, land-based recirculating aquaculture systems should replace sea-cage and pen culture; and 5) new species, such as bluefin trevally, should be developed for aquaculture to diversify production.

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Introduction

Environmental deterioration, over-exploitation and climate change are major causes of the decline of capture fishery production relative to aquaculture; for example, between 2011 and 2020, the proportion of capture fishery production fell from 53% to 42% of total fisheries production (Food and Agricultural Organization, 2022). This has triggered the enormous expansion and development of aquaculture. However, aquaculture, especially inland aquaculture, also faces severe limitations; available land and water supplies have declined, mostly because of population growth, while global warming is gradually enhancing the intrusion of sea water into coastal areas (Sherif and Singh, 1999). As inland aquaculture seems to be reaching its limit, mariculture holds promise for further expansion, with production in 2050 forecast to be 36–74% higher than current yields (Costello et al., 2020). Among the important species used in marine fin-fish culture, substantial production comes from members of the family Carangidae, such as pompano (*Trachinotus* spp.) and yellowtail (*Seriola quinqueradiata*).

The Carangidae is the largest family in the Order Carangiformes, with 30 genera and 148 species, known as jacks, pompanos, jack mackerels, runners, and scads (Froese and Pauly, 2023). Most carangid fish inhabit marine habitats of the tropical, subtropical and temperate zones in the Atlantic, Indian and Pacific Oceans, with a few species living in brackish water environments (Froese and Pauly, 2023). Recent fishery statistics revealed a contribution of approximately 0.56% from cultured carangid fishes to the global fin-fish aquaculture production (Food and Agricultural Organization, 2022).

Aquaculture of carangid fishes was first established in Japan, with the first recorded production in 1950 being 40 t of yellowtail; by 2020, production of this species had increased to 137,100 t (Food and Agricultural Organization, 2022). Japanese jack mackerel (*Trachurus japonicus*) was the second species to be commercially cultured, starting in 1971; production peaked at 7,161 t in 1992 and gradually decreased to 600 t in 2020 (Food and Agricultural Organization, 2022), as shown in Table 1. Over the past decade, the increase in global production of carangid fish species has been about 45% from 277,005 t in 2011 to 329,097 t in 2020 (Food and Agricultural Organization, 2022). However, there are still many species in this family that warrant research and development as potential candidates for aquaculture. Therefore, this article aimed to compile information on carangid aquaculture species and systems and to identify their common features. The review also considered some recommendations for future research and development, which may help guide the expansion of culture of existing carangids to new areas, as well as the development of new aquaculture species.

Important carangid species contributing to aquaculture production

Currently, according to the Food and Agricultural Organization (FAO) statistics, there are at least 13 carangid species of 6 genera (*Caranx*, *Gnathanodon, Pseudocaranx, Seriola, Trachinotus* and *Trachurus*) having commercial culture importance (Food and Agricultural Organization, 2022). A detailed list of these species and their annual production is presented in Table 1. Pompano (*Trachinotus ovatus*) represents the highest quantity, followed by yellowtail. However, the identity of the species cultured in China is still ambiguous, as generally, the primary carangid species cultured in China is called pompano (Food and Agricultural Organization, 2022) or golden pompano (Cai et al., 2016; Guo et al., 2018; Yu et al., 2018). Officially, and according to most scholars in China, both names refer to *T. ovatus*; however, in recent years, some authors have argued that the species may in fact be *Trachinotus anak* (Fan et al., 2021), also citing cytochrome c oxidase I (COI) sequences (Smith-Vaniz and Walsh, 2019). Since the specific production cannot be verified, this article refers to the Chinese-cultured pompano collectively as *Trachinotus*. In addition, for references to *T. ovatus* from cited works related to Chinese aquaculture and production, it will appear herein as *T. ovatus**. In terms of producers, China is the leader, with an annual production of more than 180,000 t in 2020, comprising pompano (*Trachinotus*), amberjack (*Seriola* spp.) and snubnose pompano (*Trachinotus blochii*), as shown in Table 2. Japan has the second largest carangid fish production, reporting 137,000 t in 2020 (Food and Agricultural Organization, 2022), with the production mainly from yellowtail (99%). The other two countries or regions that contribute more than 1,000 t/yr are Malaysia and Taiwan (Food and Agricultural Organization, 2022). However, it should be noted that some producer countries (Australia and New Zealand) do not appear in the current FAO records (Chambers and Ernst, 2005; Loew, 2021).

Table 1 Aquaculture production data of important carangid fish species in 2019 and 2020 (Food and Agricultural Organization, 2022), excluding Australia and New Zealand

Common name	Scientific name	Production (t)	
		2019	2020
Pompano	*Trachinotus ovatus* (Linnaeus, 1758)*	155,000	160,000
Yellowtail, Japanese amberjack	*Seriola quinqueradiata* Temminck & Schlegel, 1845	136,367	137,100
Amberjacks	*Seriola* spp.	32,445	22,940
White trevally, Striped jack	*Pseudocaranx dentex* (Bloch & Schneider, 1801)	4,409	4,000
Snubnose pompano	*Trachinotus blochii* (Lacepède, 1801)	3,918	3,298
Japanese jack mackerel	*Trachurus japonicus* (Temminck & Schlegel, 1844)	839	600
Florida pompano	*Trachinotus carolinus* (Linnaeus, 1766)	613	18
Jacks, Crevalles	*Caranx* spp.	506	559
Yellowtail amberjack	*Seriola lalandi* Valenciennes, 1833	477	435
Greater amberjack	*Seriola dumerili* (Risso, 1810)	38	65
Golden trevally	*Gnathanodon speciosus* (Forsskål, 1775)	3	5
Giant trevally	*Caranx ignobilis* (Forsskål, 1775)	0.55	4.25
Jack and horse mackerels nei		< 0.5	69
Crevalle jack	*Caranx hippos* (Linnaeus, 1766)	< 0.5	< 0.5
Bigeye trevally	*Caranx sexfasciatus* Quoy & Gaimard, 1825	< 0.5	< 0.5
Malabar trevally	*Carangoides malabaricus* (Bloch & Schneider, 1801)	< 0.5	< 0.5
Total		334,618	329,097

* Food and Agricultural Organization defines "pompano" as *Trachinotus ovatus*, but Fan et al. (2021) indicated that the species produced by China may be *T. anak*.

