Check for updates

Received: 23 December 2022 | Revised: 9 March 2023 | Accepted: 14 March 2023

DOI: 10.1111/jwas.12963

REVIEW ARTICLE

Journal of the World Aquaculture Society Open Access | WORLD AQUACULTURE Society | WILEY

The contribution of aquaculture systems to global aquaculture production

Marc Verdegem[1] | Alejandro H. Buschmann[2] | U. Win Latt[3] | Anne J. T. Dalsgaard[4] | Alessandro Lovatelli[5]

[1]Department of Animal Sciences, Wageningen University, Wageningen, the Netherlands

[2]Centro i-mar & CeBiB, Universidad de Los Lagos, Puerto Montt, Chile

[3]Aqua Global Environs Co. Ltd., Yangon, Myanmar

[4]Technical University of Denmark, DTU Aqua, Section for Aquaculture, Hirtshals, Denmark

[5]Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome, Italy

Correspondence
Marc Verdegem, Department of Animal Sciences, Wageningen University, Wageningen, the Netherlands.
Email: marc.verdegem@wur.nl

Abstract

Since 2000, aquaculture became well-integrated into the global food system. Aquaculture systems are highly diverse, producing globally equal amounts of fed and extractive species. In Asia and Africa, inland aquaculture provides the bulk of aquaculture production, while in the Americas, Europe, and Oceania, marine aquaculture dominates. The realized growth of annual production since 2000 is due to intensification, the use of more and better feeds, improved production management, and increased attention to biosecurity. Fed and extractive aquaculture, both need to pay more attention to scaling, site selection, and the health of the wider production environment. In terms of land use, aquaculture is more efficient than terrestrial animal production. Still, water use remains a challenge. More attention should be given to water recycling in land-based systems, reducing water consumption and facilitating nutrient recovery and reuse. Future development should focus on making aquaculture climate neutral and on reducing environmental impacts, both inland and at sea. More attention must be given to making aquaculture an important part of local food systems on all continents, as is the case in Asia today. Integration of aquaculture into local nutrition-sensitive, circular, and sustainable food systems should become the major driver for future aquaculture system development.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.
© 2023 Food and Agriculture Organization of the United Nations. *Journal of the World Aquaculture Society* published by Wiley Periodicals LLC on behalf of World Aquaculture Society.

KEYWORDS
aquaculture production, aquaculture systems, development priorities, fed aquaculture, sustainable practices

1 | INTRODUCTION

This paper summarizes the development of aquaculture between 2000 and today. Aquaculture systems are highly diverse with presently ca. 425 species in production (Naylor et al., 2021). As each one of these species can be cultured in different production systems ranging from extensive to super-intensive, the number of possible systems is enormous. Therefore, we define an "aquaculture production system" in broad terms as a production environment in which interventions aim to enhance the value and/or the amount of biomass produced, to the benefit of the people and communities organizing and executing these actions. Actions range from stimulating recruitment of desired species to stocking fast-growing strains, protecting against disease, fertilization, feeding, and creating production environments like ponds, rafts supporting hanging or floating ropes or long lines, cages, pens, raceways, and recirculating aquaculture systems (RAS) that allow control on resource use efficiency to a higher degree than in natural systems.

Aquaculture can only optimize its contribution to society and nature through the responsible use of resources and strong integration within the global food system. Claims by aquaculture for freshwater and for space on land and at sea should be coordinated with claims from agriculture, urbanization, industry, and nature at regional or water basin scales. These are complex questions that require multi-objective analysis (Pelletier et al., 2018). Similar complex dilemmas exist for the selection of ingredients for fish feeds to replace animal-based resources with plant-based ones, finding the right balance with impacts on the environment, biodiversity, climate change, competition with human foods, fish health, fish welfare, and nutritional quality of aquaculture products.

FAO holds every 10 years a Global Conference on Aquaculture. The most recent meeting was held in September 2021, following up on meetings organized in Thailand in Phuket in 2010 (Subasinghe et al., 2013) and Bangkok in 2000 (NACA/FAO, 2000). The goal of these meetings is to set priorities for aquaculture development during the next decade. This paper summarizes the present state of aquaculture looking from a systems perspective and sets priorities for the future. Because the Phuket declaration in 2010 was an extension of the Bangkok declaration in 2000, providing a small extension to the recommendations given 10 years earlier during the Bangkok conference, we analyze progress since 2000 with a focus on the last decade.
The manuscript is organized in 3 major sections:

- Aquaculture development since 2000.

Addresses how well the sector developed during the last decades. Considering the large differences that exist in system requirements for the production of fish, crustaceans, mollusks, and seaweed, these are reviewed separately.

- Current issues and challenges in aquaculture.

Addresses what are the current issues and challenges facing the industry today. Harmful and positive impacts of aquaculture production systems on the environment, society, and the ability to produce within planetary boundaries are reviewed.

- Priorities for future aquaculture development.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Discusses which key developments in the aquaculture sector need prioritization to deliver sustainable growth during the next decade.

2 | AQUACULTURE DEVELOPMENT SINCE 2000

2.1 | Development of aquaculture production (2000–2019)

Aquaculture is one of the fastest-growing food sectors worldwide. During the last 20–30 years, the sector showed a constant and significant increase in the contribution of commercial and industrial aquaculture to global production. Also, small-scale and medium-scale aquaculture enterprises benefited from this growth of the aquaculture industry. By growing and commercializing, the sector increased its contribution to food security, income, and trade. Growth has been mainly in Asia, with other continents lagging behind in realizing the potential of aquaculture to contribute to food production and food security. There are, however, signs of change. During the last decade, growth rates in production were higher in Africa and Latin America than in Asia, showing a growing interest in food production through aquaculture outside Asia. Naylor et al. (2021), looking at all sub-sectors of the aquaculture sector, state that during the last decades, aquaculture became better integrated within the global food system, while realizing large improvements in environmental performance. Responsible aquaculture today is considered a legitimate user of resources that improves livelihoods and contributes to environmental enhancement.

Between 2000 and 2019, world aquaculture production increased from 43.0 to 120.1 million metric ton (Mt), an increase of close to 180% (Table 1). In 2019, animal production through aquaculture reached 85.4 Mt and the production of aquatic plants 34.7 Mt. Asia, with China as the main producer, has always been the continent's leading aquaculture production. Asia was responsible for 90% of global production in 2000 and increased its share to 92% in 2019. The other continents are lagging behind, with the Americas, Europe, Africa, and Oceania producing respectively 3.5%, 2.7%, 2.0%, and 0.2% of the global production in 2019. The large difference in production between Asia and the other continents indicates a vast potential for aquaculture development outside Asia.

The contribution of Europe and Oceania to global aquaculture production is declining, is more or less steady in the Americas, and has doubled in Africa between 2000 and 2019. In the Americas, the average annual growth rate (AAGR) of aquaculture between 2000 and 2010 was 3%, but increased to 6% between 2010 and 2019, mainly due to growth in Central and South America. Over the same period, the AAGR in Africa was also 6% (Table 1, Figure 1; FAO/FishStatJ, 2023; Garlock et al., 2020). With higher growth rates in Africa and the Americas than in Europe, these continents most likely will in the near future overtake Europe as the second largest aquaculture producer. If interest in aquaculture spreads to more countries than is presently the case in Africa and Latin America (Figure 1), and the annual growth rate remains above average as is presently the case, then these continents will increase their contribution to global aquaculture production during the next decade.

Between 2000 and 2019, the contributions of finfish, crustaceans, and other aquatic animals to global aquatic animal production through aquaculture increased by 2%, 7%, and 0.5%, respectively. In contrast, the share of molluscan culture to global aquatic animal production declined by 9% during the same period. Overall, the contribution of aquatic plants to global aquaculture production increased by 4% between 2000 and 2019, concurring with a decline from 75% to 71% of the contribution of aquatic animals to global aquaculture production (Table 2).

Most striking is the 5.2-fold increase in global production of crustaceans between 2000 and 2019. This is mainly due to their high market value. In 2000, the average price on a global scale of finfish was 1.2 US$/kg compared to 4.8 US$/kg for crustaceans, a 4-fold price difference. By 2019, the price of finfish and crustaceans increased to 2.6 and 7.3 US$/kg, respectively, representing nearly a 3-fold price premium for crustaceans compared to finfish (FAO/FishStatJ, 2023). Despite the much higher price for crustaceans than finfish, the production cost of crustaceans is substantially higher, with higher system requirements and input costs. When all goes right, crustacean farmers earn, on average more than finfish farmers. Still, commercial risks are also higher, given the increased

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 1 Global aquaculture production in 2000, 2010, and 2019 by continent (FAO/FishStatJ, 2023).

	2000		2010			2019		
Country (name)	Production (Mt)	% Global production	Production (Mt)	% Global production	% AAGR 2000–2010	Production (Mt)	% Global production	% AAGR 2010–2019
Asia	38.9	90	71.3	91.4	6.2	110.0	91.6	4.9
Americas	1.5	3.4	2.5	3.2	5.7	4.2	3.5	5.8
Europe	2.1	4.8	2.5	3.2	2.1	3.2	2.7	2.8
Africa	0.5	1.0	1.4	1.8	12.2	2.4	2.0	5.9
Oceania	0.1	0.3	0.2	0.3	3.9	0.2	0.2	1.1
World	43.0	100	78.0	100	6.1	120.1	100	4.9

Abbreviations: AAGR, average annual growth rate calculated for the period indicated; Mt, million metric ton.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

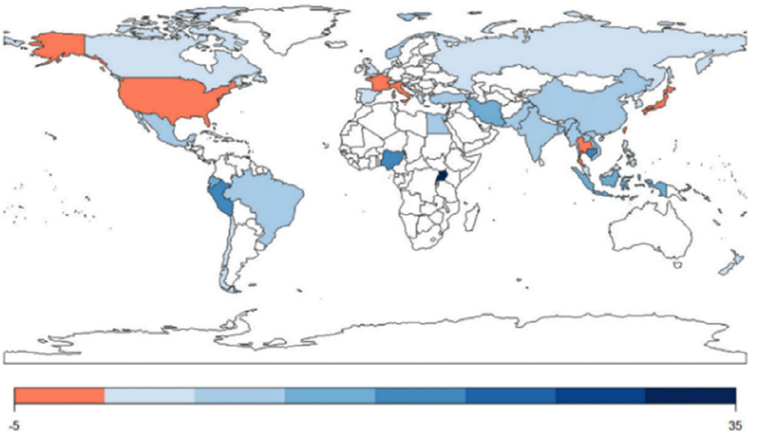

FIGURE 1 Growth in aquaculture production quantity (%) between 2006 and 2016 for countries with production greater than 100,000 metric ton (MT). Reproduced from Garlock et al., 2020.

potential for culture failure due to disease or environmental disasters. Nevertheless, considering the present high demand for crustaceans in Asian markets, the further fast growth of crustacean production is expected during the next decade with a minor impact on the price premium for crustaceans (Miao & Wang, 2020).

In contrast to the global finfish production which nearly tripled between 2000 and 2019, global production of mollusks only doubled. Also, the average price for mollusks doubled from 0.9 US$/kg in 2000 to 1.8 US$/kg in 2019. On average, the price of mollusks is 2/3 the price of finfish, a ratio that remained similar between 2000 and 2019 (FAO/FishStatJ, 2023). The low price, combined with low consumer demand, might partly explain the slow development of molluscan aquaculture, although there is considerable room for further development.

The vast majority of finfish, except for ca. 8 Mt of carp species, and crustaceans are fed formulated pelleted feed, while mollusks are not fed (FAO, 2020). Seaweeds are grown at sea, nearly always without fertilizer addition, although in coastal waters or bays, there might be substantial nutrient runoff from land (Mahmood et al., 2016b). Therefore, we refer to finfish, except 8 Mt of carps, and crustaceans as fed species and to 8 Mt carps, mollusks, and seaweed as extractive species. The main species group "other aquatic animals" are also considered fed species (Table 2).

2.1.1 | Fed species

Production overview

Global finfish production through aquaculture increased from 20.8 million Mt in 2000 to 56.3 Mt in 2019, an increase of 170% (Table 2). Global crustacean production increased from 1.7 to 10.5 Mt during the same period, an increase of 520% (Table 2). Combined, the share of crustaceans and finfish to global animal production through aquaculture grew from 69% in 2000 to 78% in 2019; however, including seaweed, the fed species: extractive species ratio of aquaculture by volume is 50:50. Since 2000, when this ratio was 46:54 the importance of fed species gradually increased, a trend that will continue in the near future (Table 2). When considering only animal production through aquaculture, the fed species: extractive species ratio of aquaculture was 70:30 in 2019, whereas this ratio was 61:39 in 2000 (Table 2).

In total, 56 Mt of finfish was produced in 2019, representing 66% of the global animal production through aquaculture, of which 86% is produced inland and 14% in marine areas (Table 3). The importance of inland aquaculture is mainly due to the dominant position of Asia worldwide, which produces 91% of its aquatic animal production inland.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 2 Global aquaculture production in 2000, 2010, and 2019 by main species group (FAO/FishStatJ, 2023).

	2000		2010			2019		
Main species grouping	Production (Mt)	% Global production	Production (Mt)	% Global production	% AAGR 2000–2010	Production (Mt)	% Global production	% AAGR 2010–2019
Finfish[a]	20.8	64	37.7	65	6.1	56.3	66	4.5
Crustacea[a]	1.7	5	5.5	9	12.5	10.5	12	7.5
Molluscs[a]	9.8	30	13.8	24	3.5	17.6	21	2.7
Other aquatic animals[a,b]	0.2	0	0.8	1	17.7	1.0	1	2.4
All aquatic animals[c]	32.4	75	57.8	74	6.0	85.4	71	4.4
All aquatic algae[c]	10.6	25	20.2	26	6.7	34.7	29	6.2
Fed species[d]	19.7	46	38.7	50		59.8	50	
Extractive species[e]	23.3	54	39.3	50		60.3	50	
All species	*43.0*	*100*	*78.0*	*100*	*6.1*	*120.1*	*100*	*4.9*

Abbreviation: Mt, million metric ton.

[a]Percentage (%) global production calculated against "All aquatic animals" production.

[b]Other aquatic animals include amphibians, reptilians, and aquatic invertebrates.

[c]% Global production calculated against "All species" production'.

[d]Fed species include finfish minus non-fed carps, Crustacea, and Other aquatic animals.

[e]Extractive species include non-fed carps, Mollusks, and All aquatic algae. Of the global finfish production in 2019, 8.2 Mt were non-fed (FAO, 2022).

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

However, with the exception of Africa where 87% of aquaculture production is inland, in other continents marine aquaculture is more important. In the Americas, Europe, and Oceania culture, respectively, 50%, 79%, and 95% of their finfish are in marine areas. Inland aquaculture consists mainly of finfish culture representing on all continents ≥90% of global inland production of aquatic animals, reaching 100% in Africa and Europe. Looking at marine aquaculture, the picture is much more diverse. Asia for instance produces more crustaceans than finfish in marine aquaculture (20 vs. 17%). On other continents, the contribution of finfish to marine aquaculture production varies between 39% and 96% (Table 3).

Globally, 60% of crustaceans are produced in marine areas, with large variations between continents. In total, 10.5 Mt was produced in 2019, representing 12% of the global production of aquatic animals through aquaculture. Of the inland aquaculture production in the Americas, 8% are crustaceans, while for marine aquaculture this is 36%. In Asia, the contribution of crustaceans to marine aquaculture is 20%, similar to the global average. On the other continents, the productions of crustaceans are negligible to very small (Table 3).

Shrimp production is mainly destined for export in many producing countries while with the exception of high-value finfish species (e.g., salmon, grouper), finfish are consumed domestically or in the region of production. For crustaceans, the international trade volume and traffic vary between the regions of production, depending on shifts in the balance between supply and demand.

Many factors are affecting crustacean production, including climate, technology, disease, natural disaster, pandemic, economy, and so forth, but these events are occurring irregularly, and have a minor effect on global production. Historically, disease outbreaks have been causing severe losses in crustacean production and can be traced in production statistics of major shrimp-producing countries, showing large drops in regional production. For example, white spot syndrome virus (WSSV) and early mortality syndrome (EMS = AHPND) outbreaks in major shrimp-producing countries caused significant production declines and hence affected the year-on-year growth rate globally and in Asia (Shinn et al., 2018) (Figure 2). On the other hand, global crustacean production increases, as shown by consistent positive AAGR values (Table 2). Nevertheless, AAGRs would have been higher, provided disease-related losses would have been lower (Stentiford et al., 2012).

Main culture species

In 2019, there were 13 finfish species with production above 1 Mt (Table 4), representing 71% of the global finfish production. Of these 13 species, seven were carps, with a combined production of 26 Mt in 2019. The share of these carp species in global finfish production declined from 60% in 2000 to 46% in 2019. This decline was to a large extent compensated by increased production of tilapias and catfishes, whose contribution to global production increased by 5% and 6%, respectively, between 2000 and 2019. The percentage contributions of Atlantic salmon and milkfish to global finfish production increased by 1% between 2000 and 2019, providing 5% and 3%, respectively, of global finfish production in 2019.

In 1950, when aquaculture was still in its infancy, freshwater species provided 78% of total production, diadromous species 21%, and marine species 1%. By 2000, the share of freshwater species to total production increased to 84%, diadromous species dropped to 11% and marine species increased to 5%. After 2000, the contributions of marine fishes increased by 1%, mainly compensating for a decline in diadromous fishes (Table 5) (FAO/FishStatJ, 2023).

In 2019 there were 4 crustacean species with a production above 0.75 Mt, together providing 87% of the global crustacean aquaculture production (Table 6). This share most likely will continue to increase slowly during the next decade. Whiteleg shrimp (*Penaeus vannamei*) alone, with a production of 5.4 Mt provides more than half of the global crustacean production through aquaculture. Red swamp crayfish (*Procambarus clarkii*), the majority of which is produced in rice-crayfish farming systems in China (Gui et al., 2018), comes in second with a production of 2.2 Mt in 2019 (FAO/FishStatJ, 2023). During the last 20 years culture of this species exploded, from 0.5% of the global crustacean production in 2000 to 21% in 2019, due to market promotion followed by consumer preference (Wang et al., 2018). Chinese mitten crab (*Eriocheir sinensis*) comes third with a production of 0.78 Mt, followed by giant tiger prawn (*Penaeus monodon*) with 0.77 Mt, each contributing 7% to the global crustacean production in 2019.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 3 Inland and marine finfish and crustacean production (thousand metric tons) through aquaculture by continent compared to global aquaculture production in 2019 (FAO/FishStatJ, 2023).