Table 2 Aquaculture production data of important carangid fish species in 2019 and 2020, by country (Food and Agricultural Organization, 2022), excluding Australia and New Zealand

Country or region	Species*	Production (t)	
		2019	2020
China	Pompano**; Amberjacks nei; Snubnose pompano	185,080	180,966
Japan	Yellowtail (Japanese amberjack); Japanese jack mackerel, White trevally	141,615	141,700
Malaysia	Snubnose pompano; Jacks, crevalles nei	3,669	2,912
Taiwan	Amberjack nei; Greater amberjack, Malabar trevally	1,780	1,296
Korea, Republic of	Amberjacks nei; Jack and horse mackerels nei	668	781
Panama	Florida pompano	613	18
Mexico	Crevalle jack, Jacks, crevalles nei	495	549
Denmark	Yellowtail amberjack	292	274
Netherland	Yellowtail amberjack	110	110
Singapore	Snubnose pompano, Bigeye trevally, Giant trevally, Golden trevally	113	143
United Arab Emirates	Greater amberjack	70	40
Brunei Darussalam	Snubnose pompano; Jacks, crevalles nei	59	205
Greece	Greater amberjack	20	50
Spain	Greater amberjack	17	15
Philippines	Snubnose pompano; Jacks, crevalles nei	8	23
Chile	Yellowtail amberjack	5	11
Bahama	Florida pompano	< 0.5	< 0.5
Dominican Republic	Florida pompano	< 0.5	< 0.5
Portugal	Greater amberjack	< 0.5	< 0.5
Total		334,618	329,097

*Scientific names as appear in Table 1

**See note on species cultured in China in Table 1

Total carangid production in Japan (mainly yellowtail) declined slightly over the period 2011–2020 (Fig. 1), while production in China (mainly *Trachinotus*) increased.

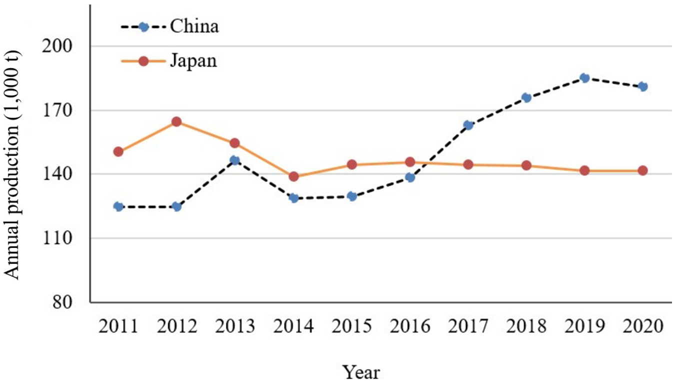

Fig. 1 Aquaculture production of carangid fish species by Japan and China during 2011–2020 (Food and Agricultural Organization, 2022)

In the following section, important carangid fishes and their culture methods are reviewed. Notably, academic publications on the general aquaculture of these species are scarce. As a result, information from technical papers represents a major source of the following content. Summaries are presented by species group.

1. Pompanos: Pompanos are a group of medium-sized carangids (compared to the larger amberjack) in the genus *Trachinotus* with an average total length of 35–40 cm and a body weight of approximately 2.8–3.8 kg (Froese and Pauly, 2023). Among the 21 *Trachinotus* species listed as valid names in Fishbase, only three appear in the FAO statistics for aquaculture production. Of these, the majority of production (approximately 97%) was from *Trachinotus* reared in China, with minor contributions from snubnose pompano (approximately 2.3%) and less than 1% of Florida pompano (*Trachinotus carolinus*) (Table 1).

1.1 Pompano (*Trachinotus*): The production of 160,000 t of *Trachinotus* from China in 2020 represented the highest output in that year among cultured carangid species (Food and Agricultural Organization, 2022). This species is popularly cultured along the southeast coast of China, in the South China Sea (Xia et al., 2012; Liu et al., 2018). Successful captive breeding of *Trachinotus* was first achieved in 1997 in Taiwan (Liao et al., 2000) and later in mainland China in 2003 (Xia et al., 2012; Liu et al., 2018). Breeding uses brooders aged 5–7 yr (Guo et al., 2014) based on hormone injection followed by natural spawning (Liao et al., 2000). The success of fry production, together with the availability of commercial feed for this species, has led to the rapid expansion of *T. ovatus** culture. Open-sea cages and outdoor ponds are commonly used for grow out. The main constraints in rearing this species are outbreaks of infectious diseases and parasites, such as viral nervous necrosis, nocardiosis and *Cryprocaryon irritans* disease that can cause mass mortality (Xia et al., 2012; Guo et al., 2018; Liu et al., 2018).

1.2 Snubnose pompano/Golden pompano (*Trachinotus blochii*): Culture of this species is centered in East and Southeast Asia, with relatively small production of less than 4,000 t/yr (Tables 1 and 2). Fingerlings have been commercially produced in Taiwan since 1989; however, technical details are not available (Shinn-Pyng, undated). Intensive studies in India revealed successful fry production, whereby male and female brooders (wild or captive) cultured under controlled light intensity (2,000 lux) and photoperiod (14 hr light and 10 hr darkness), were injected with 350 international units (IU)/kg body weight of human chorionic gonadotropin (Gopakumar et al., 2012), followed by natural spawning (Table 3). Grow out is done in sea cages, low-salinity ponds or land-based tanks. Details of the culture practices used for this species can be found in FAO documents (Food and Agricultural Organization, 2016). Usually, snubnose pompanos are cultured in low-salinity ponds by stocking 2.5–3 cm length fingerlings at a stocking density of 0.85 fish/m^2. The fingerlings are fed with artificial pellets for 240 d, which can produce fish weighing up to 400–500 g at harvest with a 94% survival rate. In the Indian study, rearing in freshwater ponds with the same conditions resulted in low survival and growth rates (Food and Agricultural Organization, 2016). In Malaysia, which currently contributes 80% of the world's production of snubnose pompano, seeds and fingerlings are mainly procured from Taiwan, with deep-sea cage farming being the most common culture method used. However, one of the biggest problems faced by Malaysia in deep-sea caging is the occurrence of viral nervous necrosis caused by the betanodavirus. This pathogen infects the brain and retinal tissues of the fish, which leads to mass mortality in juveniles (Ransangan et al., 2011).

1.3 Florida pompano (*Trachinotus carolinus*): Despite a long history of research and development (since the 1950s) aimed at the establishment of aquaculture of this species, success has only recently been achieved (reviewed by Weirich et al., 2021). Aquaculture of this species relies on hatchery-produced fingerlings obtained from hormone-induced wild-caught broodstocks (luteinizing hormone-releasing hormone analogue (LHRHa)-implanted, Weirich and Riley, 2007), as shown in Table 3. The fingerlings are stocked in a recirculating aquaculture system (RAS) or sea net-pen and can reach market size (450–500 g) in less than 1 yr (reviewed by Weirich et al., 2021). The production is mainly from Panama, while the Bahamas and the Dominican Republic each produce small quantities.

Table 3 Experimental spawning induction in some carangid fish species where hormone administration was by injection or otherwise modified (modified from Corriero et al., 2021).

Species	Source of broodstock	Timing	Location	Hormone	Dosage	Spawn/Strip	Reference
Giant trevally (*Caranx ignobilis*)	Wild-caught juveniles reared until 5–7 y old	Mar.–Apr.	the Philippines	hCG	F: 1,000 IU/kg divided into 2 injections with 12 hr interval M: 500 IU/kg at 2nd female injection	Volitional spawning at 24–36.5 hr post-injection	Mutia et al. 2020
				LHRHa	F: 50 µg/kg divided into 2 injections with 12 hr intervals M: 25 µg/kg at 2nd female injection	Volitional spawning at 25–52 hr post-injection	
Blue trevally (*Caranx melampygus*)	Wild-caught juveniles reared until aged ≈2–3.25 yr	Jan.–Nov. (peak in May–Aug.)	Hawaii	None	-	Natural spawning	Moriwake et al. (2001)
Golden Trevally (*Gnathanodon speciosus*)	Aquarium reared (age unknown, size > 2 kg)	Apr.	Florida, USA	Salmon gonadotropin-releasing hormone analog [sGnRHa] (implanted)	75 µg (brooders: 2.41 ± 0.73 kg; 49.28 ± 2.75 cm fork length)	Volitional; 24 hr, 72 hr and 96 hr post-implantation	Broach et al. (2015)
White trevalley (*Pseudocaranx dentex*)	Wild-caught juveniles and captive bred reared until aged 10–11 yr	ND	Kochi, Japan	Induced to spawn by increasing water temperature to 22ºC	-	Volitional; on day temperature reached 22ºC and again 1 d later	Watanabe et al., 1998
	Captive bred aged 7 yr	ND	Kochi, Japan	hCG* Used only for first time spawners	F&M: 600 IU/kg at 22°C	Volitional; 36 hr post-injection	Vassallo-Agius et al. (2001)
	Wild-caught juveniles reared for 4 yr	May – Jun.	Portugal	None	None	Naturally spawned	Nogueira et al. (2018)
California yellowtail (*Seriola dorsalis**)	Wild-caught adults (4–9 mth after capture); captive bred, reared until aged 3–4 yr	Mar.–Aug.	California	None	-	Natural spawning	Reviewed by Rotman et al. (2021)
Greater amberjack (*Seriola dumerili*)	Wild caught adults; captive bred, reared until aged 2 yr	May–Jun.	Tokyo, Japan; Southern Japan	None	-	Natural spawning	Kawabe et al. (1996, 1998)
	Wild-caught juveniles, reared until aged > 6 yr (12–16 kg)	Jun.–Jul.	Greece	LHRHa (implanted)	F: ≈ 53 µg/kg once a month (3 mth) M: 67.9 µg/kg followed by ≈ 39 µg/kg in 2 consecutive months	Volitional spawning 36 hr and 5 d post-implant	Mylonas et al. (2004)
	> 11 kg	Jun.–Oct.	Spain	GnRHa	20 µg/kg, weekly applied (June−October)	Volitional spawning	Sarih et al. (2019)

Table 3 Continued

Species	Source of broodstock	Timing	Location	Hormone	Dosage	Spawn/Strip	Reference
	F1 hatchery-reared (age unknown; size F: >20 kg, M: ≈ 5 kg)	May–Sep.	Canary Islands, Spain	GnRHa (implanted)	Dosage not defined	Volitional spawning 1–2 d post-implant	Jerez et al. (2018)
	Wild-caught juveniles reared until aged > 4 yr	ND	Greece	GnRHa	F: 64 ± 17 μg/kg M: 48 ± 12 μg/kg	Volitional spawning	Fakriadis et al. (2020)
Yellowtail amberjack (*Seriola lalandi*)	Wild-caught adults reared for 2–3 yr (average body weight 17 kg)	Nov.– Feb.	New Zealand	None	-	Natural spawning	Moran et al. (2007)
	Captive bred (aged 47 yr, 7.3–15.6 kg)	Jan. –Feb.	New Zealand	LHRHa (implanted)	500 μg/fish	Volitional spawning (number of spawned F > control)	Setiawan et al. (2016)
				None	-	Volitional spawning (better egg quality than GnRH implanted females)	
Yellowtail (*Seriola quinqueradiata*)	Captive bred (aged 4 yr)	Mar.	Japan	hCG or GnRH implant	500 IU/kg hCG or 2 injections of hCG (100 or 50 IU/kg followed by 500 IU/kg at 1 d intervals) or single 220–400 μg/kg GnRHa implantation	Volitional spawning 42–48 hr post-injection	Chuda et al. (2001)
	Wild-caught juveniles reared until aged > 2 yr	Mar.–Apr.	Kochi, Japan	hCG	600 IU/kg	Volitional spawning 48 hr post-injection	Mushiake (1996)
Longfin yellowtail (*Seriola rivoliana*)	Wild-caught juveniles reared until >4 kg	late May	Canary Islands, Spain	LHRHa	20 μg/kg injected every 10 d (total of 15 injections)	Volitional spawning 17–44 hr post- injection	Fernández-Palacios et al. (2015)
Snubnose Pompano, (*Trachinotus blochii*)	Wild-caught juveniles reared until aged > 1 yr (≈2 kg)	Jul.–Nov.	Tamil Nadu, India	hCG	350 IU/kg	Volitional spawning; 30–36 hr post-injection	Gopakumar et al. (2012)
	Captive bred (≈1 kg)	ND	Indonesia	hCG	250 IU/kg along with fibrogen (50 IU/kg) and done twice across period of 2 d	Volitional spawning	Juniyanto et al. (2008)

Table 3 Continued

Species	Source of broodstock	Timing	Location	Hormone	Dosage	Spawn/Strip	Reference
Florida pompano (*Trachinotus carolinus*)	Wild-caught adults 0.7–1.6 kg	May–Aug.; Jul.–Oct.	Florida, USA	LHRHa (implanted)	75 µg (mean weight~1–1.6 kg for M & F)	36 hr post-implantation	Weirich and Riley (2007)
Indian pompano (*Trachinotus mookalee*)	Wild-caught juveniles reared until aged 21 mth	ND	Andhra Pradesh, India	hCG	F&M: 350 IU/kg	Volitional; 36–38 hr post-injection	Ranjan et al. (2018)
Japanese jack mackerel, (*Trachurus japonicus*)	Wild-caught adults (age unknown, size 266–407 g)	May–Jun.	Fukuoka, Japan	LHRHa	F&M: 400 µg/kg	Spawning occurred 1–2 d post injection and continued for 3 consecutive days	Nyuji et al. (2013)

ND = not defined; M = male; F = female; IU = international units; ≈ = approximately.
* identified as *S. lalandi* in the past.