Species group	Finfish						Crustacean					
Continent	Africa	Americas	Asia	Europe	Oceania	World	Africa	Americas	Asia	Europe	Oceania	World
Inland aquaculture production												
Species group	1966	1151	44,713	536	5	48,370	0	73	4108	0.2	0	4181
Total inland aquaculture	1966	1224	49,572	536	5	53,303	1966	1224	49,572	536	5	53,303
Species group % of total	100%	94%	90%	100%	98%	91%	0%	6%	8%	0%	2%	8%
Marine aquaculture production												
Species group	299	1152	4369	2052	84	7957	5	1075	5213	0.4	6	6301
Total marine aquaculture	311	2979	25,889	2700	204	32,060	311	2979	25,889	2700	204	32,060
Species group % of total	96%	39%	17%	76%	41%	25%	2%	36%	20%	0%	3%	20%
Global aquaculture production												
Species group	2265	2303	49,082	2588	89	56,327	5	1148	9321	1	7	10,481
Total aquaculture	2277	4202	75,461	3236	209	85,363	2277	4202	75,461	3236	209	85,363
Species group % of total	99%	55%	65%	80%	43%	66%	0%	27%	12%	0%	3%	12%
Inland and marine aquaculture as % of production by continent												
% Inland aquaculture	87%	50%	91%	21%	5%	86%	0%	6%	44%	36%	1%	40%
% Marine aquaculture	13%	50%	9%	79%	95%	14%	100%	94%	56%	64%	99%	60%

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

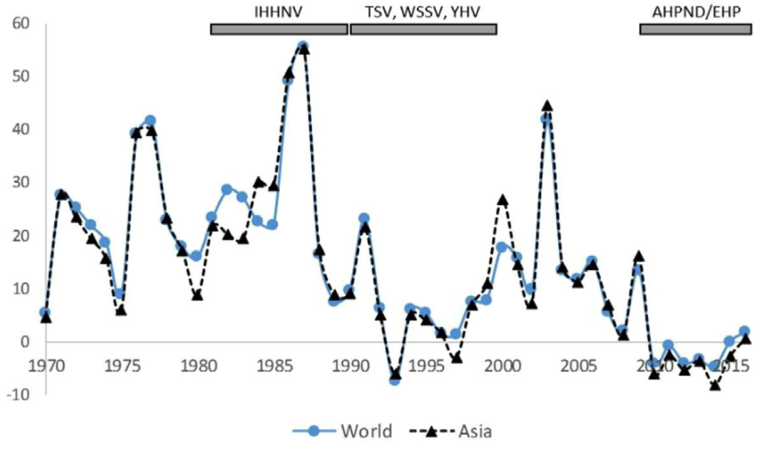

FIGURE 2 The percentage year-on-year change in the growth of Asian and global shrimp production (Shinn et al., 2018). Data from FAO FishStatJ (2023) and national feed sale figures (where available) are used. AHPND, acute hepatopancreatic necrosis disease; EHP, Enterocytozoon hepatopenaei; IHHNV, infectious hypodermal and hematopoietic necrosis virus; TSV, Taura syndrome virus; WSSV, white-spot syndrome virus; YHV, yellow head virus.

Mitten crab culture is practiced mainly in China. For juveniles, the principal culture system is rice-crab polyculture, while grow-out is mainly done in monoculture or polyculture systems (Cheng et al., 2018). Between 2000 and 2019, whiteleg shrimp and giant tiger prawn swapped leading positions as the most important crustacean aquaculture species. However, large improvements were made through selection in the growth and disease resistance of giant tiger prawn. Its high price and the possibility to stock the new strains at high density in ponds trigger speculation about a possible comeback during the next decade (The Shrimp Blog | Shrimp Insights, May 2021).

2.1.2 | Extractive species

Production overview

The share of mollusks in the global animal production through aquaculture dropped from 30% in 2000 to 21% in 2019. The AAGR of mollusks is with 3.5% and 2.7% for the periods 2000–2010 and 2010–2019, respectively, much lower than the global aquaculture AAGRs of 6.1% and 4.9% over the same periods (Table 2). Of the global mollusk production in 2019, only 1% was produced in inland waters. In marine areas, mollusks provide 54% of the aquaculture production in marine areas. In Africa, mollusks production is negligibly small. In Oceania, mollusks production is also small, but responsible for 56% of the total aquaculture production on the continent. In the Americas, Europe, and Asia, mollusks aquaculture is important, providing 17%, 20%, and 21% of the total aquaculture production on the respective continents (Table 7).

Similar to mollusks, 99% of aquatic algae are produced in marine areas. The vast majority of aquatic plants are produced in Asia, with only 0.5% of the global production produced outside Asia. Nevertheless, all other continents are experimenting with algae culture and report productions (Table 7). Interest in seaweed (= macroalgae) for improved nutrition, industrial use, and ecosystem services, grew globally during the last decades, beyond the main producing countries China, Japan, Korea, and parts of South America (Buschmann et al., 2017). Overall, seaweed aquaculture has not been analyzed in depth (Chopin & Tacon, 2020). FAO statistics related to the production of aquatic plants and algae show production tripled from 10 Mt of wet biomass in 2000 to 35 Mt in 2019. Table 9 summarizes the production, culture system, and use of the main seaweed species. Seaweeds are special, considering

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 4 Annual production of finfish species with a production above 1 Mt year^{-1} (FAO/FishStatJ, 2023).

Species (>1 Mt year^{-1})		2000 Production (Mt year^{-1})	2000 % Global production	2019 Production (Mt year^{-1})	2019 % Global production
Carps					
Grass carp	*Ctenopharyngodon idellus*	3.0		5.7	
Silver carp	*Hypoththalmichthys molitrix*	3.0		4.8	
Common carp	*Cyprinus carpio*	2.4		4.4	
Catla	*Catla catla*	0.6		3.3	
Bighead carp	*Hypophthalmichthys nobilis*	1.4		3.1	
Crucian carps	*Carassius spp.*	1.2		2.8	
Rohu	*Labeo rohita*	0.7		2.0	
Total		12.4	60%	26.1	46%
Tilapias					
Nile tilapia	*Oreochromis niloticus*	1.0		4.6	
Tilapia nei	*Oreochromis spp.*	0.1		1.1	
Total		1.1	5%	5.7	10%
Catfishes					
Striped catfish	*Pangasionodon hypophthalmus*	0.1		2.6	
Torpedo-shaped catfishes nei	*Clarias spp.*	0.0		1.3	
Total		0.2	1%	3.9	7%
Salmonids					
Atlantic salmon	*Salmo salar*	0.9	4%	2.6	5%
Milkfish					
Milkfish	*Chanos chanos*	0.5	2%	1.5	3%
Total		15.0	72%	39.9	71%
Global finfish production		20.8		56.3	

Abbreviation: Mt, million metric ton.

TABLE 5 Percentage contribution of freshwater, diadromous, and marine finfish species to global aquaculture production (FAO/FishStatJ, 2023).

	1950	2000	2019
Freshwater fishes	78	84	84
Diadromous fishes	21	11	10
Marine fishes	1	5	6

ca. 31%–38% of the global seaweed production is consumed directly as food (Naylor et al., 2021). Today, the brown seaweed *Saccharina japonica* (wakame) consumed for food and alginate production and the red algae *Eucheuma* spp. for the carrageenan industry are the 1st and 2nd most productive aquaculture species worldwide (Buschmann et al., 2017). The industry sector uses the majority of seaweed biomass as polysaccharide additives and functional food ingredients and by the non-food sector as hydrocolloid products in nutraceuticals, pharmaceuticals, and

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 6 Crustacean species with a production above 0.75 Mt in 2019 (FAO/FishStatJ, 2023), and their contribution to global crustacean production.

		2000		2019	
English name	Scientific name	Production ('000 MT year^{-1})	% Global production	Production ('000 MT year^{-1})	% Global production
Whiteleg shrimp	*Penaeus vannamei*	155	9	5446	52
Red swamp crayfish	*Procambarus clarkii*	8	0.5	2162	20.6
Chinese mitten crab	*Eriocheir sinensis*	203	12	779	7
Giant tiger prawn	*Penaeus monodon*	631	37	774	7
Total		996	59	9162	87
Global production		1691		10,481	

Abbreviation: Mt, million metric ton, MT metric ton.

cosmetics, and to a lesser extent as fertilizers, feed ingredients, biofuels, bioplastics, and other industrial outputs (Naylor et al., 2021).

Main culture species

Cupped oysters and Japanese carpet shells dominate mollusks production, followed by scallops and sea mussels. Together these 4 culture groups provide 70% of the global mollusk production (Table 8). The highest production is for cupped oysters, responsible for 30% of the global mollusk production. The highest production increase was for Japanese carpet shells, raising production by 170% between 2000 and 2019, to provide 23% of the global mollusks production in 2019.

Three brown algae and four red algae species have an annual production above 1 Mt (Table 9). Together they represented 96% of the aquatic plants production in 2019. The most important culture species are the brown algae Japanese kelp (*Laminaria japonica*), providing 39% of global production, and the red algae *Eucheuma* spp. and *Gracilaria* spp. providing 28% and 10%, respectively, of global production.

It has been postulated that seaweeds could substitute some terrestrial crops and animal production in protein, fat (omega 3), and energy intake, alleviating pressure on freshwater and land use and impact on biodiversity. Still, there is little evidence to date that seaweeds will contribute substantially to human macronutrient intake in the future (Wells et al., 2017). On the other hand, seaweed farming is widely recognized for its ecosystem services beyond the provision of food and feed, yet producers have not been able to capture this value in financial returns (Chopin & Tacon, 2020). Bioremediation is one of the main services propagated and studies at large-scale seaweed farming areas indicate these organisms are effective in reducing nitrogen levels, controlling phytoplankton blooms, and limiting the frequency of toxic algal blooms (Xiao et al., 2017; Yang et al., 2015). In addition, large-scale seaweed aquaculture positively regulates and improves environmental conditions in coastal ecosystems (Xiao et al., 2021). However, the effectiveness of the impact of ecosystem services provided by seaweed farming still requires attention across culture systems, seasons, and scales.

2.2 | Aquaculture systems

2.2.1 | Fed systems for finfish

Forty years ago it was still common practice to use locally available crop wastes, manure, waste water, or grains as nutrient sources to stimulate fish production in aquaculture ponds (Hickling, 1962; Huet, 1986). Today, the role of

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 7 Mollusks and aquatic plants production (thousand metric ton) through aquaculture by continent in 2019.

Species group	Mollusks						Aquatic algae					
Continent	Africa	Americas	Asia	Europe	Oceania	World	Africa	Americas	Asia	Europe	Oceania	World
Inland aquaculture production												
Species group			201			201	0.4	1	55	0.4		56
Total inland aquaculture	1966	1224	49,572	536	5	53,303	1966	1225	49,627	536	5	53,359
Species group % of total			0.4%			0.4%	0.0%	0.1%	0.1%	0.1%		0.1%
Marine aquaculture production												
Species group	7	728	15,885	643	113	17,376	118	23	34,513	11	14	34,679
Total marine aquaculture	311	2956	25,889	2700	204	32,060	429	2979	60,402	2711	218	66,739
Species group % of total	2%	25%	61%	24%	56%	54%	27%	1%	57%	0%	6%	52%
Global aquaculture production												
Species group	7	728	16,086	643	113	17,577	118	24	34,568	11	14	34,736
Total aquaculture	2277	4179	75,461	3236	209	85,363	2395	4203	110,029	3248	223	120,098
Species group % of total	0.3%	17%	21%	20%	54%	21%	5%	1%	31%	0%	6%	29%
Inland and marine aquaculture as % of production by continent												
% Inland aquaculture			1%			1%	0.3%	4%	0.2%	3%		0.2%
% Marine aquaculture	100%	100%	99%	100%	100%	99%	99.7%	96%	99.8%	97%	100%	99.8%

Note: Mollusk production is compared to global animal production through aquaculture. Aquatic algae production is compared to the global aquaculture production, including algae (FAO/FishStatJ, 2023). When cells are empty no values have been reported.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 8 Mollusk species with a production above 1 Mt in 2019 (FAO/FishStatJ, 2023), and their contribution to global crustacean production.

English name	Scientific name	2000 Production ('000 MT year^{-1})	2000 % Global production	2019 Production ('000 MT year^{-1})	2019 % Global production
Cupped oysters nei	Crassostrea spp.	2923	27	5265	30
Japanese carpet shell	Ruditapes philippinarus	1504	14	4028	23
Scallops nei	Pectinidae	811	7	1828	10
Sea mussels nei	Mitylidae	720	7	1116	6
Total		5958	55	12,237	70
Global production		10,866		17,577	

Abbreviation: Mt, million metric ton, M, metric ton.

locally available ingredients in many integrated agriculture-aquaculture farming systems has been replaced by pelleted feed (Tacon, 2020). Because pelleted feeds are produced off-farm, farmers were no longer dependent on a limited supply of on-farm or local nutrients, allowing them to intensify. With this feed-driven intensification, the contribution of these mixed farming systems to total finfish production declined (Edwards, 2015). Nevertheless, still, numerous small-scale farmers depend upon integrated pond farming systems, not only for fish, but also for water, and to improve food security (Ahmed et al., 2014).

Until recently, in developing countries, a distinction was made between small-scale and industrial fish farming. Small-scale aquaculture provided a source of animal protein for home consumption and/or surplus income from fish sold locally to poor and food-insecure households (Ahmed & Lorica, 2002). This notion enticed governments and donors to propagate small-scale aquaculture to reduce hunger and improve food security, and support education in aquaculture. The knowledge level of farmers improved, facilitating the development of a largely overlooked "missing middle" of commercially oriented fish farmers. These middle farmers were reacting to increased demand for fish and buying power within their communities. Mainly low-value species, including carps, tilapias, and catfishes are raised by these 'middle' farmers (Belton et al., 2018). As such, aquaculture contributed to rural development and poverty alleviation, making aquaculture an integral part of the rural economy.

The mix of small-, middle-, and large-scale commercial farmers has made finfish production in ponds highly diverse. Until early 2000, production ranged between 50 and 100,000 kg/ha (Table 10). In stocked ponds receiving no fertilizers and feed, production levels of 50–500 kg/ha were reached. With a combination of fertilizers and supplemental feeds, production increased to 1000–4000 kg/ha, which could be further increased to 10,000 kg/ha using well-formulated feeds and aeration. Without water exchange, production up to 10,000 kg/ha was possible, with dissolved oxygen availability being the principal factor limiting production (Table 10).

Production levels of 20,000–35,000 up to 100,000 kg/ha become possible, when removing metabolites (e.g., NH_4, CO_2) and suspended solids (Table 10). The latter can be done through water exchange or by stimulating in-pond water purification processes, as done in partitioned ponds, in-pond raceways, or split ponds. In these systems, fish are raised in high density in 5%–25% of the pond area. The remaining pond area mainly acts as an algal reactor, where algae remove metabolites and provide oxygen. The higher the primary productivity, the higher the capacity of the pond to hold fish. If the primary production is raised by a factor of 2–4, the production capacity of the pond raises with the same factor. These systems work well, provided the algal density is controlled to avoid dissolved oxygen depletion due to algal die-off (Cremer & Chappell, 2014; Tucker & Hargreaves, 2012). A technique used in the past, but with little follow-up today, is confinement of fed fish in in-pond cages, with free-roaming fish feeding on natural food between cages fed pelleted feed. The increase in primary production was small, raising total production by ca. 25%. Another in-pond water purification technique is the creation of biofloc through intensive

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 9 The production, culture system, and use of the major seaweeds cultured in 2019, their production system, and use for food and non-food purposes.

Cultured seaweed	Culture system Primary	Secondary	Production MT(fresh)	Use % Used as food	Other uses
Brown algae					
Alaria esculenta	Suspended long lines		105	100	
Laminaria japonica	Suspended long lines		12,273,519	50	Alginate industry
Macrocystis pyrifera	Suspended long lines		2	0	
Nemacystus decipiens	?		20	100	
Saccharina latissima	Suspended long lines		229	20	Alginate industry
Sargassum fusiforme	Suspended long lines		303,797	100	
Undaria pinnatifida	Suspended long lines		2,563,477	100	
Other Phaeophyceae	?		1,252,264	unknown	
Total			16,393,413	55	
Red algae					
Eucheuma denticulatum	Suspended long lines	Lines attached to the Bottom	179,360	0	
Eucheuma spp.	Suspended long lines	Lines attached to the bottom in shallow waters	9,817,689	0	
Gracilaria spp.	Suspended long lines		3,638,554	1	Agar industry
Gracilaria gracilis	Wild harvesting		273	0	Agar industry
Gracilaria verrucosa	Bottom culture		1006	0	Agar Industry
Kappaphyccus alvarezii	Suspended long lines		1,625,164	0	Carrageenan industry
Porphyra spp.	Suspended nets	Intertidal based nets	2,123,040	100	
Porphyra tenera			861,083	100	
Total			18,246,169	17	
Green algae					
Capsosiphon fulvescens	?		3386	100	
Caulerpa spp.	Ponds		1090	100	
Chlorella vulgaris	Bioreactors		5	0	Health Food
Codium fragile	Ponds		3258	100	
Dunaliella salina	Bioreactors		0	0	Carotene production
Enteromorpha clathrata	Suspended long lines		0	100	
Haematococcus pluvialis	Bioreactors		242	0	Carotene Production
Monostroma nitidum	Suspended long lines		6321	100	
Total			14,302	98	
Grand total			34,653,884		
FAO reported production in 2019 (FishStatJ, 2023)			34,735,590		

Note: Species listed represent 99% of the global seaweed production. MT, metric ton (FAO/FishStatJ, 2023).

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 10 Aquaculture production at increasing levels of input for pond-raised channel catfish and tilapia in 1985 until early 2000 (Modified from Boyd (1990) and Verdegem et al. (2006) in Tucker and Hargreaves (2012)).

	Annual production (kg/ha)		
Management input	Channel catfish	Tilapia	Limiting factor
Stocking only	50–100	200–500	Primary productivity
Stocking, fertilization	200–300	1000–3000	Primary productivity
Stocking, fertilization, supplemental feeding	500–1000	3000–4000	Dissolved oxygen
Stocking, feeding	1000–2000	3000–4000	
Stocking, feeding, emergency aeration	4000–6000	4000–6000	Dissolved oxygen
Stocking, feeding, continuous aeration	6000–10,000	6000–10,000	Dissolved oxygen, metabolites
Stocking, feeding, continuous aeration, water exchange	10,000–20,000	15,000–35,000	Metabolites
Stocking, feeding, continuous aeration, intensive mixing		20,000–100,000	Metabolites, suspended solids

aeration and water agitation. Bioflocs are a mix of autotrophic and heterotrophic bacteria that purify the water and can be eaten by filter feeders (e.g., tilapia) improving the feed utilization efficiency (Avnimelech, 2007; Dauda, 2020).

Since the first use of fish feeds, the quality of pelleted feed continually improved (Edwards, 2015), due to better processing (extrusion, floating or sinking pellets, higher water stability), formulation (novel ingredients, better balance of macro- and micro-nutrients) and use of additives (prebiotics, probiotics, enzymes). Better feed quality improves the feed utilization efficiency and reduces waste accumulation, leading to 15%–40% higher production levels today than indicated in Table 10 under similar management conditions (Boyd et al., 2020).

With the development of feeds that directly address the nutrient requirements of culture species and the availability of efficiently electric-powered aerators (Boyd et al., 2020), the self-purifying capacity of ponds improved (Boyd & Chainark, 2009) allowing the increase of feed inputs. This concurred with improvements in nutrient utilization efficiency, and less waste accumulation and discharge per kg fish produced. Nevertheless, due to the high culture intensity, more nutrients are produced than the pond can handle. An important constraint is that fish waste resulting from the pelleted feed is nutrient rich (e.g., nitrogen, phosphorous) and energy poor (e.g., carbon), causing microorganisms in the pond lacking the energy to mineralize the waste. Raising the C:N ratio of the nutrient input to aquatic systems above 12 by providing more carbohydrates, fish performance (e.g., growth, survival, FCR) and water quality improves, in systems ranging from extensive to intensive, the latter including biofloc systems (Asaduzzaman et al., 2009; Kabir et al., 2019). A constraint is that by raising the carbon input, the carbon emission from the pond increases (Tinh et al., 2021). Therefore, Kabir, Verdegem, et al. (2020) replaced pelleted feed easily with digestible starch with fibers, which are difficult to digest by the fish. A large fraction of these fibers will enter the pond through the feces, where microorganisms can break them down to get energy. As a result, more nutrients are assimilated into the food web, providing natural food. Using this concept, up to 74% of the nitrogen supplied with the feed was harvested in fish biomass, without a need to add extra carbon to the system. In consequence, CO_2 emissions also declined. This nutritious pond concept (Joffre & Verdegem, 2019; Verdegem et al., 2021) can be applied with herbivorous and omnivorous species in fed and/or aerated ponds with a biomass of up to 15,000 kg/ha at harvest.

To intensify further, wastes should be either discharged, recycled, or purified. Discharging nutrients without treatment causes environmental damage (e.g., eutrophication, biodiversity loss) (Boyd et al., 2007), and this practice should be abandoned. Options are to collect wastes and turn them into fertilizers or biogas. Wastes can also be (partially) recuperated through integrated multi-trophic aquaculture, or treated in recirculation systems (sections below).

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

As an industry, the combination of all these technologies made aquaculture more environmentally sustainable and resource-efficient. In addition, these mature technologies can be adjusted to other geographies, facilitating the development of sustainable aquaculture outside Asia.

It should be noted that ponds are integrated into the landscape, playing a key role in trapping nutrients from run-off, and the apparent nutrient use efficiency (NUE) can be higher than for other animal production systems. A broader analysis of the reactive nitrogen (Nr) flow in Chinese inland aquaculture ecosystems suggests 72% of the feed nitrogen is retained in aquatic products (Luo et al., 2018). This is a very high efficiency, and, in doing so, more focus on aquaculture can make food production systems more resilient to climate change.

2.2.2 | Crustacean aquaculture systems

Factors influencing finfish culture (Table 4) also affect crustacean production. One important difference is that most crustaceans live on the bottom. Therefore, it is important to maintain the bottom clean and with sufficient oxygen. When wastes accumulating at the bottom are not regularly removed, this restricts the culture capacity for crustaceans, resulting on average in a lower production output than with finfish for similarly designed and managed finfish ponds, and thus higher operational costs. In addition, crustaceans are vulnerable to predation and reduced feed intake when molting.

Shrimp aquaculture started with stocking post larvae (PL) that were caught in the coastal zone in ponds with tidal water exchange. The latter helped to maintain water quality and provided nutrients to the system. The farming system gradually improved. Hatchery-reared PL replaced wild-caught PL and commercial feed was applied during the last month of culture. Systems were extensive, stocking 2–15 PL/m^2. Semi-intensive culture systems use emergency aeration, pelleted feed, and exchange water daily, especially during the last months of culture, stocking 25–30 PL/m^2 and producing 3–6 metric ton/ha. Intensive cultures start with stocking densities of 30–50 PL/m^2 aiming to produce 10 metric ton/ha. In super-intensive systems, this goes up to 300–800 PL/m^2 to produce 35–110 metric ton/ha. The more intensive, the more aeration, water exchange, probiotics, and feed additives are used to maintain a healthy culture environment. Production is further enhanced by intermediate partial harvests, allowing to produce more while staying within the carrying capacity of the farming system and providing more frequent income.

Losses due to disease in shrimp farming are high (Shinn et al., 2018; Stentiford et al., 2012). Various approaches to minimize the impact of disease on production are possible. In Latin America, the aim is to develop farming systems resilient to disease and to cope with pathogens present in the production environment (Alday-Sanz, 2018). Large semi-intensively operated ponds are used for grow-out, focusing on maintaining a healthy culture environment.

Another approach to keep the pathogen pressure low is the polyculture of shrimp and finfish, either in crop rotation or in co-culture (Paclibare et al., 1998). This practice makes shrimp farming more sustainable (Yi & Fitzsimmons, 2004) by reducing the environmental impact and reducing the incidence of shrimp disease (Halim and Juanri, 2016; Martínez-Porchas et al., 2010). One method is to stock fish (e.g., tilapia) in a reservoir pond and circulate water between the reservoir and adjacent shrimp ponds. Antimicrobial peptides in the fish skin kill shrimp pathogens, keeping the pathogen pressure of bacteria (Masso-Silva & Diamond, 2014) and viruses low. The latter approach was applied in tilapia-shrimp-intensive polyculture systems in Indonesia (Figure 3).

The use of specific pathogen-free (SPF) or specific pathogen-resistant (SPR) shrimp stocks allowed hatcheries and broodstock multiplication centers to upgrade biosecurity, benefiting the downstream grow-out farming sector. In addition, large corporate producers incorporated this aspect into the quality assurance (QA) system linked to their biosecurity and operation management. Every input into the hatchery or farm requires quality control (QC) approval as part of the QA system. This results in higher profits and sustainability, and could be applied more widely to raise efficiency across the shrimp industry. The "vannamei PL efficiency index" calculates the amount (metric ton) of shrimp produced per million PL stocked by country. The index gives a broad indication of disease-related losses.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

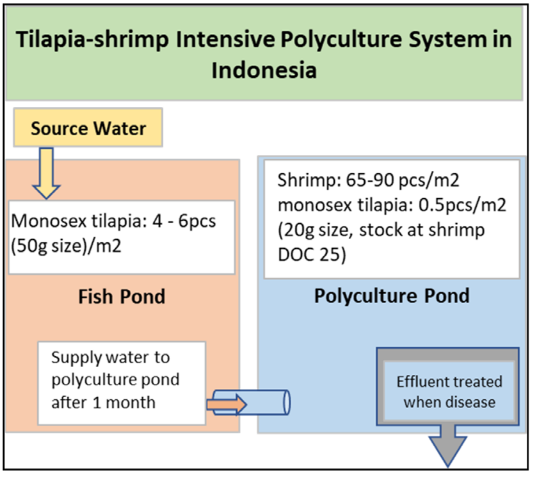

FIGURE 3 Example of an integrated intensive tilapia-shrimp polyculture system. The approach is flexible, as the water exchange between the fish pond and polyculture pond can vary, as well as the stocking density of tilapia in the polyculture pond. In case disease occurs, it is important to make sure pathogens are eliminated from waste leaving the farm. unpublished data, PT. AWS, Indonesia, 2011.

Whereas strong-producing countries have an index of 9–11 metric ton/million PL, the index can be close to 1 in poor-performing countries, indicating that large improvements across the shrimp industry are still possible (Merican, 2021).

Technological solutions are also proposed. One approach is to apply a combination of using (i) small, easy-to-operate, grow-out ponds, (ii) high on-farm aeration and energy capacity, (iii) a shrimp "toilet" at the center of each pond, and (iv) a large reservoir area for water exchange, taking 60% of the farm area and leaving maximum 40% for grow-out (Kawahigashi, 2018). The goal is to maintain a clean bottom environment while minimizing off-farm water exchange during culture for biosecurity and operating small, easy-to-manage, super-intensive grow-out ponds. Different mixes of physical and chemical treatment methods are today commonly applied in shrimp hatcheries and grow-out operations using partial or complete combinations of sedimentation, filtration, foam fractionation, ozonation, and UV irradiation.

Another important technological improvement is the development of precision hardware and software allowing hatcheries and farms to collect reliable data (e.g., PL or larval counting with >95% accuracy) and get feedback through artificial intelligence and the Internet of Things. A similar development is ongoing in feeding technology. Commercial feeds represent 60% of the operating cost of shrimp farming. The use of automatic feeders, reacting to the noise made by foraging shrimp, is effective in reducing feeding costs and improving efficient and profitable nutrient use. This technology is presently spreading quickly through the industry. Joint efforts between feed manufacturers and companies making automated feeders to adjust the physical properties of manufactured aquafeeds to automatic feeder design and operation are ongoing and will lead to further improvements in feeding efficiency (Molina & Espinoza, 2018).

2.2.3 | Extractive systems

Mollusks

While there are common and general methods and gear for shellfish grow-out, there is some regional specificity with regard to methodologies. Many innovations are shared between growers and incorporated into local practices. Bottom culture employs direct planting, mesh bottom culture bags, rack and bag systems (oysters and clams), and off-bottom culture systems using primarily long line and raft systems with hanging lines (mussels, scallops).

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Offshore aquaculture requires specialized gear that is technically and economically viable, can withstand the challenges of the offshore environment, and meet government regulations. There are successful offshore aquaculture systems in operation currently, but they are few. Many are still experimental or struggling to obtain the necessary permits to allow commercial expansion.

Reliance on wild seed/spat for the culture of bivalve mollusks is still very high for many regions and species globally. Hatchery design and technology have made major advances during the last few decades in conditioning, spawning, larval care, and setting, with higher survival of the animals seen as this occurred. As noted by Sarkis et al. (2021), they vary with site characteristics, target species, production level, culture methodologies, and available funds, and range from small family operations to large corporate multi-species facilities with automated systems. Phytoplankton production in hatcheries has similarly advanced with computer-aided monitoring and metering of feed to larval shellfish, again enhancing survival and growth. Development of improved settling procedures and equipment have allowed growers to produce seed aimed at their specific needs, and advances in large-scale settling and planting, especially of oysters, was a direct result of more effective handling of materials.

Most molluscan shellfish in aquacultures such as oysters, clams, scallops, and mussels are filter-feeders that do not require artificial input of feed. Farming of these species has little impact on the environment and is expected to expand significantly in the future (Shumway, 2011). Molluscan shellfish are cultured in open waters and are subjected to wild fluctuations in environmental parameters. Mollusks have high fecundity and a Type III survivorship and, even in the adult stage, they are prone to mass mortality triggered by environmental stress and diseases. Climate change, for example, warming and acidification of the ocean, pose a great challenge to molluscan aquaculture. Most molluscan shellfish in aquaculture have little or no history of domestication. Selective breeding and advanced genetic improvements are therefore needed to enhance the production efficiency and resilience of molluscan shellfish (Shumway, 2021).

Selective breeding has contributed to shellfish aquaculture through the development of disease-resistant and fast-growing strains, and varieties with unique shell colors (Guo, 2021). Sterile triploids that grow faster and maintain meat quality during their spawning season have become important to oyster farming. Hybridization has also proven to be useful in the genetic improvement of mollusks. In China and elsewhere, over 30 molluscan species have been subjected to some genetic improvement, although the level of breeding is far inadequate for what the shellfish aquaculture industry needs. Long-term and well-maintained shellfish breeding programs are few, and genetic improvements are mostly moderate (Shumway, 2021). While traditional selective breeding is insufficiently implemented to have an impact on most mollusk species, new breeding technologies are posed to make a great impact on aquaculture (Stokstad, 2020). Genomic selection that has demonstrated its power in agriculture crops and livestock, promises to accelerate the genetic improvement of molluscan shellfish. Genomic selection is more effective and can eliminate the need for expensive phenotyping. Genomes have been sequenced for many cultured mollusks, and high-throughput genotyping platforms, such as single-nucleotide polymorphism (SNP) chips, are being developed in several species for genomic selection. Gene-editing through CRISPR/cas9 offers the opportunity of modifying target genes in a way that mimics natural mutation, an approach that is fundamentally different from the introduction of foreign genes in genetic engineering. While these new technologies are exciting, they have to be rigorously evaluated for shellfish aquaculture following proper regulations and with the support of the shellfish industry (Shumway, 2021).

Seaweed

During the past 300 years, and particularly since the second half of the 20 century, mariculture of seaweed became common, starting with culturing wild seaweed (Buschmann et al., 2017). The discovery that the commonly grown *Pyropia* life history included heteromorphic life stages identified previously as two different species allowed the development of a whole farming industry that now provides nori globally. Around the same time, introducing the kelp *Saccharina japonica* (formerly *Laminaria japonica*, kombu) in China, allowed the change from simply harvesting the wild seaweed stands to the culture of selected strains reproduced under controlled conditions. From this point, other countries such as Korea also started culturing seaweed. Soon, seaweed mariculture bypassed the amounts of

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

seaweed collected in the wild. In contrast to other aquaculture commodities, the amount of seaweed collected in the wild is today negligible compared to the amount of seaweed cultured (Chopin & Tacon, 2020; Naylor et al., 2021). Nevertheless, considering a large number of seaweed species, and with seven species to provide 97% of the global production of aquatic plants, many species remain today to be tested for culture. In consequence, the full potential of seaweed mariculture remains largely unknown and requires further research (Hafting et al., 2015).

Algal productivity depends primarily on light and nutrient availability, with nitrogen being the limiting nutrient in the marine environment. Important modulating factors include temperature, salinity, pH, and other environmental factors affecting seaweed metabolism (Santelices, 1999). As light decreases rapidly with depth, the development of floating near-surface cultivation technologies gave a major boost to the expansion of seaweed culture, allowing to culture in regions further offshore. The majority of seaweeds today use near-surface cultivation techniques (Table 9). The growth in the production of *Pyropia* and *Eucheuma/Kappaphyccus* illustrates this point (López-Vivas et al., 2015). In addition, the industry seeks to raise its value by developing highly productive strains and through novel processing technologies both for food and phycocolloid extraction (Hwang & Park, 2020). Nevertheless, the domestication of seaweeds demands better insight into the ecological and genetic diversity of wild populations and the impact of cultivars on the production environment (Valero et al., 2017). Experience with seaweed farming, including how to make optimal use of the prevailing environmental conditions at the production sites, is largely missing in occidental countries, making capacity building a prerequisite to the successful development of seaweed farming (Santelices, 1999).

2.2.4 | Inland and marine cage aquaculture

With the exception of extensive cage culture of filter-feeding species (e.g., silver and bighead carp, milkfish) in eutrophic lakes (Delmendo & Gedney, 1976; Husen et al., 2012), cage aquaculture is intensive, relying on pelleted feed. Fish can be maintained in high density, as feed wastes are flushed out from the pond with exchange water. If the waste loading is higher than the lake can absorb fish kills might occur due to oxygen depletion. Therefore, limits must be set to the total biomass produced in public water bodies. Models exist to indicate safe limits to production (David et al., 2015). Pollution in marine areas from cage aquaculture is also a concern, especially in shallow, partially enclosed areas.

In 2019, 16% of the global finfish production was produced in marine or coastal environments, of which nearly 1/3rd was Atlantic salmon (Tables 2 and 3). High-value and high-profit margins give Atlantic salmon, which is the third most valuable aquaculture finfish species produced today, room to innovate, including making larger and stronger cages that can be deployed offshore, away from heavily used coastal zones (Chu et al., 2020). A downside is the high capital and production costs involved (Jansen et al., 2016), which also holds for other species cultured at sea. This partially explains the slow growth of marine cage aquaculture, in spite of the fact that from an environmental point of view, there is ample room for the development of marine cage aquaculture (Gentry et al., 2017). Another reason is that herbivorous or omnivorous species produced inland are cheaper than marine species which are mostly carnivores and more expensive to produce. For now, cheaper herbivorous and omnivorous fish species are more widely accessible and contribute significantly to food security and reduced poverty reduction. This trend will not change within the near future (Belton et al., 2018; Belton et al., 2020), but might change over the long term. Considering the projected increase in global income, Costello et al. (2020) predict a 36%–74% increase in the production of marine aquaculture by 2050, when the majority of people will be middle class.

Coastal areas for shrimp pond development are limited, while the sector aims to expand further. One option is cage farming. Crustaceans, especially shrimps, are difficult to culture in marine cages, mainly due to cannibalism during molting. Shrimp culture in cages, either as shrimp–seaweed polyculture (Lombardi et al., 2006) or monoculture at varying stocking densities (Cuvin-Aralar et al., 2009) looked economically feasible, also at high stocking density. Biosecurity is, however, a problem in marine shrimp culture at sea, as is pollution control. The latter might be partially controlled by the implementation of integrated multitrophic aquaculture.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

2.2.5 | Recirculating aquaculture systems (RAS)

The term RAS is not well defined. The key element is that RAS use significantly less water than traditional systems by fully or partially purifying and reusing culture water. They range from semi-intensive open systems to fully recirculating indoor systems and are used for producing a broad range of freshwater and saline species. While finfish are mainly produced in RAS, also crustaceans, mollusks, and aquatic plants can be produced, the latter mainly for hatchery and nursery purposes. The simplest RAS remove suspended solids (feces and uneaten feed) from the recirculation loop by sedimentation or mechanical filtration and aeration (e.g., airlifts), while higher intensity RAS apply biofiltration and more advanced treatment technologies such as for example, UV treatment, ozonation, and foam fractionation to maintain good water quality. Compared to traditional aquaculture systems, it is possible to exert a higher degree of control on rearing conditions in RAS and to collect and treat waste/effluents, reducing the impact on external environments. The risk of escapees is reduced (and eliminated in fully closed systems), treatment of intake-and outlet water improves disease control and reduces the need for medicine, it is possible to produce year-round, and the most advanced RAS can be situated almost anywhere, including close to markets saving transportation costs and ensuring full product traceability (Timmons et al., 2018).

Recirculation technology has been used since 1980 to produce fry and fingerlings of different species, for instance for African catfish rearing in the Netherlands. Partial RAS technology has been applied in Chile since the 1990s as a means to comply with environmental regulations and save pumping energy for land-based production of exotic abalone (*Haliotis rufescens* and *Haliotis discuss hannai*) in seawater (Flores-Aguilar et al., 2007), and later for cultivation of endogenous species such as Chilean scallops (*Argopecten purpuratus*).

To produce fish for consumption, RAS are mainly used for finfish production, both indoor or outdoor. Semi-intensive, commercial RAS termed "Model-Trout-Farms" have been used in Denmark since 2004 as a means to increase land-based production of rainbow trout (*Oncorhynchus mykiss*) while reducing the impact on adjacent aquatic environments and complying with the EU Water Framework Directive (Dalsgaard et al., 2013; EU-Water-Frame-Directive, 2000; Jokumsen & Svendsen, 2010). This concept, or parts of it, has spread to other European countries although not as part of regulatory setups.

During the last decade, investments in RAS have intensified. These RAS are increasingly used in northern Europe and Chile for producing Atlantic salmon smolt before transfer to sea cages (EUMOFA, 2020). Growing smolt in RAS improves their growth and reduces subsequent sea-lice infestation problems in net cages (Clarke & Bostock, 2017). Environmental concerns such as lack of freshwater and limited in-fjord permits have further contributed to this development. An increasing number of intensive RAS have—or are currently—being constructed globally aimed at producing primarily Atlantic salmon, but other species are also targeted such as African catfish, barramundi, grouper, rainbow trout, seabass, seabream, sturgeon, tilapia, pike perch, and yellow tail kingfish (EUMOFA, 2020).