2. Yellowtail and greater amberjack (*Seriola* spp.): The genus *Seriola* comprises nine valid species (Froese and Pauly, 2023), among which three species (yellowtail, greater amberjack and yellowtail amberjack, *Seriola lalandi*) are reported to have major aquaculture production (Food and Agricultural Organization, 2022). In addition, longfin yellowtail (*Seriola rivoliana*) was unofficially recorded with significant production in the USA (Loew, 2021). These species are much larger than the pompanos, commonly with total length of 80–100 cm and maximum weight of 40–96 kg (Froese and Pauly, 2023). Japan was the first country to develop aquaculture methods for this genus and remains its leading producer. Most of the Japanese production of *Seriola* is yellowtail, with a recorded production of 137,100 t in 2020. Notably, in the FAO statistics on aquaculture production, *Seriola* species are occasionally pooled as "Amberjack nei", for which the annual production exceeded 30,000 t, mostly by mainland China and Taiwan (Food and Agricultural Organization, 2022).

2.1 Yellowtail (*Seriola quinqueradiata*): Yellowtail has been cultured since the 1950s in the south of Japan (Masumoto, 2002) and its production rapidly expanded in the 1960s (Egusa, 1983; Nakada, 2002); at present, it ranks second in global annual production among the carangids (Food and Agricultural Organization, 2022). The culture relies mainly on wild-caught fingerlings that are regularly found along the southern coast of Japan (Nakada, 2002). At least 25–27 million fingerlings are caught annually to supply the demand from producers (Nakada, 2008; Loew, 2021). Although the supply of wild fingerlings has fluctuated in the range 25–100 million during 1970–1997 (Nakada, 2008), the demand for fingerlings has been fulfilled using imported fry from Korea despite their higher price (Nakada, 2008). To sustain the yellowtail stock, an enhancement program of the National Center for Stock Enhancement (NCSE, formerly the Japan Sea-Farming Association) was initiated in 1977 (Mushiake et al., 2007). The NCSE has applied additional measures, such as control of fishing seasons and numbers of fishing permits (Nakada, 2008). Yellowtail grows remarkably fast and reaches a body weight of 1–2 kg (30–50 cm length) in the first year, 3–5 kg in the second year, and 6–9 kg after three years of grow out (Egusa, 1983). This species is cultured in net-cages, wherein the young fingerlings (< 200 g, the so-called "Mojako") are stocked in cages measuring 5 m × 5 m × 5 m. Later, the larger fingerlings ("Hamachi") are transferred into larger cages (8 m × 8 m × 8 m) until they reach 1.0 kg. Finally, these fish ("Buri") are reared in even large cages (10 m × 10 m × 10 m) until they reach a market weight of 3.5–4.5 kg (Masumoto, 2002;

Nakada, 2002). In the past, feeding was done with low-value raw fish, such as sardine, sand lance and mackerel; however, due to a decline in supply and other associated problems (such as unstable nutrition, diseases and parasites transferred from the raw fish, and water pollution caused by the uneaten fish), formulated feed now supplies at least 40% of the diet (Food and Agricultural Organization, undated; Masumoto, 2002); this change has reduced the feed conversion ratio (FCR; defined as the weight in kilograms of feed for the production of a 1 kg fish) to 0.9–2.6 (reviewed by Sicuro and Luzzana, 2016).

Diseases and parasites are the most serious problem in yellowtail (and other *Seriola*) culture. The most devastating diseases are caused by bacteria and specifically: *Enterococcus seriolicida* (Kusuda et al., 1991), which was initially identified as *Streptococcus* sp. (Kusuda et al., 1979; Egusa, 1983); the recently isolated *Streptococcus dysgalactiae* (Nomoto et al., 2004; Abdelsalam et al., 2010), which causes severe necrotic lesions of the caudal peduncle and leads to mortality; *Photobacterium damselae* subsp. *piscicida* (Egusa, 1983; Kanai, 2017) (formerly *Pasteurella piscicida*), a causal agent of psudotuberculosis, which has resulted in mass juvenile death (Egusa, 1983); and *Nocardia kampachi*, a pathogen of nocardiosis (Kariya et al., 1968; Egusa, 1983). Viral diseases can be devastating in yellowtail. For example, the yellowtail ascites virus can cause infection, with its virulence depending on the strain. The strain YTAV-06 of this virus caused severe notable losses of yellowtail fry and fingerlings in Kochi, Japan (Hirayama et al., 2007). Occasionally, diseases caused by iridovirus cause severe losses (Egusa, 1983; Nakada, 2008). In addition, in some areas, the spore-forming myxosporean parasite Kudoa, found in the muscles and internal organs, causes severe health problems for consumers (Egusa, 1983). Another major problem with this species is ciguatoxin, which is caused by dinoflagellates and accumulates in fish tissue, resulting in poisoning in humans when ingested (Nakada, 2008).

Currently, aquaculture of yellowtail faces several problems along the production chain. The production cost has increased due partly to the rising price of the juveniles, since the availability of wild-caught juveniles is limited. Feed costs, which account for 50% of the total production cost, have increased for both the farms that use small marine fish and those that use artificial feed. Labor shortage is also an important obstacle for an aging society such as in Japan. Adding to these problems, consumer preference for this species has declined, which has resulted in a lower market value (Food and Agricultural Organization, undated). The culture of yellowtail has attracted the interest of aquaculture companies in Australia, the Netherlands, the USA and Mexico (Loew, 2021).

2.2 Yellowtail amberjack (*Seriola lalandi*): This species was first cultured in Japan, but in relatively small quantities compared to yellowtail. Its culture is based on sea cages and uses mainly wild-caught juveniles. Australia has produced substantial amounts of yellowtail amberjack, notably 2,000 t in 2004–2005 (Chambers and Ernst, 2005) using its native stock, although this figure has not been officially recorded by FAO. The aquaculture of this species *started in 1998 and has a current annual production of about 3,000 t (Loew, 2021).* Unlike in Japan, the culture of this species in Australia is based on hatchery-produced fingerlings. Captive broodstock are preferred, although wild fish are also used. The size of female brooders ranges from 83.4 cm (at age 3+ yr in New South Wales, Australia) to 94.4 cm (age 7–8 yr) in colder regions such as New Zealand (reviewed by Fielder, 2013). Spawning is mostly regulated by controlling the temperature and photoperiod in 20–70 m^3 land-based tanks that are at least 2 m deep, with reported stocking rates in the range 5–14 kg/m^3. However, hatchery-produced fingerlings have a high incidence of deformity (Kolkovski and Sakakura, 2004). Grow out occurs in sea cages (25 m diameter, 8 m length). Fish are fed an artificial diet and can reach a weight of 4–5 kg in 18 mth (reviewed by Rimmer and Ponia, 2007). *The major problems encountered in the culture of this species include* high mortality and reduced growth rates.