In Thailand, vertically integrated shrimp farming corporations developed RAS technology. These systems are challenging when culturing crustaceans in water reuse systems as the molting cycles require extra mineral inputs to compensate for minerals lost with each shed exoskeleton. This requires the development of special feeds to compensate for mineral deficiencies. In addition, cannibalism during molting leads to lower survival, and sale prices cannot cover the high production costs in RAS. In addition, the price of shrimp broodstock is very high, while these animals do not molt frequently. Combined with high biosecurity and product quality, this makes raising broodstock in RAS commercially feasible. To produce consumption-size shrimp, however, the production cost is too high. Some RAS farms to raise whiteleg shrimp or lobster have also been constructed in Europe and elsewhere. These farms can be successful if producing for special markets that fetch high prices.

Simple RAS technology has been applied in China since the 2000s for producing a range of species in both freshwater and seawater (shrimp, sturgeon, grouper, trout, turbot, sole, crab, salmon, seabass, pufferfish, sea cucumber, tilapia, a.o.). In the 2010s, RAS in China gained more governmental attention and advanced so-called "precision RAS" have been developed focusing on improving the engineering design, water treatment technology, and automation control (Huang, 2019).

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

On the downside, RAS are expensive to build and operate and they are challenging to manage, requiring a skilled workforce to ensure successful operation. They have a high carbon footprint in terms of compound feed (as applies to all compound-fed aquaculture systems) and on-site energy requirements (especially for pumping) if electricity comes from fossil fuels (Badiola et al., 2018; Martins et al., 2010; Midilli et al., 2012; Samuel-Fitwi et al., 2013; Song et al., 2019; Van Rijn, 2013; Wilfart et al., 2013). In addition, saltwater RAS require equipment that can withstand corrosion, and risks of gas accumulation such as toxic H_2S and CO_2 are higher than in freshwater RAS (EUMOFA, 2020).

2.2.6 | Culture-based fisheries, integrated multi-trophic aquaculture and aquaponic systems

Culture-based fisheries

Numerous seasonal water bodies are scattered throughout the world. Through culture-based fisheries, the fish production from these water bodies can be enhanced, contributing to food security and enhancing rural livelihoods (Subasinghe et al., 2013). Conversely, wetlands and deltas worldwide have been transformed into agricultural or urban land, and sustaining the natural productivity and species diversity can be challenging. Due to the construction of dams and diversion of the natural water flow, fisheries production declined, although traditionally, fisheries significantly contributed to income and food security in wetland areas. In rice field areas in Cambodia, different forms of culture-based fisheries, ranging from pure fisheries to nearly fully controlled aquaculture are practiced side by side. Through proper management, these systems contribute to food and nutrition security, rural livelihood diversification and income improvement, and biodiversity conservation (Freed, Barman, et al., 2020; Freed, Kura, et al., 2020).

Considering a large number of existing water bodies suitable for culture-based fisheries, the potential contribution to global fish production is large. De Silva (2016) calculated that if 20% of the small water bodies in Asia would be used for culture-based fisheries, aiming for a production of 900 kg/ha, in Asia alone, 10.7 Mt could be produced annually. When developing culture-based fisheries, care should be taken to produce within the capacity of the water bodies to neutralize the wastes resulting from feeding.

Integrated multi-trophic aquaculture (IMTA)

One concern of marine-fed aquaculture is the release of organic and inorganic wastes (Schneider et al., 2005; Wang et al., 2012). In integrated multi-trophic aquaculture systems (Chopin et al., 2001; Neori et al., 2007; Troell et al., 2009) fed species are linked to extractive species so that feed waste becomes food for extractive species (Chopin, 2010; Chopin et al., 2001; Neori et al., 2007; Troell et al., 2003). The idea behind the IMTA approach is that recycling of waste nutrients results in a reduced nutrient release into the environment, while the overall productivity of the production system improves (Chopin et al., 2012). Schneider et al. (2005) and Troell et al. (2003) reported variations in nutrient retention efficiency in IMTA ranging between 2% and 100% depending on species, waste type, culture technique, and culture intensity. Most IMTA systems are deployed at sea, with land-based IMTA reaching higher nutrient retention efficiencies than open-water IMTA (Reid et al., 2017). Combining different species is not always easy, due to differences in growth rate and seasonality and the large areas needed (Broch et al., 2013). Also, the retention efficiency of fish wastes by bivalves in IMTA is limited because they need a minimum of 15%–30% organic matter from fish waste in their diet to contribute to bioremediation (Cranford et al., 2013). Consequently, IMTA at sea for bioremediation is still in its pilot phase, with the exception of China. Hughes and Black (2016) suggested that extractive species can also obtain nutrients not originating from fed species. This agrees with practices in China, where nitrogen inflow from land and phosphorous influx from open sea are the major sources of nutrients in IMTA, with fed cage culture contributing a minor fraction of the nutrient flow through the IMTA (Li et al., 2016; Mahmood et al., 2016a). Successful IMTA requires significant architecture. Variations on this system have become routine in China including combinations of seaweed, bivalves, finfish, sea cucumbers, and others

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

(Liu Hui, Pers. Comm.). IMTA is theoretically appealing in terms of sustainability, but from a management perspective, it is often not possible to optimize the production and marketing of multiple crops that are linked in these systems.

Aquaponics

In aquaponics, effluents from RAS supply bioavailable nutrients for plants (Paudel, 2020; Wongkiew et al., 2017). These are expensive systems (Palm et al., 2018) because both a RAS and a hydroponic system need to be installed. Plants that do well in hydroponics also do well in an aquaponic system. If nutrients for plants are lacking in the RAS effluent, extra fertilizers can be applied to the plants (Eck et al., 2019; Maucieri et al., 2019). Whereas in coupled aquaponic systems, the same water flow passes through all components of the aquaponic system, in a decoupled system water flows through fish tanks, filters, and hydroponics can be adjusted (Goddek et al., 2016; Monsees et al., 2017). Aquaponic systems are promising because nutrient losses from aquaculture are reduced. A recent development is a flocponic system in which instead of a RAS a biofloc system is linked to a hydroponic system (Pinho et al., 2017). Major constraints to the profitability of aquaponic or flocponic systems include the need to have access to high-value markets for vegetables and for fish, the broad range of know-how involved, and the leading role of vegetables in securing financial success (Bosma et al., 2017). This in part explains the slow uptake by the industry.

3 | CURRENT ISSUES AND CHALLENGES IN AQUACULTURE

3.1 | Environmental impact from aquaculture

3.1.1 | Fed species

Concerns about the environmental impact of finfish aquaculture were flagged decades ago (Klinger & Naylor, 2012; Naylor et al., 2000). Although considerable improvements were achieved in technologies to reduce pollution through water treatment processes and better feeding methods (Xiao et al., 2019; Zhou et al., 2018), the environmental impacts of fed aquaculture remain high. Globally, the demand for animal products, including aquaculture species, will continue to grow due to population growth and rising incomes during the next decades (Hilborn et al., 2018). With fed aquaculture, impacts are mainly due to nutrients provided in the feed that are not retained by the cultured species (Hilborn et al., 2018), and increased energy inputs per unit surface area in relation to intensification (Ghamkhar et al., 2021). In a life cycle assessment of aquaculture systems with different levels of culture intensity in Bangladesh, Henriksson et al. (2018) found that across systems, fish yield is positively correlated with eutrophication and negatively correlated with water use, while no significant correlation was found with land use and climate change (CO_2 emission). The feed conversion ratio (FCR) is an easy-to-measure indicator of NUE (Boyd et al., 2007), and is a better indicator of the environmental impact of fed aquaculture than the type of farming system, the latter being either low-or high-intensity ponds, marine or freshwater cages, or RAS (Ghamkhar et al., 2021). Henriksson et al. (2018) identified improving the NUE in aquaculture as the most effective way to reduce the environmental impacts of aquaculture. This notion concurs with the concept of ecological intensification, which, in addition to improving the NUE of aquaculture, also aims to maintain or restore ecosystem functioning and diversity (Aubin et al., 2017). Nevertheless, further improvements are necessary. For instance, in China, the total nitrogen and phosphorous discharge through surface waters was similar for livestock and aquaculture, although the livestock sector is four times larger than the aquaculture sector (Zhang et al., 2015). Priority should be given to the recycling of nutrients as fertilizer, energy sources, or nutrient input for other organisms (Chopin et al., 2012; Drózdz et al., 2020; Nhut et al., 2019; Wang et al., 2012).

Aquaculture in ponds has been intensified several times above the natural carrying capacity of a conventional pond by providing intensive aeration (Itano et al., 2019; Jayanthi et al., 2021; Kumar et al., 2013) and removing waste

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

from the system (Nhut et al., 2019). This helps to raise the production, but the cost to the environment remains critical. Area-based wastewater treatment in combination with renewable energy generation and use can transform pollution mitigation from ponds into a productive and green practice. Aquatic plants and sediments can trap waste nutrients while photovoltaic cells or wind energy can reduce fossil fuel use. The economic feasibility of such interventions is location dependent. Integrating this approach for a cluster of farmers might be more feasible than for individual farmers.

3.1.2 | Extractive systems

There is clearly a consensus that extractive species (filter-feeders; algae) exhibit orders of magnitude lower ecological footprint than cultured-fed species (e.g., tuna, salmon, shrimp) (Naylor et al., 2021). It is important, however, to realize that if the aquaculture production does not properly consider aspects such as scale, site selection, and the effect of culture species on their environment, extractive species can also trigger environmental issues. In the case of seaweed, the competition for space with seagrass meadows, the addition of fertilizers, and the use of chemicals for controlling grazers are potential risks that should be avoided. For example, in South Korea and Japan, fertilization of seaweed farms has been banned (Hurd et al., 2014). Hence, careful consideration of possible negative impacts on the coastal or offshore marine environment is needed.

Coastal pollution remains a significant challenge to shellfish aquaculture. The input of sediment, soils, and nutrients from numerous point and non-point sources affects the growth and survival of the animals as well as their ability to be sold for human consumption (Boyd et al., 2020; Danopoulos et al., 2020). In addition to point sources, runoff from increasing amounts of impervious surfaces in many coastal areas can lead to waters being banned for use in shellfish cultivation.

Harmful algal blooms (HAB) have increased in frequency and range, and increased their seasonal growth windows (Hallegraeff, 2010). These HAB occur regularly in areas occupied by shellfish aquaculture and can have significant impacts on shellfish culture through mortalities or delayed harvests until toxins are depurated (Basti et al., 2018; Matsuyama & Shumway, 2009; Shumway, 1990; Trainer et al., 2020). Shellfish culturists are already addressing many climate-related issues and identifying new species for culture, as well as implementing IMTA practices and HAB mitigation strategies. Climate change and HAB interactions will be ongoing and become increasingly important considerations for shellfish culturists. Mitigation and remediation measures, coupled with the ability of bivalve mollusks to adapt to environmental perturbations, will allow for the continued success of aquaculture systems.

Seaweed aquaculture systems are lagging behind in relation to other food sectors in breeding, pathogen management, and adaptation of production systems to local nutrient, light, and temperature conditions (Buschmann et al., 2017; Naylor et al., 2021). Here too, disease interferes with farming efficiency. Bacterial and viral outbreaks are especially high in intensively farmed seaweed systems, where disease management can account for up to 50% of farm-variable costs (Barbier et al., 2019). New seaweed cultivars with higher yield potential, disease resistance, nutritional qualities, and consumer attributes are needed to ensure production, growth, and increased value for the industry, but an understanding of factors that impact breeding programs and how they can affect wild seaweed populations is needed (Valero et al., 2017). In addition, the use of thalli fragmentation propagation techniques seems to have reduced the genetic diversity of species like *Eucheuma/Kappaphyccus* and *Gracilaria chilense* (Eggertsen & Halling, 2021; Guillemin et al., 2008) by unforeseen selection that appears to influence productivity and resistance to pathogens and epiphytes (Hurtado et al., 2019). Nevertheless, other selected genotypes did not show evidence of decreased productivity or loss of resistance to epiphytes (Usandizaga et al., 2020). Clearly, these aspects require further in-depth studies to avoid the loss of genetic diversity or the introduction of genetically distinct individuals of a species in a region, thus introducing new genes that might modify the adaptation capacity of the species under cultivation (Valero et al., 2017).

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

3.2 | Land area

With fed aquaculture, ca. 0.1–0.4 ha of the land area is needed to provide dietary plant ingredients to produce 1 MT of carnivorous and herbivorous/omnivorous animals, respectively (Aas et al., 2019; Boyd et al., 2007). An advantage of fish culture is that, in contrast to terrestrial animals, it is possible to move production to aquatic environments (Boyd et al., 2020), reducing space and freshwater constraints. With intensification, more fish are produced per unit area, but, because feed is the main nutrient input, intensification has a minor impact on land area requirements per ton of fish produced. Compared to terrestrial animal production, aquaculture requires less land than terrestrial animals, using only ca. 4% of the total land area for crops dedicated to animal feed production (Hua et al., 2019; Troell, Naylor, et al., 2014). If the production volume of terrestrial animals from today onwards did not increase, with aquaculture fulfilling the increased demand for animal protein until 2050, then only 10% extra cropland for feed production would be needed for aquaculture feeds. Such a shift toward a human diet richer in aquaculture products would save 70–76 million ha of cropland, an area close to the land mass of Turkey, compared to a scenario with no shift in the balance between terrestrial and aquatic meat consumption (Froehlich et al., 2018).

In shrimp farming, farmers and investors might abandon shrimp production sites after a few consecutive crop failures due to disease. The area of these derelict ponds is large, covering an estimated 100,000 ha globally, although exact data are missing. Reuse of these areas is possible, mainly by focusing on soil and water quality in the wider production area. By focusing on mixed mangrove-pond systems, shrimp production can recover, raising production and creating direct and indirect employment (Alam et al., 2022; Bosma et al., 2012).

3.3 | Water use

Compared to plant and terrestrial animal production, water use in aquaculture is relatively small and not well accounted for in food-water budgets (Gephart et al., 2016). Feed (ingredients, transport, processing), on-farm water use, and fish processing are major categories of water use in aquaculture (Gephart et al., 2016; Henriksson et al., 2017; Verdegem & Bosma, 2009). Intensification reduces the water use per unit production (Henriksson et al., 2018; Verdegem et al., 2006), making aquaculture more water efficient than meat production. With the expected growth in marine aquaculture (Costello et al., 2020; Naylor et al., 2009), the overall freshwater use efficiency by aquaculture will improve further.

3.4 | Climate change and greenhouse gas emissions

The high diversity in species, culture systems, feeds, and salinity tolerance contributes to the resilience of aquaculture to climate change but does not make aquaculture disaster proof (Troell, Metian, et al., 2014). Extreme weather events and sea level rise might cause flooding, water shortage, and changes in salinity, temperature, and dissolved oxygen availability. Diseases might become more frequent, resulting in higher losses and reduced animal welfare, and affecting the supply of external feed inputs to aquaculture (Reid et al., 2019). Conversely, aquaculture contributes to global warming, due to increased energy and feed inputs linked to intensification (Bostock et al., 2010) and greenhouse gas (GHG) emissions. Although GHG emissions from aquaculture are modest compared to beef production (MacLeod et al., 2020), in semi-intensive coastal shrimp ponds or rice-fish systems methane emission is a concern, while there is nitrous oxide (N_2O) volatilization in more intensive systems (Henriksson et al., 2018; Yang et al., 2020). Estimates are that by 2030, aquaculture will release 5.7% of the anthropogenic N_2O emission. Culture systems that trap nitrogen waste in biomass (microalgae, biofloc, seaweed, vegetables) are realistic options to reduce N_2O emissions from aquaculture (Hu et al., 2012).

Climate change will provide challenges for shellfish and seaweed production (Allison et al., 2011; FAO, 2016). As the sea level rises, erosion of coastal areas increases, and the soils are washed into estuaries where they increase turbidity and can affect the growth of submerged aquatic vegetation as well as disrupt shellfish feeding. Increased temperatures, changes in sea level, precipitation, salinity, water circulation patterns, storm frequency and severity, and other factors will challenge shellfish farmers in different ways in different geographic regions. It will be important to consider actual technological innovations in aquaculture practices in response to climate change including material, procedural and informational dimensions of practice (Lebel et al., 2020). It will be crucial to understand the impacts of climate change at the local level to promote sustainable shellfish culture. Global analyses for finfish species indicate regions where culture conditions improve and other regions where conditions will decline (Klinger et al., 2017; Oyinlola et al., 2018). Insights into local impacts are needed to inform policy and management officials.

Due to seawater level rise in some estuaries in South Sumatra, Indonesia, dikes of shrimp ponds had to be raised 10–15 centimeters to protect against flooding. One mitigation measure to reduce economic loss from extreme events due to climate change could be insurance. Although aquaculture insurance would redeem the costs due to production loss or infrastructure damage, it will not bring back the lost production and still will reduce food security. However, most producers across the aquaculture industry do not have a ‘crop’ insurance. Large-scale companies sometimes opt not to insure their crop (product), assuming that the biosecurity and management systems employed are robust enough to guarantee production, but ensure their production infrastructure.

In the future, for small and medium-sized farms, crop insurance may become more important. The technical and physical infrastructure and management demanded by insurance companies may not be easy for farmers to adopt. Either way, the technical and management conditions could be assured by a specialized technical service body to the benefit of both parties.

3.5 | Feed additives

High feed loads in highly and super-intensive culture systems quickly reduce water quality, stressing the immune system and the health of farm animals. A range of ingredients is used to enhance the immunocompetence and growth of the culture stock and/or improve water quality, including prebiotics, probiotics, enzymes, nucleotides, bacterial peptidoglycans, and carotenoids (Boyd et al., 2020). Most additives are mixed with, or coated on the pelleted feed, but probiotics are often applied directly to the pond.

There are numerous manufacturers of probiotics, the effectiveness of which is not well defined. In addition, the action of a probiotic differs between fish species. More studies that test in depth the response of one fish species to one probiotic are needed to get a better understanding of the effectiveness of the probiotic (Ninawe & Selvin, 2009). The numerous genome-sequencing and metabolomic tools can further help to elucidate how the immune system, nutrition, and growth affect nutrition (Kumar et al., 2016). Little is known of the long-term effects of probiotic use on the culture environment and needs further investigation.

3.6 | Food security and poverty alleviation

Off the 20.5 million people employed full-time or part-time in aquaculture, most are small-scale workers, of which a large fraction is engaged in other agricultural activities or off-farm employment. Others are commercial producers, some of them employing workers during busy periods (Belton et al., 2018). With future increasing incomes, the contribution of farmers engaged part-time in aquaculture to global production will continue to decline (Edwards, 2015), while the contribution of commercial family-owned producers will increase. The shift toward more intensive commercial production coincides with stocking fewer species, favoring those species with a high market demand (Edwards, 2015), with some low-priced species contributing to improved food security for the poor (Belton et al., 2020). On the other hand,

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

this might result in less diversified and nutritious diets (Castine et al., 2017) by reducing options to culture species adapted to the local environment and local food preferences. To help small-scale aquaculture farmers to integrate into the value chain, education, reliable property rights, credit, institutional support, and active engagement in decision-making are highly important (Salazar et al., 2018).

3.7 | Technological innovation

3.7.1 | Fed systems

Technological innovation should allow the aquaculture sector to upgrade productivity, lower costs, and reduce environmental impacts. From a system perspective, key areas for innovation include water quality maintenance, water purification (Xiao et al., 2019), feeding systems (Zhou et al., 2018), online monitoring, and early warning systems (FAO, 2020; Hassan et al., 2016), and to share information bi-directionally through internet (Boyd et al., 2020; Gui et al., 2018; Hassan et al., 2016; Zhou et al., 2018). The latter is only meaningful if supported with local education and capacity building (Lebel et al., 2020; Weitzman, 2019), and guidance through best management practices (BMP). New technologies must be communicated with farmers and integrated with sound BMP, in which attention to the use of chemicals and antibiotics, habitat destruction, fish escapees, and waste management is integrated (Boyd et al., 2007; Diana et al., 2013). Measures can also be taken to reduce the effect of salt-water intrusion in coastal zones due to climate change through land use planning and shifts in the selection of species adapted to the locally prevailing salinity (Nhung et al., 2019).

Water purification technology and waste treatment in aquaculture got a boost with the increased interest in RAS technology during the last decade, and the technology is available for any aquaculture operation to treat wastes. Numerous farmers already apply aeration, concentrate and remove wastes from the culture unit, or partially control toxic nitrogen levels. These are simple technologies, that if planned will raise farm production in a cost-effective way. A prerequisite is to have electricity next to the production facility, which is more and more the case in rural areas around the world and making intensification possible. These technological innovations are a necessity for farmers who wish to intensify while maintaining good water quality conducive to a healthy cultural environment and production. In addition, it creates options to collect and treat waste on the farm.

Installing a full RAS is different. At present, there are financial, operational, social, and marketing risks associated with the development of intensive RAS (Figure 4). Investment and operational costs are generally high when it comes to establishing a RAS. Most development is therefore seen in large-scale systems assuming that "bigger is better" in terms of reducing capital expenditures/kg (Vielma et al., 2022). Capital expenditures are required upfront, time between initial investments and (potential) revenue is typically long, and many things can go wrong before a system generates profit. Operating costs can also be higher than in more traditional farming due to expenditures on commodities such as oxygen, CO_2 stripping, and electricity (https://www.undercurrentnews.com/2020/03/06/aquamaof-says-large-scale-salmon-ras-projects-will-produce-at-costs-of-around-3-kg/).

In addition, there are many legislative and marked related risks and challenges associated with RAS, and risk of failure should not be overlooked (https://www.intrafish.com/finance/analysis-heres-a-list-of-high-profile-land-based-aquaculture-failures/2-1-712748, https://thefishsite.com/articles/rabobank-why-the-tide-is-turning-in-favour-of-ras-production, EUMOFA, 2020), including in smaller-scale systems (Clarke & Bostock, 2017).

While freshwater RAS has proven successful for producing fry and juveniles of several species including salmon smolts, and for rearing portion-sized trout, saltwater RAS is still a challenge (Vielma et al., 2022), with many farms going bankrupt. Gear that can withstand corrosion is required, biofilter performance may be hampered at higher salinity (Kinyage et al., 2019), and even a minor accumulation of sludge can result in the sudden formation of H_2S with devastating consequences. Currently, no sensors for reliable detection and early warning of H_2S are in use, and sensor technology in general is a ubiquitous issue in both fresh and saltwater RAS.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

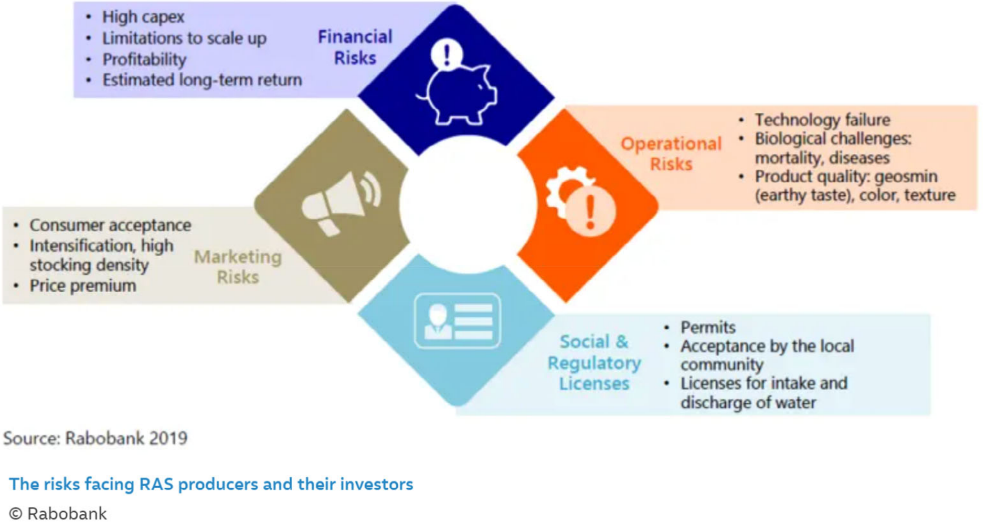

FIGURE 4 Four sets of risks for RAS operations facing large-scale RAS producers and investors. Reproduced with permission from www.thefishsite.com/articles/rabobank-why-the-tide-is-turning-in-favour-of-ras-production. RAS, recirculating aquaculture systems.

System management and qualified staff are key to successful RAS operations (Bregnballe, 2022; EUMOFA, 2020), in addition to good knowledge of cultured species biology. Staff need to be skilled in water quality monitoring and assessment, in operating different treatment technologies (including end-of-pipe solutions), and in managing surveillance and backup systems.

The market value of the cultivated species must justify higher production costs. Product value may change over time due, for example, to competition and changes in consumer preferences and willingness to pay extra for seafood cultivated in RAS. In line with this, it is essential that product quality be optimized and that, for example, a ubiquitous issue with off-flavor is reduced and preferably avoided (EUMOFA, 2020).

Site selection, permits, and licenses for establishing a RAS facility can be difficult, time-consuming, and costly, and may involve a high degree of stakeholder involvement. Getting a permit in the USA may, for example, add up to 5% of the total budget (Hadlock, 2020), and in Europe, processes of obtaining a permit are challenged by interactions between local, regional, national, and EU legislation (EUMOFA, 2020).

3.7.2 | Extractive systems

Improved mitigation strategies for the control of biofouling of shellfish grow-out equipment are still needed. While there are numerous physical methods for the removal of biofouling (Watson et al., 2009), they are labor intensive and can result in damaged crops. Promising new research and development of environmentally friendly coatings have shown good results (Shumway, 2021) and will lead to reduced labor and increased yield per area, which in turn will lead to increased production of crops.

Improved methods to assess biomass during production in bottom culture will continue to be a challenge. Bottom culture methods are still quite primitive and utilize harvest equipment that has changed little during the past century. They lack the ability to assess biomass quickly and effectively, and improved techniques will increase production and expand markets.

There is a need for advanced technology in production to increase output and lower labor input to make businesses more profitable and competitive. Some of this technology can be adapted from agricultural industries.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Two recent examples include planting and harvesting using technology adapted from the bulb industry and sorting and grading technology that evolved from that developed for apples. A long-elusive component of oyster processing has been automated shucking machinery that could quickly remove meats from the shells without manual labor. Current advances in sensing and computer-aided machinery should make this possible. The economic and managerial feasibility of production systems will ultimately drive their development and acceptance. The inclusion of increased automation will ultimately depend upon the increased additional costs as compared to the additional economic benefits (Shumway, 2021).

The majority of marine plants are grown on suspended long lines or suspended nets. Some red algae are harvested from the wild or grown in bottom culture in shallow water, but they represent a minor percentage of the global production. Harvesting of seaweeds is labor intensive, and, here too, the industry will benefit from wider use of existing or improved semi-automated harvesting techniques. Improving existing technology to seed and deploy long lines effectively, with minimum labor input is presently getting a lot of attention and will help to reduce labor inputs.

4 | PRIORITIES FOR FUTURE AQUACULTURE DEVELOPMENT

4.1 | Climate change

The relation between aquaculture and climate change has been recognized and studied for some time (Cochrane et al., 2009). During the last 20 years, the aquaculture industry improved from a technological, governance, management, and siting perspective. This made aquaculture better able to cope with harmful algal blooms, disease, and extreme weather events. However, generalization is difficult. There is a need to better monitor the effects of environmental changes on on-farm production to validate concepts developed in laboratory simulations across production environments and culture species (Naylor et al., 2021).

Similarly, little information is available on GHG from aquaculture facilities because emissions are influenced by the culture environment, and system management. There is insufficient evidence that study outcomes can be generalized, nor about which management practices minimize GHG emission from specific culture systems. Important parameters include the type of ingredients used in feed formulation, NUE of carbon and nitrogen, and dissolved oxygen dynamics (Kabir, Phillips, & Verdegem, 2020).

More research is needed to find ways to improve the energy use efficiency in fed aquaculture. One approach is the nutritious food concept (Verdegem et al., 2021), but much more research is needed. In addition, contributing to circularity by making use of crop residues in aquaculture feeds contributes to reducing the energy expenditure of food systems.

4.2 | Sustainable aquaculture

4.2.1 | Improved pelleted diets and fish meal and fish oil use

A major public concern is the use of wild small pelagic species as forage fish to culture high-value finfish species (Diana et al., 2013; Little et al., 2016; Naylor et al., 2000). During the last decade, substantial improvements have been achieved in reducing the percentage of fishmeal and fish oil in pelleted feeds (Naylor et al., 2021). Improved insights into the requirements for some 40+ essential nutrients as opposed to ingredients (e.g., fishmeal and fish oil) allow the industry to include a broader range of plant and animal ingredients in fish feed. This includes reusing products like crop residues otherwise not used, making aquaculture part of the circular economy (Van Zanten et al., 2019). Specific limiting essential nutrients, such as amino acids, fatty acids, vitamins, minerals, and trace elements, can be added to the diet to fulfill the nutrient requirements of the target species (Boyd et al., 2020).

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

In addition, by enzyme or probiotic inclusion in the diet, the utilization efficiency by the fish of low-quality ingredients can be upgraded, enlarging further the range of ingredients that can be used in fish diets (Maas et al., 2018; Maas et al., 2020; Maas et al., 2021). This combined approach gives the industry many options to reduce the use of fishmeal and fish oil in fish diets and to test a broad range of alternative ingredients to fishmeal or fish oil. Promising ingredients tested include fishery (bycatch) and aquaculture by-products (trimmings from fish and other seafoods), food waste, insects, microbial biomass (e.g., microalgae, bacteria, yeasts), and macroalgae (Boyd et al., 2022; Ghamkhar et al., 2021; Hua et al., 2019; Matassa et al., 2016). Some ingredients are already better optimized for use in aquaculture than others. For example, Maiolo et al. (2020) tested the effect of insect meal, poultry by-product meal, and microalgal biomass as partial substitutes for fish meal, assessing the environmental effects through life cycle analysis (LCA). Poultry by-product meal has the smallest environmental impact, showing optimal environmental performance, while the environmental impact of insect meal and microalgal biomass could be further reduced by improving the NUE and reducing energy use. For food wastes and microbial biomass products, considering the economics of commercial production, supply, and supply consistency, are still large hurdles that must be overcome to be able to meet demand (Hua et al., 2019). This makes insects and microalgae currently the most promising candidates for fishmeal and fish oil replacement, respectively, in fish diets (Cottrell et al., 2020). Nevertheless, a wide range of factors needs to be considered in concert (e.g., substitutability, nutritional profiles, scalability, environmental impacts) when aiming for sustainable growth in production. Doing so often leads to opposing conclusions, highlighting the need to integrate multi-objective analyses in the decision process (Pelletier et al., 2018).

A result of shifting from ingredient availability to essential nutrient requirements to guide diet formulation is that the differences in the trophic level of diets between herbivores, omnivore, and carnivores reduce and converge (Cottrell et al., 2021), while resources that previously could not be used can now be recycled through fish diets. Once replacements for fishmeal and fish oil become available at a competitive price and in sufficient quantity, then large-scale production of carnivorous marine fish species in response to consumer demands might develop quickly (Gephart et al., 2020).

One development is that strains developed for fast growth require a protein and nutrient-rich high-quality diet to be able to maintain fast growth. This makes the feed expensive while feed companies aim to formulate diets at a cost that allows the farmer to make a profit. Farmers and consumers should have insight into the quality of the diet and the selection of ingredients used. This is politically and environmentally sensitive information, requiring full attention from the feed companies (Personal communication based on interview discussion with feed manufacturing sector specialists from Australia, India, Indonesia, and Thailand, 2020–21; W. Latt). Selective breeding can quickly improve the digestibility of dietary nutrients (e.g., C, N) (Kause et al., 2022), but fast growth and digestibility are often negatively correlated traits (Dvergedal et al., 2019), because fast-growing fish eat more, causing faster food passage through the gut, leading to reduced digestibility. Farmers with no access to fast-growing strains, might aim for cheaper diets containing relatively more low-quality ingredients and still realize good production and feed utilization efficiency. Through domestication and, if scale permits, selective breeding, the digestibility of locally produced diets will gradually improve.

4.2.2 | Waste treatment technology and RAS development

Today, numerous aquaculture farms use technologies first applied in RAS. Having the option of temporarily recirculating the water, for example, by simple airlifts, may help a farmer circumvent upstream disease outbreaks or water shortages (Palić & Scarfe, 2019). This also reduces the use of antibiotics and therapeutants.

Continuous removal of solids (fish feces and uneaten feed) prior to discharge, for example, via sludge cones, drum filters, swirl separators, or fix-bed biofilters, may reduce the discharge of particulate organic matter and phosphorus considerably, benefitting the recipient and improving internal water quality (Ahmad et al., 2022). As stocking density or recirculation intensity increases, biofiltration will be necessary to convert ammonia to nitrate. Here, the use of locally available filter material such as coconut shells rather than commercially manufactured plastic bioelements might be both cheaper and more sustainable (Mnyoro et al., 2022).

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

To reduce eutrophication further, nitrate may be removed from farm effluent by treating it in simple, low-cost denitrifying bioreactors. These are water-logged beds filled with locally available, slow-releasing carbon sources such as woodchips or coconut husks (Rambags et al., 2019; von Ahnen et al., 2018). In addition to removing nitrate, denitrifying bioreactors are known to be effective in reducing microbial contaminants, providing complimentary disinfection (Rambags et al., 2019). Water treated in denitrifying bioreactors may potentially be recycled back to ponds following, for example, sand filter filtration, to remove harmful or toxic substances potentially released from the filter material (Lepine et al., 2021; Lindholm-Lehto et al., 2020).

Finally, education and training are imperative if these technologies first developed for RAS are to contribute massively to the sustainable production of healthy aquatic foods in the future.

4.2.3 | Disease prevention and biosecurity

Increasing demand for aquaculture products and the expansion of seafood stimulate intensification, and with intensification reliance on high-density monocultures which are vulnerable to disease. Predictions are that in tropical shrimp production alone, 40% of the production will be lost annually to mainly viral-disease-related mortality for which standard preventative measures (e.g., such as vaccination) are not feasible (Stentiford et al., 2012). When it comes to antibiotic use in aquaculture, there is a risk of the development and spreading of antibiotic resistance (Hossain et al., 2022). A recent study across aquaculture areas along the Yellow Sea in China showed that the presence of antibiotic residues in ponds increased during the culture period, in contrast to non-used ponds. A conclusion of the study was that regulations are needed to reduce antibiotic use in aquaculture (Zhang et al., 2023).

Raising temperatures due to climate change are also a concern. Temperature had a major impact on the disease susceptibility of shrimp, but insights into how to manipulate temperature or any other abiotic factor to control the disease are still lacking (Millard et al., 2020). Knowledge of balances/imbalances in the microbiome of aquaculture systems is still in its infancy, although quickly developing (Infante-Villamil et al., 2020). More research on creating a healthy environment for culture organisms is needed, requiring more meta-analyses and cross-sectoral studies in addition to disciplinary research (Reverter et al., 2021). The latter is important in view of global warming and ocean acidification (Green et al., 2014; Rowley et al., 2014).

Although the root of many disease problems in aquaculture lies to a high degree with the culture system applied, the main goal of the industry and the research community is to find effective disease treatments, which can be a time-consuming and long-term effort. For instance, in shrimp farming, there are currently no effective treatments for most viral, but also for some bacterial diseases, even after decades of research (Flegel, 2019). Through development and application of BMP, including biosecurity measures, the industry tries to minimize the impact of disease. The principal key to success is how well-recommended practices of the BMP help to maintain or restore a healthy production environment for the farmed animals.

In relation to biosecurity, there is a high level of misunderstanding among stakeholders regarding "the fundamental principles and practices of aquaculture pond management". When aiming for disease control, the main objectives are (1) to prevent a pathogen from entering the farm, and (2) to prevent any pathogens present from spreading around the farm. These objectives must be part of a quality assurance (QA) program. Aquaculture farms are often clustered, therefore requiring coordination and cooperation among stakeholders in applying biosecurity. If all actors involved apply the biosecurity measures correctly, then disease incidences can be drastically reduced. Large industrial farms are more successful in applying biosecurity, as they are able to implement and cover the costs of QA/QC protocols. Small-scale farmers need to work collectively to implement the biosecurity measures to be able to bear the QA/QC costs. Latt (2019) suggested protocols for a QC laboratory to inform the right QA actions for clusters of shrimp hatcheries, which can be collectively implemented by a cluster of 4–5 small or medium-sized hatcheries. Hence, effective biosecurity, including good QA/QC protocols can be implemented. Successful biosecurity application will require adequate training of farmers in aquaculture pond management and enforcement of government regulations, conductive to creating and

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

maintaining a healthy production environment. Existing loopholes breaching biosecurity enforcement should be prevented, requiring strong political will and multi-stakeholder cooperation, involving government, education, and the aquaculture and food industry stakeholders (Personal communication; W. Latt).

In shrimp farming, biosecurity is further enhanced by the provision of SPF, specific pathogen tolerant (SPT) or SPR, PL, which today is common practice across the industry (Alday-Sanz et al., 2020). This development concurs with efforts to reduce pond size, in combination with better control on the application of biosecurity protocols. Similar developments are observed in China, Vietnam, Thailand, and Indonesia, all major players in the shrimp industry.