Besides a few start-up companies in the USA, Mexico and Chile, where attempts have been made to culture this and other *Seriola* species, the Netherland has had some success in producing yellowtail amberjack in inland-based facilities, with production of 110 t in 2020 (Food and Agricultural Organization, 2022). The RAS used there produces a "green and clean" premium product, by using no antibiotics or vaccines and only green energy (wind, solar and biogas), with complete recycling of nutrients from the outflow and full protection from fish escapes (Kingfish Zeeland, https://www.kingfish-zeeland.com/about).

2.3 Greater amberjack (*Seriola dumerili*): Despite its rapid growth rate, the culture of this species is limited to only a few countries including Spain, Greece, Portugal and the United Arab Emirates, according to FAO statistics (Food and Agricultural Organization, 2022) and to Taiwan (Liao et al., 2001; Shinn-Pyng et al., undated). One impediment to the aquaculture of this species is the limited supply of fry. Breeding strategies for greater amberjack have not been well developed, although Liao et al. (2001) reported breeding success in Taiwan as early as 1996. Past investigation revealed that natural spawning sometimes occurred with hatching rates in the range from 16.49% (Jerez et al., 2006) to 84 ± 21.9% (Kawabe et al., 1996) from wild and hatchery broodstock of 4.7–16.5 kg (Kawabe et al., 1996, 1998; Jerez et al., 2006). Although natural spawning only occurred during a short period (May–June), the spawning could be extended (May–September) by using implanted luteininzing hormone-releasing hormone analogue (LHRHa) at about 30–50 μg.kg^{-1} body mass (Mylonas et al., 2004; Jerez et al., 2018; Fakriadis et al., 2019, 2020); see Table 3 for more detail. Recently, Corriero et al. (2021) reported that impaired gonadal development was common among captive greater amberjack and that this might be related to broodstock nutrition. Despite these promising findings, fingerling production currently appears insufficient to fully support commercial culture of greater amberjack.

2.4 Longfin yellowtail *Seriola rivoliana*: This species is relatively large, with a maximum total length of 160 cm (common length of 90 cm) and maximum weight of 59.9 kg (Froese and Pauly, 2023). It is considered to have high potential for aquaculture. However, like most of the other cultured carangids, efforts at fry production have not yet been successful. Successful spawning induction has been achieved using wild-caught brooders that were cultured for 3 yr (initial weight 1.76 ± 0.25 kg, reaching 6.0 ± 1.1 kg in 3 years). However, nursing of the resulting fry was unsuccessful (Roo et al., 2012). Although the culture technology of this species is not well documented, an unofficial record mentioned annual production of 800 t from open-ocean cages in the USA (Loew, 2021).

3. White trevally or striped jack (*Pseudocaranx dentex*): White trevally is commonly found with a total length of about 40 cm but sometimes reaching 122 cm and 18.1 kg body weight (Froese and Pauly, 2023). This species is one of the most delicious and expensive fish in Japan, where it is considered the best fish for sashimi (Watanabe et al., 1998; Watanabe and Vassallo-Agius, 2003). Initially, its culture was established using wild-caught fingerlings in the 1960s, with hatchery-produced fingerlings first being produced in 1973 (Harada et al., 1984a, b). This species first appeared in FAO statistics in 1974, with production of 46 t; this figure increased steadily until its peak of 4,763 t in 2018 (Food and Agricultural Organization, 2022). The output has plateaued during the past 5 yr, with the most recently recorded production of 4,000 t in 2020 (Food and Agricultural Organization, 2022). In Japan, white trevally is cultivated offshore. Both wild and cultured individuals are used as breeders; net cages are used for rearing and indoor concrete tanks are used for spawning, while the fish are fed with raw fish mix or dry pellets (Watanabe et al., 1988).

4. Japanese jack mackerel (*Trachurus japonicus*): Aquaculture production of Japanese jack mackerel was first documented by FAO statistics around 1970 (Food and Agricultural Organization, 2022). Culture of this species depends on wild-caught juveniles that are harvested from the East China Sea, along the Japan Sea coast and off the Pacific coast of southern Japan. Rearing is done in sea cages in the southwestern regions of Japan (Nakada, 2002; Tamotsu et al., 2012) with a market size of 80–200 g (Nakada, 2002). Hatchery production of fingerlings has not yet been successful, particularly because female broodstock fail to complete oocyte development (Imanaga et al., 2014). This might partly account for the continuous decline in production from the peak in 1992 (>7,000 t) to a low of 600 t in 2020 (Food and Agricultural Organization, 2022). Other factors that may contribute to the contraction of aquaculture activity in Japan in general are a low market price and high feed costs (Demura, 2010), as well as fewer farmers due to the aging workforce and lack of successors (Watanabe and Sakami, 2021).

5. Other carangids, including golden trevally (*speciosus*), giant trevally (*Caranx ignobilis*), crevalle jack (*Caranx hippos*), bigeye trevally (*Caranx sexfasciatus*) and Malabar trevally (*Carangoides malabaricus*): These species have all been recorded with low annual production regardless of their cultural history. Among the known producers of golden trevally, giant trevally and Malabar trevally, Singapore produces the first two species by sea-cage culture (Chou, 1994), but the source of fry is unknown; while in 1998, fry production of golden trevally in Singapore was reportedly around 10,000 fish/mth (Mackay and Chua, 2001). In the Philippines, giant trevally is regarded as a high-value species, and thus has the potential to be used in aquaculture. In a study conducted by Mutia et al. (2020), successful induced spawning of giant trevally in captivity was achieved after injecting human chorionic gonadotropin (hCG) at 1,000 IU/kg or luteinizing hormone-releasing hormone analogue (LHRHa) at 100 μg/kg into ripe female broodstock, while males received one-half of the female dosage.

The production of golden trevally has fluctuated considerably, with the most recent record of about 6 t in 2020 (Food and Agricultural Organization, 2022). Bigeye trevally and giant trevally have less than 10 yr of culture history, with small and varied production. The most recent (2020) production of these two species was <0.5 and 4.25 t, respectively (Food and Agricultural Organization, 2022). Although crevalle jack culture in Mexico has a longer history (recorded since 2002), the production has remained very low. Malabar trevally is cultured in Taiwan, also with small annual production.

No documents describing the culture of these species were found, with the exception of golden trevally, for which fry production was reported in Singapore during 1998 without detail (Mackay and Chua, 2001); in addition, commercial culture has been documented (Chou, 1994). More recently, successful spawning was reported using aquarium-reared brooders. Hormone (a single dose of 75 µg Ovaplant—a salmon gonadotropin-releasing hormone analog) was administered to induce spawning, and fry survival at 45 d after hatching was 4.3% (Broach et al., 2015), as shown in Table 3.

Generalized characters of carangid fish culture:

Based on these reviewed publications, it can be said that efforts to culture carangid fishes share some common features. These characteristics may be useful as guidelines for aquaculture development of new species of carangids or for the expansion of currently cultured species into new areas.

(1) Culture was first established before successful breeding. This is true for almost every species, with the culture of some species (yellowtail and giant trevally) still depending mainly on wild fingerlings, despite a concern that they harbor several species of parasites (Nakada, 2002).

(2) Successful hatchery production of fingerlings has been a key factor for successful carangid culture, such as *Trachinotus* culture in China. However, fingerling production technology has not been well established in most species. Among factors determining successful fingerling production, the priorities are the sources of the broodstock, broodstock diets, induced spawning technology and larval rearing.

(2.1) Source of broodstock: In most cases, broodstock are collected as juveniles or sub-adults from the wild and reared in captivity until maturation (see Table 3). Broodstock rearing often takes a long time, such as 3 yr (starting with 300 g fish) for greater amberjack (Fakriadis et al., 2019), 4–5 yr for giant trevally (Mutia et al., 2020) and 4 yr in captivity (Nogueira et al., 2018) or 7–10 yr (Watanabe et al., 1998) for white trevally. An exception is Florida pompano, for which wild-caught broodstock can spawn after 2 mth of captive rearing (reviewed by Weirich et al., 2021). Rearing also requires a large amount of space, with the photoperiod and temperature being either ambient or controlled.

(2.2) Broodstock diets: Like other marine fishes, the broodstock diet plays a key role in gamete quality, hatching success and quality of larvae (Watanabe et al., 1998; Watanabe and Vassallo-Agius, 2003). In the early years of carangid culture, broodstock were reared with low-cost raw fish and cuttlefish. Today, artificial diets are preferred, as the ingredients can be manipulated to fulfill broodstock requirements. It is well documented that lipid and fatty acid composition of broodstock diet is among the most important factors determining successful spawning of fish (Izquierdo et al., 2001). For example, the review by Corriero et al. (2021) recommend that the feed for greater amberjack broodstock should contain long-chain highly unsaturated fatty acids, docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) in the range 1–1.7% dry weight. In addition, increased histidine and taurine in diets improved the reproductive performance and egg production of greater amberjack (Sarih et al., 2019). A series of studies in yellowtail revealed improved spawning performance when astaxanthin was added in the broodstock diet at around 30 mg/kg (Watanabe et al., 1998; reviewed by Watanabe and Vassallo-Agius, 2003), while similar improvement was seen with the same concentration of paprika ester supplement. Notably, although general nutrient requirements of broodstock may be similar among fish species, variation has been reported. For example, astaxanthin supplement is required for yellowtail (Watanabe et al., 1998) but not for white trevally (Vassallo-Agius et al., 2001); thus, species-specific research is needed to develop optimal broodstock diets.

Furthermore, broodstock rearing is high cost, which may be reduced by implementing a feeding strategy, such as reduction of the feed ration before the onset of the breeding season, such as has been reported with a 50% reduction of feed ration in yellowtail broodstock (Higuchi et al., 2018) to reduce the production cost.

(2.3) Induced spawning technology: Some carangid species reach gonadal maturation and spontaneously spawn in captivity, such as blue trevally (Moriwake et al., 2001), California yellowtail (reviewed by Rotman et al., 2021), greater amberjack (Kawabe et al., 1996, 1998), yellowtail amberjack (Moran et al., 2007; Setiawan et al., 2016) and white trevally (Nogueira et al., 2018). However, in most cases, hormonal administration is required by either injection of hCG or injection/implantation of luteinizing hormone releasing hormone analogue (LHRHa), as detailed in Table 3. Notably, some species, such as greater amberjack, do not respond well to hormone injection (Kawabe et al., 1996, 1998), but have better fry quality when naturally spawned or induced with environmental cues, such as an increase in temperature (Watanabe et al., 1998)).

(2.4) Larval rearing: Larval rearing in carangid fishes follows the general practices used for other marine fishes. Larvae (2–3 d after hatching) are first fed with small-sized zooplankton, such as rotifers or copepod nauplii, or both. Then, as the fry grow, increasingly larger live food are used sequentially, such as *Artemia* instar I and instar II. Examples of larval feeding patterns reported for some carangid larvae are shown in Table 4.

Although live feed contributes high nutritional value, enrichment is required in most cases to meet the complete requirements of each species. It is well documented that n-3 HUFA plays a key role in the performance of marine fish larvae, especially in terms of survival, growth and deformities (Takeuchi, 2001; Cavalin and Weirich, 2009; Roo et al., 2019). Therefore, enrichment of *Artemia* with n-3 HUFA is recommended. Studies in yellowtail and striped jack revealed that DHA is more important than EPA for larval performance, with the DHA-to-EPA ratio being more important than their absolute amounts (Takeuchi, 2001). The recommended amount of DHA is 1.4–2.6% for yellowtail and 1.6–2.2% for striped jack, during *Artemia* feeding (Takeuchi, 2001), while for greater amberjack larvae, 12−17% n-3 HUFA is recommended for the same life stage (Roo et al., 2019). A similar finding regarding the importance of the DHA-to-EPA ratio in feed was reported in Florida pompano (Cavalin and Weirich, 2009).

Besides fine-tuning the nutritional value of feed, optimization of feeding strategies may improve the survival of fry and also reduce costs. Among the scant published evidence, Woolley et al. (2012) reported a 20% increase in the survival of yellowtail amberjack fry at 13–17 d after hatching by avoiding excessive feeding with *Artemia* before dusk. This prevented overfed fry from sinking to the tank bottom and dying. Other aspects of hatchery management are also important, such as vigorous upwelling aeration to prevent mass mortality of newly hatched yellowtail larvae (Mushiake, 1996).

In general, knowledge on larval rearing of carangid fishes is still insufficient. Further studies are needed to optimize all aspects, so that efficient larviculture technology is developed and hence demand for fingerlings can be fulfilled.