4.3 | Monitoring and early warning systems

Automation in any system, if applied judiciously, can improve production and profits. For example, the introduction and implementation of "smart technology" and robotics to enhance shellfish farm production is currently being explored. Technologies such as artificial intelligence, Big Data, Internet-of-Things, and robotics are used routinely in modern agriculture and result in increased efficiency and lowered costs. These technologies are not yet readily applicable throughout the aquaculture industry, although they are applied in automated feeding technology or remote monitoring of weather and water quality developments around cage culture operations at sea. For shellfish culture, it is proposed that the use of these technologies could improve the bottom culture of oysters by aiding in planting oysters accurately in the right densities (Yadav et al., 2023). Site selection of finfish, shellfish, or seaweed operations at sea can be guided by means of geographical information system (GIS) and farm-scale models (Ferreira et al., 2009; Silva et al., 2011). Advanced sensing gear will allow growers to determine the growth and mortality of their crops for management decisions, and can be used to monitor crops in situ, reduce mortality, and develop advanced and selective harvest methods (D. Webster, Personal Communication). More specifically, in shellfish farming, technological developments in precision aquaculture can be used to promote autonomous and continuous monitoring using underwater sensors that observe, analyze, interpret, and assist decision-making support for farm operations (Donncha & Grant, 2019). While there are still issues to be addressed including long-term maintenance of the sensors, limited battery capacity of the sensors, high energy consumption during signal transmission, environmental impacts on the sensors, and cost (Parra et al., 2018), these are promising technologies that will provide further means to improve the efficiency of shellfish aquaculture.

Monitoring systems in source waters as well as disease surveys in the near environment have been part of planning and management of production in some vertically integrated aquaculture industries since early 2000. Such programs and practices require significant resources, both financial and human, to produce beneficial outcomes. Small and medium-sized enterprises should organize in clusters or farmer groups, and closely cooperate and collaborate with government and academic sectors to develop and implement better planning and management of productions. Weather predictions and climate change impact scenarios have also been incorporated into production, marketing, and strategy formulation of certain medium-and large-scale shrimp farming enterprises since late 2000. If properly implemented and acted upon immediately, mitigation of climate change-related impact on production is possible, allowing farmers to react swiftly (Personal communication; W. Latt).

4.4 | Enabling environment

4.4.1 | Institutions and regulation

Shellfish aquaculture has a bright future. It is a sustainable protein source and can significantly boost local economies and food security globally. Several species will likely continue to dominate the international shellfish aquaculture community, most notably clams, oysters, scallops, and mussels. In addition, other less recognized species will be

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

successfully cultured and provide jobs on more local levels, for example, cockles (FAO/FishStatJ, 2023). Not all species, systems, and technologies will be commercially feasible, but without continued research, positive attitudes, and a willingness to explore and accept new possibilities, there can be no growth.

The same holds for seaweed aquaculture. It is sustainable, contributes directly and indirectly to food systems, can mitigate environmental impacts, and generates income. The main species presently cultured will remain so in the near future.

To continue on a positive growth trajectory of extractive species, however, there will need to be improved acceptance by the public and modification of rules, laws, and regulations that currently hamper the establishment of new farms and expansion of existing ones. For example, for shellfish farming, government regulations have been a significant factor in limiting or preventing the establishment and expansion of shellfish aquaculture in many regions globally. Development of nearshore shellfish aquaculture is increasingly constrained by space, economics, human health, societal concerns, and environmental issues (Cheney et al., 2010). To a lesser extent, the same holds for cage culture at sea.

4.4.2 | Education and training

To raise public awareness and acceptance by the public, expanded educational efforts are needed. Proactive programs on aquaculture should be created to educate communities about the benefits to the economy, employment, and food security. For extractive species, benefits to the environment should be stressed.

The development of offshore aquaculture has raised a new level of concern. Offshore aquaculture will happen in countries and waters where the regulatory systems allow it to proceed. Federal and international agencies are involved in the permitting processes and often do not work collaboratively or even proactively. Significant legislation will be required to enable development of those productive and lucrative offshore waters (Falconer et al., 2023).

As with most change, there will be a period of adjustment and acceptance by both industry and consumers, and focused education and communication programs can be a great asset. For aquaculture to continue expansion, a range of support programs is needed. There needs to be strong and effective communication regarding delivering food security to local communities in the short term, while simultaneously educating them and encouraging partnerships working toward resource sustainability and community development in the longer term. These programs and their implementation will vary according to local needs, but should focus on school programs, youth programs, and public education. These programs should include general education regarding the benefits of extractive aquaculture to the environment and the community but also should include programs to teach production skills to train future aquaculture leaders.

Education related to disease prevention and BMP is important to enhance production stability in aquaculture. The education program should be developed as simple as possible, addressing a wide audience with varying educational backgrounds. The reasoning should be realistic, logical, technically sound, and acceptable. Culture system, standard operational procedure, biosecurity, management regime, and sustainability principles should be included and enhance critical thinking through WH-questioning (what, when, where, who, whom, which, whose, why, and how) for better understanding. Preferentially, each program should be designed with outcome-based implementation in mind. Delivery of the program could be monitored and continuously improved with the program developer and trainer sharing accountability on the targeted outcome (W. Latt., personal communication).

4.5 | Aquaculture development priorities

4.5.1 | Contribution of aquaculture to the 2000 & 2010 development priorities

Some of the strategies and recommendations given during the Global Conferences on Aquaculture held in 2000 in Bangkok and in 2010 in Phuket in Thailand relate to aquaculture systems. These recommendations are copied below, and advances made since 2000 are briefly outlined.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

- Aquaculture should adopt farming practices that ensure environmental sustainability, based on environmentally sound technologies and resource-efficient farming systems.

Progress: In response to public pressure, the environmental sustainability of aquaculture farming practices improved, benefiting from technological advances and improved biological insights. Public pressure will not decline, and the sector will continue improving its environmental performance over the next decade.

- Aquaculture should aim to increase its impact on rural development and poverty alleviation, making aquaculture an integral part of rural development programs.

Progress: Aquaculture contributed significantly to livelihoods of small-scale farmers, poverty alleviation, and food security. Overall, the sector has intensified, including small-scale farmers who benefitted from advances in rural infrastructure (accessibility, electricity), technology (feed technology, more and better farm equipment), and for some species improved breeds. There is a need to provide training, so farmers can take full benefit from these technological advancements.

- Develop a well-documented set of varied and adaptable technologies and systems allowing producers to make the best use of their local environment, and to make well-informed decisions on the production system and species they will use. This also includes making aquaculture systems more resilient to successfully face the uncertainties and risks wrought by climate change.

Progress: Aquaculture systems management has improved, resulting in less frequent production failures. Farm management procedures have been developed to make farming systems less vulnerable to disease-related production losses when implemented correctly. This is an ongoing effort, requiring more focus on training during the next decade.

- Pay attention to culture-based fisheries, sustainable stock enhancement, and ranching programs aiming to make efficient use of under-utilized, new or degraded resources.

Progress: Culture-based fisheries can make a significant contribution to global aquaculture production, and can be integrated with agricultural areas. Culture-based fisheries practices are location-dependent and guidelines are missing as to how to develop sustainable culture-based fisheries practices adaptable to local contexts. This is a priority for future development.

- Put emphasis on integrated aquaculture systems to improve environmental performance of aquaculture.

Progress: Numerous studies have investigated integrated aquaculture systems and documented improved NUE and environmental performance. The high knowledge requirements, however, and difficulties to make these systems economically viable hamper adoption. Only in various coastal bays in China are integrated aquaculture systems successful. Integrated culture of fish and shrimp helps to reduce disease occurrence in shrimp farming and should be promoted.

- Further develop new technologies including recirculating aquaculture, offshore cage culture, artificial upwelling, and ecosystem-based food web management.

Progress: RAS have strongly developed since 2000 and technologies are spreading to outdoor systems, both for finfish and crustaceans. Both high-intensity RAS and offshore aquaculture are costly, and, at present only feasible for expensive species. Ecosystem-based management should receive more attention: managing the food web through

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

feed formulation raises the NUE in pond systems and reduces the environmental impact, but more research is needed.

- Make aquaculture resilient to successfully face the uncertainties and risks wrought by climate change

Progress: Aquaculture systems have become more resilient, but more research is needed to gain better insight as to how different species, production environments, and management practices affect resilience to climate change.

- Accelerate the untapped potential for aquaculture development outside Asia.

Progress: High growth of aquaculture development in Africa and Latin America is recognized and is driven by fast growth in a limited number of countries. Stimulating aquaculture development in more countries on each continent will help to accelerate aquaculture development outside Asia.

4.5.2 | Priorities until 2030

Aquaculture production will continue to grow in the nearby future (Garlock et al., 2020; Little et al., 2016). This will predictably lead to ~18% higher world aquatic food consumption (including capture fisheries) in 2030 compared to 2018 (FAO, 2020). The successful integration of aquaculture into the global food system since 1997 (Naylor et al., 2021) has contributed to the provision of sufficient calories from aquatic foods. Healthy food is, however, not only about cheap calories but also about foods that contribute to a nutritious diet, the latter providing a balanced mix of bioavailable nutrients to sustain a healthy and active lifestyle. Aquatic foods play an important role in providing such a healthy nutritious diet (Thilsted et al., 2016). The latter requires a "nutrition-sensitive" food system that provides a diverse and nutritional complete set of foods, is embedded in society, and contributes to sustainable livelihoods (Uccello et al., 2017). Aquaculture can contribute to nutrition-sensitive food systems that alleviate health inequities under various scenarios ranging between endless growth versus staying within planetary boundaries and between regionalized versus globalized food systems (Figure 5) (Gephart et al., 2020).

Today the world produces enough food to meet the human nutritional needs of nearly 10 billion people in 2050, provided all people get assured access to food and human feeding habits change. The latter includes reducing the consumption of animal foods and replacing them with plant-based alternatives. This includes direct human consumption of crops such as maize, now fed to animals (Berners-Lee et al., 2018) (Figure 6).

Most people prefer not to forsake animal food as suggested by Berners-Lee et al. (2018), considering fed aquaculture a legitimate and sustainable way of producing healthy food and seeing room for further growth of aquaculture during the next decade. Important questions are (1) how much should aquaculture production expand during the next decade, and which products should be best produced, where, and how? Answers should consider the urgent challenges to the global food system, including aquaculture, to address global warming and to produce food within planetary boundaries. One possible solution is to develop a doughnut economy (Raworth, 2017) producing products so that nobody in society is left behind (inner ring of the doughnut) and leaving a healthy planet behind for generations to come (outer ring of the doughnut).

Sustainable, nutrition-sensitive food systems, when the resource base permits, are possible under each of the scenarios presented in Figure 5, but within a doughnut economy, only the scenarios of "food sovereignty" or "blue internationalism" apply. The first scenario focuses on local production by smallholders, the second on international trade. Both scenarios focus on sustainable production within the local context. Which of the two scenarios is best applied in a given situation depends on the capacity of the local food ecosystem to provide, conserve and recycle nutrients, setting limits to the degree of intensification possible. Hence the local food ecosystem determines if expanding aquaculture production is best based on expanding land and water use, or on intensification (Boyd

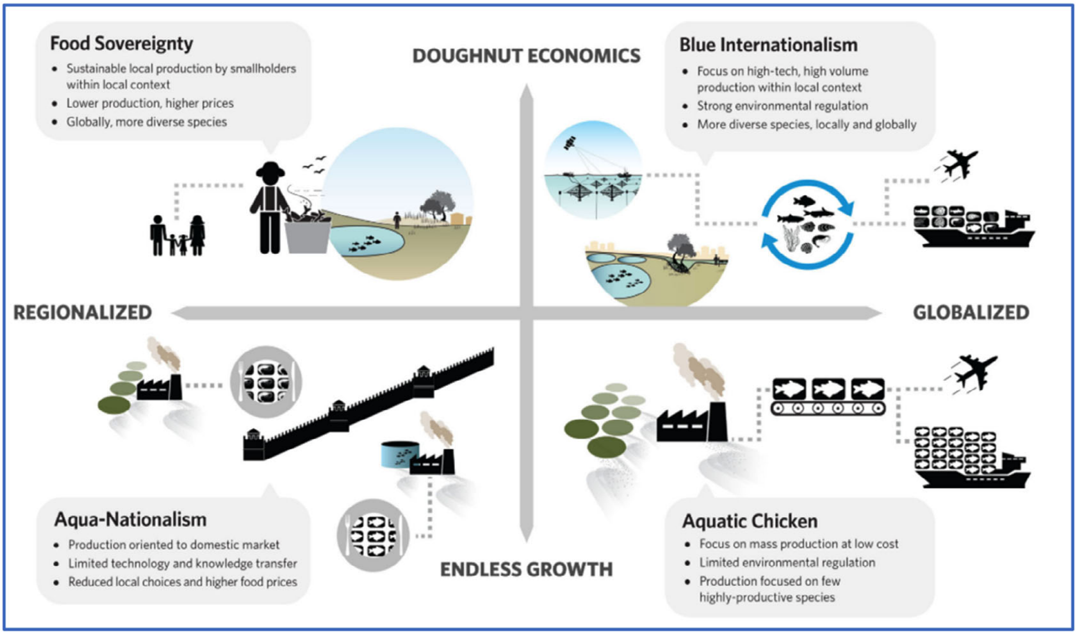

FIGURE 5 Scenarios for future growth of aquaculture considering endless growth versus sustainable growth (doughnut economics), focusing on globalization versus regional development (Gephart et al., 2020).

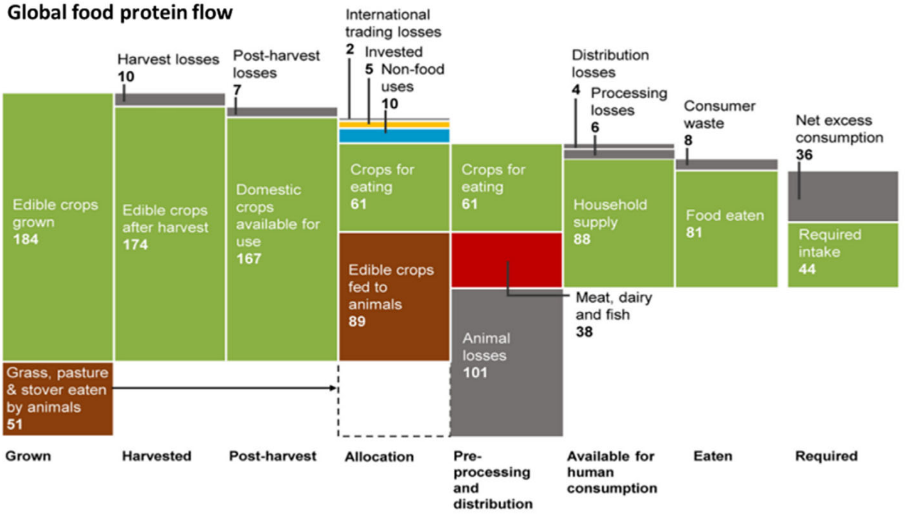

FIGURE 6 The flows of global food protein (g/person/day). The column on the left divides crops grown into directly edible by humans and only edible by animals. The column on the right divides protein eaten into protein required for healthy human living and protein consumed in excess of the requirement (Berners-Lee et al., 2018).

et al., 2022). Considering aquaculture, sustainable production within the local context would be easier if aquaculture was spread more evenly across the world. Especially in Africa and Latin America, there is room for aquaculture development with opportunities to make aquaculture an integral component of nutrition-sensitive food systems.

Considering the above, criteria to judge aquaculture development during the next decade should not focus primarily on global growth, except for extractive species. The industry found ways to improve its environmental

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

performance during the last decades, and as societal pressure to improve upon environmental performance will increase further, the aquaculture sector will continue to improve its environmental performance. Therefore, the main focus should be:

1. to develop sustainable aquaculture systems imbedded within local food systems, with focus on
   a. minimizing nutrient losses from aquaculture systems. This relates to solid, dissolved, and gaseous (including GHGs) waste. Special attention should be given to the development of innovative low-cost effective ways to reduce, collect, or process wastes from aquaculture systems,
   b. maximizing nutrient utilization efficiency of harvested products, with special attention to polycultures and multi-trophic systems,
   c. recycling nutrients across agriculture—aquaculture farming systems contributing to circularity,
   d. water reuse, minimizing water use in freshwater and brackish water aquaculture.
2. to embed aquaculture within nutrition-sensitive food systems. This requires monitoring the nutritional value of aquaculture products harvested from different aquaculture systems.
3. to provide equitable income for stakeholders, including farming households, along the aquaculture value chain. This requires multi-objective analysis, including tradeoffs between production, income, NUE, environment, and nature.
4. to increase the contribution from molluscan culture to global aquaculture, with focus on
   a. developing simple and logical procedures, laws, and regulations guiding the development of molluscan farming.
   b. education campaigns to inform the public and farmers on the benefits and advantages of molluscan farming in areas suited for molluscan culture.
   c. stimulating the development and implementation of "smart technology" and robotics to enhance especially shellfish production at sea.
5. to stimulate further growth of seaweed aquaculture not only in Asia but also on other continents. Special attention should be given to:
   a. Selecting culture species adapted to the local climate and environment,
   b. qualifying and quantifying ecosystem services provided by aquatic plants,
   c. implementing smart technology and robotics to enhance seaweed culture.
6. to stimulate aquaculture development outside Asia, especially in Africa and Latin America.
7. to address climate change, including
   a. documentation of the effects of physical and chemical changes in the production environment on production, animal health, and resilience for a wide array of culture systems and species;
   b. develop early warning systems, adapted to local contexts, to insulate farmers/communities against catastrophic effects.

ACKNOWLEDGMENTS

We thank Dr. Sandra Shumway (Department of Marine Sciences, University of Connecticut, Groton, Connecticut, USA) for sharing her expertise and advise while developing this document.

DISCLAIMER

The views expressed in this publication are those of the author(s) and do not necessarily reflect the views or policies of the Food and Agriculture Organization of the United Nations.

DATA AVAILABILITY STATEMENT

Data derived from public domain resources

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

ORCID

Marc Verdegem https://orcid.org/0000-0002-2058-3894

REFERENCES

Aas, T. S., Ytrestøyl, T., & Åsgård, T. (2019). Utilization of feed resources in the production of Atlantic salmon (Salmo salar) in Norway: An update for 2016. *Aquaculture Reports*, *15*, 100216.

Ahmad, A. L., Chin, J. Y., Mohd Harun, M. H. Z., & Low, S. C. (2022). Environmental impacts and imperative technologies towards sustainable treatment of aquaculture wastewater: A review. Journal of water. *Process Engineering*, *46*, 102553.

Ahmed, M., & Lorica, M. H. (2002). Improving developing country food security through aquaculture development - lessons from Asia. *Food Policy*, *27*, 125–141.

Ahmed, N., Ward, J. D., & Saint, C. P. (2014). Can integrated aquaculture-agriculture (IAA) produce "more crop per drop"? *Food Security*, *6*, 767–779.

Alam, M. I., Rahman, M. S., Ahmed, M. U., Debrot, A. O., Ahsan, M. N., & Verdegem, M. C. J. (2022). Mangrove forest conservation vs shrimp production: Uncovering a sustainable co-management model and policy solution for mangrove greenbelt development in coastal Bangladesh. *Forest Policy and Economics*, *144*, 144.

Alday-Sanz, V. (2018). Specific pathogen free (SPF), specific pathogen resistant (SPR) and specific pathogen tolerant (SPT) as part of the biosecurity strategy for whiteleg shrimp (Penaeus vannamei Boone 1931). *Asian Fisheries Science*, *31*, 112–120.

Alday-Sanz, V., Brock, J., Flegel, T. W., McIntosh, R., Bondad-Reantaso, M. G., Salazar, M., & Subasinghe, R. (2020). Facts, truths and myths about SPF shrimp in aquaculture. *Reviews in Aquaculture*, *12*, 76–84.

Allison, E. H., Badjeck, M., & Meinhold, K. (2011). The implications of global climate change for molluscan aquaculture. In S. Shumway (Ed.), *Shellfish Aquaculture and the Environment*, 461–490, John Wiley & Sons, Inc.

Asaduzzaman, M., Wahab, M. A., Verdegem, M. C. J., Benerjee, S., Akter, T., Hasan, M. M., & Azim, M. E. (2009). Effects of addition of tilapia Oreochromis niloticus and substrates for periphyton developments on pond ecology and production in C/N-controlled freshwater prawn Macrobrachium rosenbergii farming systems. *Aquaculture*, *287*, 371–380.

Aubin, J., Callier, M., Rey-Valette, H., Mathé, S., Wilfart, A., Legendre, M., Slembrouck, J., Caruso, D., Chia, E., Masson, G., Blancheton, J. P., Ediwarman, Haryadi, J., Prihadi, T. H., de Matos Casaca, J., Tamassia, S. T. J., Tocqueville, A., & Fontaine, P. (2017). Implementing ecological intensification in fish farming: Definition and principles from contrasting experiences. *Reviews in Aquaculture*, *11*, 149–167.

Avnimelech, Y. (2007). Feeding with microbial flocs by tilapia in minimal discharge bio-flocs technology ponds. *Aquaculture*, *264*, 140–147.

Badiola, M., Basurko, O., Piedrahita, R., Hundley, P., & Mendiola, D. (2018). Energy use in recirculating aquaculture systems (RAS): A review. *Aquacultural Engineering*, *81*, 57–70.

Barbier, M., Charrier, B., Araujo, R., Holdt, S. L., Jacquemin, B., & Rebours, C. (2019). PEGASUS - PHYCOMORPH European guidelines for a sustainable aquaculture of seaweeds. In M. Barbier & B. Charrier (Eds.), *COST action FA1406*. Roscoff.

Basti, L., Hégaret, H., & Shumway, S. E. (2018). Harmful Algal Blooms and Shellfish. In *Harmful algal blooms and shellfish. Harmful algal blooms: A compendium desk reference* (pp. 135–190). John Wiley & Sons, Ltd.

Belton, B., Bush, S. R., & Little, D. C. (2018). Not just for the wealthy: Rethinking farmed fish consumption in the global south. *Global Food Security*, *16*, 85–92.

Belton, B., Little, D. C., Zhang, W., Edwards, P., Skladany, M., & Thilsted, S. H. (2020). Farming fish in the sea will not nourish the world. *Nature Communications*, *11*, 5804.

Berners-Lee, M., Kennelly, C., Watson, R., & Hewitt, C. N. (2018). Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation. *Elementa-Science of the Anthropocene*, *6*, 52.

Bosma, R., Sidik, A. S., van Zwieten, P., Aditya, A., & Visser, L. (2012). Challenges of a transition to a sustainably managed shrimp culture agro-ecosystem in the Mahakam delta, East Kalimantan, Indonesia. *Wetlands Ecology and Management*, *20*, 89–99.

Bosma, R. H., Lacambra, L., Landstra, Y., Perini, C., Poulie, J., Schwaner, M. J., & Yin, Y. (2017). The financial feasibility of producing fish and vegetables through aquaponics. *Aquacultural Engineering*, *78*, 146–154.

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N., Gatward, I., & Corner, R. (2010). Aquaculture: Global status and trends. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *365*, 2897–2912.

Boyd, C. (1990). *Water quality in ponds for aquaculture*. Alabama Argicultural Experiment Station.

Boyd, C. E., & Chainark, S. (2009). Advances in technology and practice for land-based aquaculture systems: Ponds for finfish production. In G. Burnel & G. Allen (Eds.), *New Technologies in Aquaculture: Improving production efficiency, quality and environmental management* (pp. 984–1009). Woodhead Publishing Ltd..

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Boyd, C. E., D'Abramo, L. R., Glencross, B. D., Huyben, D. C., Juarez, L. M., Lockwood, G. S., McNevin, A. A., Tacon, A. G. J., Teletchea, F., Tomasso, J. R., Jr., Tucker, C. S., & Valenti, W. C. (2020). Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. *Journal of the World Aquaculture Society*, *51*, 578–633.

Boyd, C. E., McNevin, A. A., & Davis, R. P. (2022). The contribution of fisheries and aquaculture to the global protein supply. *Food Security*, *14*, 805–827.

Boyd, C. E., Tucker, C., McNevin, A., Bostick, K., & Clay, J. (2007). Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture. *Reviews in Fisheries Science*, *15*, 327–360.

Bregnballe, J. (2022). *A guide to recirculation aquaculture: An introduction to the new environmentally friendly and highly productive closed fish farming systems* (p. 110). Rome. FAO and Eurofish International Organisation.

Broch, O. J., Ellingsen, I. H., Forbord, S., Wang, X., Volent, Z., Alver, M. O., Handå, A., Andresen, K., Slagstad, D., Reitan, K. I., Olsen, Y., & Skjermo, J. (2013). Modelling the cultivation and bioremediation potential of the kelp Saccharina latissima in close proximity to an exposed salmon farm in Norway. *Aquaculture Environment Interactions*, *4*, 187–206.

Buschmann, A. H., Camus, C., Infante, J., Neori, A., Israel, Á., Hernández-González, M. C., Pereda, S. V., Gomez-Pinchetti, J. L., Golberg, A., Tadmor-Shalev, N., & Critchley, A. T. (2017). Seaweed production: Overview of the global state of exploitation, farming and emerging research activity. *European Journal of Phycology*, *52*, 391–406.

Castine, S. A., Bogard, J. R., Barman, B. K., Karim, M., Mokarrom Hossain, M., Kunda, M., Mahfuzul Haque, A. B. M., Phillips, M. J., & Thilsted, S. H. (2017). Homestead pond polyculture can improve access to nutritious small fish. *Food Security*, *9*, 785–801.

Cheney, D., Langan, R., Heasman, K., Friedman, B., & Davis, J. (2010). Shellfish culture in the open ocean: Lessons learned for offshore expansion. *Marine Technology Society Journal*, *44*, 55–67.

Cheng, Y., Wu, X., & Li, J. (2018). Chinese mitten crab culture: Current status and recent Progress towards sustainable development, aquaculture in China. In J.F. Gui, Q. Tang, Z. Li, J. Liu, & S.S. De Silva (Eds.), *Aquaculture in China: Success Stories and Modern Trends* (pp. 197–217). Wiley Blackwell.

Chopin, T. (2010). *Integrated multi-trophic aquaculture* (pp. 184–205). OECD Publishing.

Chopin, T., Buschmann, A. H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G. P., Zertuche-González, J. A., Yarish, C., & Neefus, C. (2001). Integrating seaweeds into marine aquaculture systems: A key toward sustainability. *Journal of Phycology*, *37*, 975–986.

Chopin, T., Cooper, J. A., Reid, G., Cross, S., & Moore, C. (2012). Open-water integrated multi-trophic aquaculture: Environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. *Reviews in Aquaculture*, *4*, 209–220.

Chopin, T., & Tacon, A. G. J. (2020). Importance of seaweeds and extractive species in global aquaculture production. *Reviews in Fisheries Science & Aquaculture*, *29*(2), 1–10.

Chu, Y. I., Wang, C. M., Park, J. C., & Lader, P. F. (2020). Review of cage and containment tank designs for offshore fish farming. *Aquaculture*, *519*, 734928.

Clarke, R., & Bostock, J. (2017). *Regional review on status and trends in aquaculture development in Europe - 2015*. FAO Fisheries and Aquaculture Circular.

Cochrane, K., De Young, C., Soto, D., & Bahri, T. (2009). Climate change implications for fisheries and aquaculture. *FAO Fisheries and Aquaculture Technical Paper*, *530*, 212.

Costello, C., Cao, L., Gelcich, S., Cisneros-Mata, M. Á., Free, C. M., Froehlich, H. E., Golden, C. D., Ishimura, G., Maier, J., Macadam-Somer, I., Mangin, T., Melnychuk, M. C., Miyahara, M., de Moor, C. L., Naylor, R., Nøstbakken, L., Ojea, E., O'Reilly, E., Parma, A. M., … Lubchenco, J. (2020). The future of food from the sea. *Nature*, *588*, 95–100.

Cottrell, R. S., Blanchard, J. L., Halpern, B. S., Metian, M., & Froehlich, H. E. (2020). Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. *Nature Food*, *1*, 301–308.

Cottrell, R. S., Metian, M., Froehlich, H. E., Blanchard, J. L., Jacobson, N. S., McIntyre, P. B., Nash, K. L., Williams, D. R., Bouwman, L., Gephart, J. A., Kuempel, C. D., Moran, D. D., Troell, M., & Halpern, B. S. (2021). Time to rethink trophic levels in aquaculture policy. *Reviews in Aquaculture*, *13*, 1583–1593.

Cranford, P. J., Reid, G. K., & Robinson, S. M. C. (2013). Open water integrated multi-trophic aquaculture: Constraints on the effectiveness of mussels as an organic extractive component. *Aquaculture Environment Interactions*, *4*, 163–173.

Cremer, M., & Chappell, J. (2014). New intensive pond aquaculture technology demonstated in China. *Global Aquaculture Advocate*, January-February, 60–62.

Cuvin-Aralar, M. L. A., Lazartigue, A. G., & Aralar, E. V. (2009). Cage culture of the Pacific white shrimp Litopenaeus vannamei (Boone, 1931) at different stocking densities in a shallow eutrophic lake. *Aquaculture Research*, *40*, 181–187.

Dalsgaard, J., Lund, I., Thorarinsdottir, R., Drengstig, A., Arvonen, K., & Pedersen, P. B. (2013). Farming different species in RAS in Nordic countries: Current status and future perspectives. *Aquacultural Engineering*, *53*, 2–13.

Danopoulos, E., Jenner, L. C., Twiddy, M., & Rotchell, J. M. (2020). Microplastic contamination of seafood intended for human consumption: A systematic review and meta-analysis. *Environmental Health Perspectives*, *128*, 126002.

Dauda, A. B. (2020). Biofloc technology: A review on the microbial interactions, operational parameters and implications to disease and health management of cultured aquatic animals. *Reviews in Aquaculture*, *12*, 1193–1210.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

David, G. S., Carvalho, E. D., Lemos, D., Silveira, A. N., & Dall'Aglio-Sobrinho, M. (2015). Ecological carrying capacity for intensive tilapia (Oreochromis niloticus) cage aquaculture in a large hydroelectrical reservoir in southeastern Brazil. *Aquacultural Engineering*, *66*, 30–40.

De Silva, S. S. (2016). Culture based fisheries in Asia are a strategy to augment food security. *Food Security*, *8*, 585–596.

Delmendo, M. N., & Gedney, R. H. (1976). Laguna de Bay fish pen aquaculture development - Philippines. *Proceedings of the Annual Meeting – World Mariculture Society*, *7*, 257–265.

Diana, J. S., Egna, H. S., Chopin, T., Peterson, M. S., Cao, L., Pomeroy, R., Verdegem, M., Slack, W. T., Bondad-Reantaso, M. G., & Cabello, F. (2013). Responsible aquaculture in 2050: Valuing local conditions and human innovations will be key to success. *Bioscience*, *63*, 255–262.

Donncha, F. O., & Grant, J. (2019). Precision Aquaculture. *IEEE Internet of Things Magazine*, *2*, 26–30.

Drózdz, D., Malińska, K., Mazurkiewicz, J., Kacprzak, M., Mrowiec, M., Szczypiór, A., Postawa, P., & Stachowiak, T. (2020). Fish pond sediment from aquaculture production-current practices and the potential for nutrient recovery: A review. *International Agrophysics*, *34*, 33–41.

Dvergedal, H., Ødegård, J., Øverland, M., Mydland, L. T., & Klemetsdal, G. (2019). Indications of a negative genetic association between growth and digestibility in juvenile Atlantic salmon (Salmo salar). *Aquaculture*, *510*, 66–72.

Eck, M., Körner, O., & Jijakli, M. H. (2019). Nutrient cycling in aquaponics systems. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics food production systems: Combined aquaculture and hydroponic production Technologies for the Future* (pp. 231–246). Springer International Publishing.

Edwards, P. (2015). Aquaculture environment interactions: Past, present and likely future trends. *Aquaculture*, *447*, 2–14.

Eggertsen, M., & Halling, C. (2021). Knowledge gaps and management recommendations for future paths of sustainable seaweed farming in the Western Indian Ocean. *Ambio*, *50*, 60–73.

EUMOFA. (2020). *Recirculating aquaculture Sstems* (p. 45). European Market Observatory for Fisheries and Aquaculture Products.

EU-Water-Frame-Directive. (2000). Ditective 2000/60/EC of the European Parlement and of the Council of 23 Octover 2000 establishing a framwork for Community action in the field of water policy, OJ L 327, December 22, 2000. 1–40.

Falconer, L., Cutajar, K., Krupandan, A., Capuzzo, E., Corner, R. A., Ellis, T., Jeffery, K., Mikkelsen, E., Moore, H., O'Beirn, F. X., O'Donohoe, P., Ruane, N. M., Shilland, R., Tett, P., & Telfer, T. C. (2023). Planning and licensing for marine aquaculture. *Reviews in Aquaculture*. In press.

FAO. (2016). *The state of world fisheries and aquaculture 2016*. FAO.

FAO. (2020). *The state of world fisheries and aquaculture 2020. Sustainability in action*. FAO.

FAO. (2022). *The state of world Fishreis and aquaculture 2022. Towards blue transformation*. FAO.

FAO/FishStatJ. (2023). Fishery and Aquaculture Statistics. Global aquaculture production 1950-2020 (FishStatJ). *FAO Fisheries and Aquaculture Division [Online]*. www.fao.org/fishery/statistics/software/fishstatj/en.

Ferreira, J. G., Sequeira, A., Hawkins, A. J. S., Newton, A., Nickell, T. D., Pastres, R., Forte, J., Bodoy, A., & Bricker, S. B. (2009). Analysis of coastal and offshore aquaculture: Application of the FARM model to multiple systems and shellfish species. *Aquaculture*, *292*, 129–138. https://doi.org/10.1016/j.aquaculture.2008.12.017

Flegel, T. W. (2019). A future vision for disease control in shrimp aquaculture. *Journal of the World Aquaculture Society*, *50*, 249–266.

Flores-Aguilar, R. A., Gutierrez, A., Ellwanger, A., & Searcy-Bernal, R. (2007). Development and current status of abalone aquaculture in Chile. *Journal of Shellfish Research*, *26*, 705–711.

Freed, S., Barman, B., Dubois, M., Flor, R. J., Funge-Smith, S., Gregory, R., Hadi, B. A. R., Halwart, M., Haque, M., Jagadish, S. V. K., Joffre, O. M., Karim, M., Kura, Y., McCartney, M., Mondal, M., Nguyen, V. K., Sinclair, F., Stuart, A. M., Tezzo, X., … Cohen, P. J. (2020). Maintaining diversity of integrated Rice and fish production confers adaptability of food systems to global change. *Frontiers in Sustainable Food Systems*, *4*, 4.

Freed, S., Kura, Y., Sean, V., Mith, S., Cohen, P., Kim, M., Thay, S., & Chhy, S. (2020). Rice field fisheries: Wild aquatic species diversity, food provision services and contribution to inland fisheries. *Fisheries Research*, *229*, 105615.

Froehlich, H. E., Runge, C. A., Gentry, R. R., Gaines, S. D., & Halpern, B. S. (2018). Comparative terrestrial feed and land use of an aquaculture-dominant world. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 5295–5300.

Garlock, T., Asche, F., Anderson, J., Bjørndal, T., Kumar, G., Lorenzen, K., Ropicki, A., Smith, M. D., & Tveterås, R. (2020). A global blue revolution: Aquaculture growth across regions, species, and countries. *Reviews in Fisheries Science and Aquaculture*, *28*, 107–116.

Gentry, R. R., Froehlich, H. E., Grimm, D., Kareiva, P., Parke, M., Rust, M., Gaines, S. D., & Halpern, B. S. (2017). Mapping the global potential for marine aquaculture. *Nature Ecology and Evolution.*, *1*, 1317–1324.

Gephart, J. A., Golden, C. D., Asche, F., Belton, B., Brugere, C., Froehlich, H. E., Fry, J. P., Halpern, B. S., Hicks, C. C., Jones, R. C., Klinger, D. H., Little, D. C., McCauley, D. J., Thilsted, S. H., Troell, M., & Allison, E. H. (2020). Scenarios for global aquaculture and its role in human nutrition. *Reviews in Fisheries Science and Aquaculture*, *29*, 122–138.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Gephart, J. A., Troell, M., Henriksson, P. J. G., Beveridge, M. C. M., Verdegem, M., Metian, M., Mateos, L. D., & Deutsch, L. (2016). The 'seafood gap' in the food-water nexus literature-issues surrounding freshwater use in seafood production chains. *Advances in Water Resources*, *110*, 505–514. https://doi.org/10.1016/j.advwatres.2017.1003.1025

Ghamkhar, R., Boxman, S. E., Main, K. L., Zhang, Q., Trotz, M. A., & Hicks, A. (2021). Life cycle assessment of aquaculture systems: Does burden shifting occur with an increase in production intensity? *Aquacultural Engineering*, *92*, 102130.

Goddek, S., Espinal, C. A., Delaide, B., Jijakli, M. H., Schmautz, Z., Wuertz, S., & Keesman, K. J. (2016). Navigating towards decoupled Aquaponic systems: A system dynamics design approach. *Water*, *8*, 303.

Green, B. S., Gardner, C., Hochmuth, J. D., & Linnane, A. (2014). Environmental effects on fished lobsters and crabs. *Reviews in Fish Biology and Fisheries*, *24*, 613–638.

Gui, J., Tang, Q., Li, Z., Liu, J., & De Silva, S. S. (2018). *Aquaculture in China: Success stories and modern trends*. John Wiley & Sons Ltd.

Guillemin, M. L., Faugeron, S., Destombe, C., Viard, F., Correa, J. A., & Valero, M. (2008). Genetic variation in wild and cultivated populations of the haploid-diploid red alga Gracilaria chilensis: How farming practices favor asexual reproduction and heterozygosity. *Evolution*, *62*, 1500–1519.

Guo, X. (2021). Genetics in shellfish culture. In S. E. Shumway (Ed.), *Molluscan shellfish aquaculture: A practical guide* (pp. 393–414). 5m Publishing.

Hadlock, P. (2020). Water management in RAS systems - Maine and Denmark: *Cianbro*. *Webinar*. https://americas.ramboll.com/webinar/aquaculture/#session2

Hafting, J. T., Craigie, J. S., Stengel, D. B., Loureiro, R. R., Buschmann, A. H., Yarish, C., Edwards, M. D., & Critchley, A. T. (2015). Prospects and challenges for industrial production of seaweed bioactives. *Journal of Phycology*, *51*, 821–837.