Table 4 Feeding patterns for larval rearing of some carangid fish species

Species	Days after hatching	Feed	Major rearing conditions	Survival	Reference
Giant trevally (*Caranx ignobilis*)	1–26	*Nannochloropsis* sp., Rotifers	Salinity 28–30 ppt; temperature 27–28°C	ND	Mutia et al. (2020)
	9–16	*Artemia* nauplii			
Golden trevally (*Gnathanodon speciosus*)	1–10	Copepod nauplii	ND	≈ 4.27%	Broach et al. (2015)
	1–22	Rotifers			
	11–25	*Artemia* nauplii			
	15–27	Dry diet			
Greater amberjack** (*Seriola dumerili*)	2–20	Phytoplankton (*Chlorella minutissima*)*	Photoperiod: 24 hr light: 0 hr dark during 1–30 d	3.5%	Papandroulakis et al. (2005)
	2–27	Enriched rotifers (*Brachionus plicatilis*)			
	11–40	Enriched *Artemia* sp.			
	11–40	Artificial diet			
	26–40	Frozen sea bream (*Sparus aurata*) eggs			
Florida pompano (*Trachinotus carolinus*)	2–11	Microalgae (*Nannochloropsis oculate*)*	Photoperiod 16 hr light: 8 hr dark; light intensity 2,000– 3,000 lux	ND	Riley et al. (2009)
	3–5	Copepods and Rotifers			
	5–11	Rotifers			
	10–17	*Artemia* Instar I			
	13–20	*Artemia* Instar II + artificial feed (400–800 μm)			

ND = not defined; ppt = parts per trillion.
*phytoplankton was provided for maintaining green color of water
**copepods were induced to grow in rearing tanks

(3) Diet during grow out is among the key factors for successful culture. In most cases, the culture of carangids started with the use of raw, low-cost fish for feeding fingerlings. This is no longer viable due to the shortage of supply, high feed conversion ratio, pollution caused by uneaten feed, as well as the diseases and parasites carried by the raw fish. In the successful case of *T. ovatus**, availability of commercial artificial feed (as well as availability of seed) has enhanced production of this species (Xia et al., 2012; Guo et al., 2018; Liu et al., 2018). Generally, artificial feeds are developed based on the nutritional requirements of similar species, despite the documented evidence of slight differences in requirements among species (Booth and Pirozzi, 2022). At present, research on nutritional requirements of cultured carangid fishes is ongoing (as reviewed by Sicuro and Luzzana, 2016; Ebeneezar et al., 2019, 2020).

(4) Various diseases and parasites cause significant mortality in carangid species raised in sea cages and sea pens (Xia et al., 2012; Guo et al., 2018; Liu et al., 2018). One of the major causes of mortality of wild-caught juveniles is the presence of external parasites of various taxa (Nakada, 2002). An example is Benedenia disease, which is mainly caused by a monogenean parasite (such as *Benedenia seriolae*), and mainly affects yellowtail, yellowtail amberjack and greater amberjack (Egusa, 1983; Chambers and Ernst, 2005). *B. seriolae* feeds on the mucus of hosts, causing the fish to rub against rough surfaces in an attempt to dislodge these parasites. Subsequently, this abnormal behavior results in further damage to the external surface of these fish in the form of cuts and abrasions (Egusa, 1983; Uchino et al., 2020), and the hosts frequently develop secondary viral or bacterial infections (Noda et al., 2017). Growth impairment can also be pronounced in infected yellowtail (Noda et al., 2017). Other examples of ectoparasites found to parasitize carangids are *Caligus* spp. (sea lice: *C. seriolae, C. spinosus* and *C. lalandei* [Ho et al., 2001]) and *Anisakis* spp. (parasitic nematodes) (Food and Agricultural Organization, 2016). These two ectoparasites are known to cause body deformities and also impact the morphology of the stomach in some carangids, such as Florida pompano and snubnose pompano (Rigos et al., 2021). In addition, *Henneguya ovata* (a myxosporean parasite) causes necrosis of the gills and heart muscle of Florida pompano and snubnose pompano. According to various sources, ectoparasites can be controlled by bath treatments of the affected individuals using a hydrogen peroxide solution (Chambers and Ernst, 2005; Matsuura et al., 2019) or through an oral administration of praziquantel (Matsuura et al., 2019).

Like other farmed marine fish, diseases caused by bacteria, such as *Flexibacter* spp. and *Vibrio* spp., account for a portion of the mortality of farmed carangids by causing gill disease and vibriosis, respectively (Food and Agricultural Organization, 2016). Pseudotuberculosis, nocardiosis and enterococcal infection (Kusuda et al., 1991) have caused severe uncontrolled losses to yellowtail farms in Japan (Egusa, 1983) and *T. ovatus** farms in China (Guo et al., 2018). The more-recently identified *Streptococcus dysgalactiae* (Nomoto et al., 2004) has also been reported to cause serious problems. The occurrence of these bacterial diseases was believed to result from poor water quality and stress due to over-crowding.

In addition, diseases caused by viruses have led to significant losses in some carangid species, as previously mentioned in the case of yellowtail (Hirayama et al., 2007). Another example is the red seabream iridovirus, which caused mass mortality to Florida pompano juveniles (López-Porras et al., 2018). Likewise, striped jack nervous necrosis virus caused devastation of striped jack and white trevally culture in Japan in the mid-1990s (Watanabe and Vassallo-Agius, 2003). The causative agent was identified as betanodavirus*,* which causes necrosis and vacuolation of brain, spinal cord and retina (Leong, 2008).

Current concerns regarding adverse impacts of antibiotics, both in terms of residual effects and environmental impacts, have limited their use. As a result, there has been more focus on developing alternative measures, such as vaccines. Japan has been successful in using vaccines to reduce losses from major diseases affecting *Seriola* species. A vaccine was developed against *Lactococcus garvieae* (junior synonym: *Enterococcus seriolicida*), which is the most serious problem for the culture of *Seriola* fishes. The vaccine was approved in 1997 and its application has resulted in a significant reduction of mortality in *Seriola* due to the virus. Overall, vaccine use has reduced economic losses from infectious diseases by 70% since 1995 (Matsuura et al., 2019). However, vaccines against some minor pathogens, such as *Nocardia seriolae*, which occur in yellowtail and greater amberjack, have not yet been proven effective. Lastly, the use of DNA vaccines against ectoparasites, such as *B. seriolae,* may help counter virus infections; research is ongoing to determine their efficacy (Matsuura et al., 2019).

(5) Market constraints can have significant adverse impacts on the success of carangid culture. Like other agricultural products, the production of these fish species sometimes creates oversupply and causes domestic prices to fall below the financial break-even point. Documented examples of this scenario are scant except for one case of

yellowtail production in Japan in 2012 (Loew, 2021). In response to the oversupply, the Japanese government requested fishery cooperatives cut production by at least 10% by limiting the harvest of juveniles. Fortunately, the measure worked well and stabilized the domestic price. Where such oversight and regulation do not exist, the drop in price may create heavy losses to producers and result in the collapse of their business. Therefore, it is essential to perform market analysis before the culture of any species is promoted. It is also recommended that diversification of cultured species may prevent or limit such problems with market supply.

Way forward

This review has identified key success factors and future needs for the successful development of carangid aquaculture. First, fry production technology should be developed and implemented. Though aquaculture technologies are available, conditions need to be optimized to address differences in fish stocks and rearing environments. The capacity for fry production would enable efficient business planning, enhance disease control, and more importantly, facilitate genetic improvement. Although the adverse impact of wild fry harvesting was not explicitly documented, such practice possesses a risk to imbalance of fish stock and ecosystem. In this regard, hatchery fry production would reduce this pressure. In addition, if the hatchery-produced fry are reared until reaching maturation and used as broodstock, the domestication process would commence immediately, resulting in better adaptability of the species to rearing conditions (Doyle, 1983; Gjedrem, 2016), which may lead to improved survivability, stress tolerance and ease of gonad development, as well as perhaps even early maturation.

Second, the stocks should be genetically improved to cope with difficult culture problems, such as diseases, parasites, morphological deformities and future problems that may arise from inbreeding. The efficiency of genetic improvement based on selective breeding in enhancing growth, disease resistance and other desirable traits has been shown for Atlantic salmon (*Salmo salar*) in Norway by Gjedrem (2000) and for Pacific white shrimp (*Litopenaeus vannamei*) by Argue et al. (2002).

The genetic improvement of farmed carangid fish species is challenging because most individuals are large fish; hence, only small numbers of broodstock are kept, which may impair selection efficiency and increase the risk of inbreeding (Sriphairoj et al., 2007). However, with the advancement of molecular genetic technology, genetic markers have been applied and have shown high potential in achieving selection goals. Among carangid fish species, yellowtail amberjack has received the most intensive study and shows the possibility of improving both growth (Whatmore et al., 2013; Premachandra et al., 2017) and non-growth traits (resistance to skin flukes and deformity) using the genome selection approach, although progress in improving the latter traits may be much slower (Nguyen and Vu, 2022). In addition, using the quantitative trait loci approach, a major locus that explained 29.6% of the phenotypic variation was identified, indicating the high potential for use in the genetic improvement program to enhance resistance to this parasite (Uchino et al., 2020). Furthermore, genetic improvement programs for Benedenia-resistant yellowtail have been independently initiated by different researchers, with the goal of marker-assisted selection. For example, Ozaki et al. (2013) employed the genome-wide association study approach and successfully identified two major quantitative trait loci that explained a considerable proportion of phenotypic variance (32.9–35.5%), suggesting promise for marker-assisted selection for Benedenia disease resistance in yellowtail. Noda et al. (2017) established a base population for a selection program by selecting wild fish with the fewest Benedinia parasites to be used as the parental population for further marker-assisted selection. A resistant strain would reduce loss of production as well as the cost for disease control, while limiting environmental contamination from the chemical residues arising from disease treatments.

Third, cost-effective and environmental-friendly artificial diets should be made available for all species, as well as their associated efficient feeding strategies. The challenges are not regarding adequate knowledge of the nutritional requirements of finfish, which has been undergoing development for some time (Masumoto, 2002; Gothreaux, 2008; Tesser et al., 2014; Ebeneezar et al., 2019, 2020; Hu et al., 2019; Li et al., 2021); instead, the issue is balancing the feed cost and the market price of the fish produced. Several strategies can be applied, for example the replacement of high-value ingredients, such as fish meal, with low-cost ingredients or by-products (Aoki et al., 2000; Pham et al., 2021) and by the enhancement of feed utilization, minimizing feed loss either by improving feed stability or palatability and improving feeding efficiency (Davis and Hardy, 2022). Furthermore, environmental issues have been important drivers for the development of feeds using substitutes for fish meal and reducing nutrient leaching, as well as unwanted chemical residues from feed.

Fourth, a more cost-effective RAS should be developed to replace sea-cage and pen culture, at least for a portion of production. A land-based RAS has been efficiently used for some carangids (Kingfish Zeeland, https://www.kingfish-zeeland.com/about). Although lower growth rates of fish in RAS culture relative to sea-cage culture have been reported (Sekar et al., 2021), RAS enables efficient control of diseases and parasites, while more importantly facilitating the reduction of adverse impacts to the environment by controlling water quality and wastes (Orellana et al., 2014). Orellana et al. (2014) showed that RAS culture of yellowtail amberjack could be operated for an extended period (488 d) with very little water replacement (0.45%/d) using artificial sea water, with very satisfactory growth (from 0.7 g to 2,006 g in 488 d). High investment and operational costs are major concerns; however, systems may be optimized by adjusting key culture factors, with the benefits of increased stocking densities and survival rates, reduced water replacement rate and a reduced FCR (Orellana et al., 2014).

Finally, new species should be developed for aquaculture to diversify production. At present, rearing strategies of some species have been documented. For example, the Indian pompano (*Trachinotus mookalee*) was reported with a maximum growth of 684.9 ± 14.0 g after 12 mth in cages (Sekar et al., 2021) and the fish reached maturity after 26–29 mth of culture in sea cages. Plata pompano (*Trachinotus marginatus*), native to the southern Atlantic Ocean, is another species that has received much interest for commercial production, with a number of studies (Costa et al., 2008; Tesser et al., 2014). Recently, the California yellowtail (*Seriola dorsalis*), which commands a high price (USD 27.70/kg) in the USA, has been the subject of reports of successful breeding and rearing efforts, with the culture technology now ready for use on a commercial scale (Rotman et al., 2021). In addition, other new species, such as bluefin trevally (*Caranx melampygus*) (Moriwake et al., 2001) and longfin yellowtail (Fernández-Palacios et al., 2015; Roo et al., 2012) are under intensive studies aimed at the development of aquaculture technology.

In conclusion, the development of carangid fish aquaculture throughout the past decades has resulted in an extensive body of knowledge and technologies that can serve as congruent stepping-stones for ongoing development. Current research and development is focused on optimizing the existing technology for each culture species, developing new species or expanding production to new areas. However, issues regarding climate change as well as the changing perspective towards sustainable development goals have brought about new challenges. These challenges necessitate synergistic efforts among researchers and aquaculture business firms worldwide to efficiently tackle the issues, with the ultimate goal of feeding the world with a sufficient supply of these high-quality fish species in a sustainable way, while reducing fishing stress on these species.

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