Halim, D., & Juanri. (2016). Indonesians aquaculture industry - key sectors for future growth. http://www.jpsosconsulting.com/asean-agriculture

Hallegraeff, G. M. (2010). Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. *Journal of Phycology*, *46*, 220–235.

Hassan, S. G., Hasan, M., & Li, D. (2016). Information fusion in aquaculture: A state-of the art review. *Frontiers of Agricultural Science and Engineering*, *3*, 206–221.

Henriksson, P. J. G., Belton, B., Murshed-E-Jahan, K., & Rico, A. (2018). Measuring the potential for sustainable intensification of aquaculture in Bangladesh using life cycle assessment. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 2958–2963.

Henriksson, P. J. G., Dickson, M., Allah, A. N., Al-Kenawy, D., & Phillips, M. (2017). Benchmarking the environmental performance of best management practice and genetic improvements in Egyptian aquaculture using life cycle assessment. *Aquaculture*, *468*, 53–59.

Hickling, C. F. (1962). Fish culture. [s.n.], London.

Hilborn, R., Banobi, J., Hall, S. J., Pucylowski, T., & Walsworth, T. E. (2018). The environmental cost of animal source foods. *Frontiers in Ecology and the Environment*, *16*, 329–335.

Hossain, A., Habibullah-Al-Mamun, M., Nagano, I., Masunaga, S., Kitazawa, D., & Matsuda, H. (2022). Antibiotics, antibiotic-resistant bacteria, and resistance genes in aquaculture: Risks, current concern, and future thinking. *Environmental Science and Pollution Research*, *29*, 11054–11075.

Hu, Z., Lee, J. W., Chandran, K., Kim, S., & Khanal, S. K. (2012). Nitrous oxide (N 2O) emission from aquaculture: A review. *Environmental Science & Technology*, *46*, 6470–6480.

Hua, K., Cobcroft, J. M., Cole, A., Condon, K., Jerry, D. R., Mangott, A., Praeger, C., Vucko, M. J., Zeng, C., Zenger, K., & Strugnell, J. M. (2019). The future of aquatic protein: Implications for protein sources in aquaculture diets. *One Earth*, *1*, 316–329.

Huang, A. (2019). RAS in China. In J. Dalsgaard (Ed.), *5th NordicRAS workshop on recirculating aquaculture systems, book of abstracts. DTU aqua report No. 350–2019* (p. 50). National Institute of Aqutic Resources, Technical University of Denmark.

Huet, M. (1986). *Textbook of fish culture: Breeding and cultivation of fish*. Fishing News Books.

Hughes, A. D., & Black, K. D. (2016). Going beyond the search for solutions: Understanding trade-offs in European integrated multi-trophic aquaculture development. *Aquaculture Environment Interactions*, *8*, 191–199.

Hurd, C. L., Lobban, C. S., Bischof, K., & Harrison, P. J. (2014). Seaweed mariculture (chapter 10). In *Seaweed ecology and physiology* (pp. 413–439). Cambridge University Press.

Hurtado, A. Q., Neish, I. C., & Critchley, A. T. (2019). Phyconomy: The extensive cultivation of seaweeds, their sustainability and economic value, with particular reference to important lessons to be learned and transferred from the practice of eucheumatoid farming. *Phycologia*, *58*, 472–483.

Husen, M. A., Yadav, C. N. R., Shreshtha, M., & Bista, J. D. (2012). Growth and production of planktivorous fish species in cages stocked as monoculture and polyculture at Khapuadi in Phewa Lake, Nepal. *Asian Fisheries Science*, *25*, 218–231.

Hwang, E. K., & Park, C. S. (2020). Seaweed cultivation and utilization of Korea. *Algae*, *35*, 107–121.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Infante-Villamil, S., Huerlimann, R., & Jerry, D. R. (2020). Microbiome diversity and dysbiosis in aquaculture. *Reviews in Aquaculture*, *13*, 1077–1096.

Itano, T., Inagaki, T., Nakamura, C., Hashimoto, R., Negoro, N., Hyodo, J., & Honda, S. (2019). Water circulation induced by mechanical aerators in a rectangular vessel for shrimp aquaculture. *Aquacultural Engineering*, *85*, 106–113.

Jansen, H. M., Van Den Burg, S., Bolman, B., Jak, R. G., Kamermans, P., Poelman, M., & Stuiver, M. (2016). The feasibility of offshore aquaculture and its potential for multi-use in the North Sea. *Aquaculture International*, *24*, 735–756.

Jayanthi, M., Balasubramaniam, A. A. K., Suryaprakash, S., Veerapandian, N., Ravisankar, T., & Vijayan, K. K. (2021). Assessment of standard aeration efficiency of different aerators and its relation to the overall economics in shrimp culture. *Aquacultural Engineering*, *92*, 102142.

Joffre, O. M., & Verdegem, M. C. J. (2019). Feeding both pond and fish: A pathway to ecological intensification of aquaculture systems. *Infofish International*, 60–63. www.infofish.org

Jokumsen, A., & Svendsen, L. M. (2010). Farming of freshwater rainbow trout in Denmark, DTU Aqua Report no. 219-2010. DTU Aqua - Technical University Denmark.

Kabir, K., Phillips, M., & Verdegem, M. (2020). Reducing the carbon footprint from pond aquaculture in a changing world. *Journal of the Indian Society of Coastal Agricultural Research*, *38*, 125–131.

Kabir, K. A., Schrama, J. W., Verreth, J. A. J., Phillips, M. J., & Verdegem, M. C. J. (2019). Effect of dietary protein to energy ratio on performance of Nile tilapia and food web enhancement in semi-intensive pond aquaculture. *Aquaculture*, *499*, 235–242.

Kabir, K. A., Verdegem, M. C. J., Verreth, J. A. J., Phillips, M. J., & Schrama, J. W. (2020). Dietary non-starch polysaccharides influenced natural food web and fish production in semi-intensive pond culture of Nile tilapia. *Aquaculture*, *528*, 735506.

Kause, A., Nousiainen, A., & Koskinen, H. (2022). Improvement in feed efficiency and reduction in nutrient loading from rainbow trout farms: The role of selective breeding. *Journal of Animal Science*, *100*, skac214.

Kawahigashi, D. (2018). New paradigm for controlling EMS/APHNS in intensive p. Vannamei Boone 1931 culture ponds. *Asian Fisheries Science*, *31S*, 182–193.

Kinyage, J. P. H., Pedersen, P. B., & Pedersen, L. F. (2019). Effects of abrupt salinity increase on nitrification processes in a freshwater moving bed biofilter. *Aquacultural Engineering*, *84*, 91–98.

Klinger, D., & Naylor, R. (2012). Searching for solutions in aquaculture: Charting a sustainable course. *Annual Review of Environment and Resources*, *37*, 247–276.

Klinger, D. H., Levin, S. A., & Watson, J. R. (2017). The growth of finfish in global openocean aquaculture under climate change. *Proceedings of the Royal Society B: Biological Sciences*, *37*, 284.

Kumar, A., Moulick, S., & Mal, B. C. (2013). Selection of aerators for intensive aquacultural pond. *Aquacultural Engineering*, *56*, 71–78.

Kumar, V., Roy, S., Meena, D. K., & Sarkar, U. K. (2016). Application of probiotics in shrimp aquaculture: Importance, mechanisms of action, and methods of administration. *Reviews in Fisheries Science & Aquaculture*, *24*, 342–368.

Latt, U. W. (2019). Biosecurity application in shrimp hatchery: beneficial or a cost factor. Presentation made at *OIE Global Conference on aquatic Animal Helath*, Santiago, Chile, 2–4 April 2019.

Lebel, L., Navy, H., Jutagate, T., Akester, M. J., Sturm, L., Lebel, P., & Lebel, B. (2020). Innovation, practice, and adaptation to climate in the aquaculture sector. *Reviews in Fisheries Science and Aquaculture*, *29*, 721–738.

Lepine, C., Christianson, L., Soucek, D., McIsaac, G., & Summerfelt, S. (2021). Metal leaching and toxicity of denitrifying woodchip bioreactor outflow—Potential reuse application. *Aquacultural Engineering*, *93*, 102129.

Li, R. H., Liu, S. M., Zhang, J., Jiang, Z. J., & Fang, J. G. (2016). Sources and export of nutrients associated with integrated multi-trophic aquaculture in Sanggou Bay, China. *Aquaculture Environment Interactions*, *8*, 285–309.

Lindholm-Lehto, P., Pulkkinen, J., Kiuru, T., Koskela, J., & Vielma, J. (2020). Water quality in recirculating aquaculture system using woodchip denitrification and slow sand filtration. *Environmental Science and Pollution Research*, *27*, 17314–17328.

Little, D. C., Newton, R. W., & Beveridge, M. C. M. (2016). Aquaculture: A rapidly growing and significant source of sustainable food? Status, transitions and potential. *The Proceedings of the Nutrition Society*, *75*, 274–286.

Lombardi, J. V., de Almeida Marques, H. L., Pereira, R. T. L., Barreto, O. J. S., & de Paula, E. J. (2006). Cage polyculture of the Pacific white shrimp Litopenaeus vannamei and The Philippines seaweed Kappaphycus alvarezii. *Aquaculture*, *258*, 412–415.

López-Vivas, J. M., Riosmena-Rodríguez, R., de la Llave, A. A. J.-G., Pacheco-Ruíz, I., & Yarish, C. (2015). Growth and reproductive responses of the conchocelis phase of Pyropia hollenbergii (Bangiales, Rhodophyta) to light and temperature. *Journal of Applied Phycology*, *27*, 1561–1570.

Luo, Z., Hu, S., & Chen, D. (2018). The trends of aquacultural nitrogen budget and its environmental implications in China. *Scientific Reports*, *8*, 10877.

Maas, R. M., Verdegem, M. C., Dersjant-Li, Y., & Schrama, J. W. (2018). The effect of phytase, xylanase and their combination on growth performance and nutrient utilization in Nile tilapia. *Aquaculture*, *487*, 7–14.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Maas, R. M., Verdegem, M. C. J., Debnath, S., Marchal, L., & Schrama, J. W. (2021). Effect of enzymes (phytase and xylanase), probiotics (B. amyloliquefaciens) and their combination on growth performance and nutrient utilisation in Nile tilapia. *Aquaculture*, *533*, 736226.

Maas, R. M., Verdegem, M. C. J., Wiegertjes, G. F., & Schrama, J. W. (2020). Carbohydrate utilisation by tilapia: A meta-analytical approach. *Reviews in Aquaculture*, *12*, 1851–1866.

MacLeod, M. J., Hasan, M. R., Robb, D. H. F., & Mamun-Ur-Rashid, M. (2020). Quantifying greenhouse gas emissions from global aquaculture. *Scientific Reports*, *10*, 11679.

Mahmood, T., Fang, J., Jiang, Z., & Zhang, J. (2016a). Seasonal nutrient chemistry in an integrated multi-trophic aquaculture region: Case study of Sanggou Bay from North China. *Chemistry and Ecology*, *32*, 149–168.

Mahmood, T., Fang, J. G., Jiang, Z. J., & Zhang, J. (2016b). Carbon and nitrogen flow, and trophic relationships, among the cultured species in an integrated multi-trophic aquaculture (IMTA) bay. *Aquaculture Environment Interactions*, *8*, 207–219.

Maiolo, S., Parisi, G., Biondi, N., Lunelli, F., Tibaldi, E., & Pastres, R. (2020). Fishmeal partial substitution within aquafeed formulations: Life cycle assessment of four alternative protein sources. *International Journal of Life Cycle Assessment*, *25*, 1455–1471.

Martínez-Porchas, M., Martínez-Córdova, L. R., Porchas-Cornejo, M. A., & López-Elías, J. A. (2010). Shrimp polyculture: A potentially profitable, sustainable, but uncommon aquacultural practice. *Reviews in Aquaculture*, *2*, 73–85.

Martins, C., Eding, E. H., Verdegem, M. C., Heinsbroek, L. T., Schneider, O., Blancheton, J.-P., D'Orbcastel, E. R., & Verreth, J. (2010). New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. *Aquacultural Engineering*, *43*, 83–93.

Masso-Silva, J. A., & Diamond, G. (2014). Antimicrobial Peptides from Fish . *Pharmaceuticals*, *7*, 265–310.

Matassa, S., Boon, N., Pikaar, I., & Verstraete, W. (2016). Microbial protein: Future sustainable food supply route with low environmental footprint. *Microbial Biotechnology*, *9*, 568–575.

Matsuyama, Y., & Shumway, S. (2009). Impacts of harmful algal blooms on shellfisheries aquaculture. In G. Burnell, & and G. Allen, (Eds.), *New technologies in aquaculture: improving production efficiency, quality and environmental management*. Woodhead Publishing, 580–609.

Maucieri, C., Nicoletto, C., Os, E. V., Anseeuw, D., Havermaet, R. V., & Junge, R. (2019). Hydroponic Technologies. In S. Goddek, A. Joyce, B. Kotzen, & G. M. Burnell (Eds.), *Aquaponics food production systems: Combined aquaculture and hydroponic production Technologies for the Future* (pp. 77–110). Springer International Publishing.

Merican, Z. (2021). *Shrimp broodstock and hatchery in 2020: Making waves with fast growth lines* (pp. 6–11). AQUA Cylture Asia Pacific. https://issuu.com/aquacultureasiapacific/docs/aq21153_aap_janfeb21121_fa_sml

Miao, W., & Wang, W. (2020). Trends of aquaculture production and trade: Carp, tilapia, and shrimp. *Asian Fisheries Science*, *33*, 1–10.

Midilli, A., Kucuk, H., & Dincer, I. (2012). Environmental and sustainability aspects of a recirculating aquaculture system. *Environmental Progress & Sustainable Energy*, *31*, 604–611.

Millard, R. S., Ellis, R. P., Bateman, K. S., Bickley, L. K., Tyler, C. R., van Aerle, R., & Santos, E. M. (2020). How do abiotic environmental conditions influence shrimp susceptibility to disease? A critical analysis focussed on white spot disease. *Journal of Invertebrate Pathology*, *186*, 107369.

Mnyoro, M. S., Munubi, R. N., Pedersen, L. F., & Chenyambuga, S. W. (2022). Evaluation of biofilter performance with alternative local biomedia in pilot scale recirculating aquaculture systems. *Journal of Cleaner Production*, *366*, 132929.

Molina, C., & Espinoza, M. (2018). Rising use of automatic feeders in shrimp ponds poses new feed requirements., Global Aquaculture Advocate, August 20, 2018. https://www.aquaculturealliance.org/advocate/automatic-feeders-shrimp-ponds-new-feed-requirements/?headlessPrint=AAAAAPIA9c8r7gs82oWZB

Monsees, H., Kloas, W., & Wuertz, S. (2017). Decoupled systems on trial: Eliminating bottlenecks to improve aquaponic processes. *PLoS One*, *12*(9).

NACA/FAO. (2000). Aquaculture development beyond 2000: the Bangkok Declaration and Strategy, Conference on Aquaculture in the Third Millenium. NACA, Bangkok and FAO, Rome. 27, Bangkok, Thailand.

Naylor, R. L., Goldburg, R. J., Primavera, J. H., Kautsky, N., Beveridge, M. C. M., Clay, J., Folke, C., Lubchenco, J., Mooney, H., & Troell, M. (2000). Effect of aquaculture on world fish supplies. *Nature*, *405*, 1017–1024.

Naylor, R. L., Hardy, R. W., Bureau, D. P., Chiu, A., Elliott, M., Farrell, A. P., Forster, I., Gatlin, D. M., Goldburg, R. J., Hua, K., & Nichols, P. D. (2009). Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Sciences of the United States of America*, *106*, 15103–15110.

Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., Little, D. C., Lubchenco, J., Shumway, S. E., & Troell, M. (2021). A 20-year retrospective review of global aquaculture. *Nature*, *591*, 551–563.

Neori, A., Troell, M., Chopin, T., Yarish, C., Critchley, A., & Buschmann, A. H. (2007). The need for a balanced ecosystem approach to blue revolution aquaculture. *Environment: Science and Policy for Sustainable Development*, *49*, 36–43.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Nhung, T. T., Le Vo, P., Van Nghi, V., & Bang, H. Q. (2019). Salt intrusion adaptation measures for sustainable agricultural development under climate change effects: A case of Ca Mau peninsula, Vietnam. *Climate Risk Management*, *23*, 88–100.

Nhut, N., Hao, N. V., Bosma, R. H., Verreth, J. A. V., Eding, E. H., & Verdegem, M. C. J. (2019). Options to reuse sludge from striped catfish (Pangasianodon hypophthalmus, Sauvage, 1878) ponds and recirculating systems. *Aquacultural Engineering*, *87*, 102020.

Ninawe, A. S., & Selvin, J. (2009). Probiotics in shrimp aquaculture: Avenues and challenges. *Critical Reviews in Microbiology*, *35*, 43–66.

Oyinlola, M. A., Reygondeau, G., Wabnitz, C. C. C., Troell, M., & Cheung, W. W. L. (2018). Global estimation of areas with suitable environmental conditions for mariculture species. *PLoS One*, *13*, e0191086.

Paclibare, J. O., Verdegem, M. C., van Muiswinkel, W., & Huisman, B. (1998). The potential for crop rotation in controlling diseases in shrimp culture. *Naga, the ICLARM Quarterly*, *21*, 22–24.

Palić, D., & Scarfe, A. (2019). Biosecurity in aquaculture: Practical veterinary approaches for aquatic animal disease prevention, control, and potential eradication, biosecurity in animal production and veterinary medicine: From principles to practice. In J. Dewulf, & F. Van Immerseel (Eds.), *CABI Wallingford UK*, 497–523.

Palm, H. W., Knaus, U., Appelbaum, S., Goddek, S., Strauch, S. M., Vermeulen, T., Haïssam Jijakli, M., & Kotzen, B. (2018). Towards commercial aquaponics: A review of systems, designs, scales and nomenclature. *Aquaculture International*, *26*, 813–842.

Parra, L., Lloret, G., Lloret, J., & Rodilla, M. (2018). Physical sensors for precision aquaculture: A review. *IEEE Sensors Journal*, *18*, 3915–3923.

Paudel, S. R. (2020). Nitrogen transformation in engineered aquaponics with water celery (Oenanthe javanica) and koi carp (Cyprinus carpio): Effects of plant to fish biomass ratio. *Aquaculture*, *520*, 734971.

Pelletier, N., Klinger, D. H., Sims, N. A., Yoshioka, J. R., & Kittinger, J. N. (2018). Nutritional attributes, substitutability, scalability, and environmental intensity of an illustrative subset of current and future protein sources for aquaculture feeds: Joint consideration of potential synergies and trade-offs. *Environmental Science & Technology*, *52*, 5532–5544.

Pinho, S. M., Molinari, D., de Mello, G. L., Fitzsimmons, K. M., & Coelho Emerenciano, M. G. (2017). Effluent from a biofloc technology (BFT) tilapia culture on the aquaponics production of different lettuce varieties. *Ecological Engineering*, *103*, 146–153.

Rambags, F., Tanner, C. C., Stott, R., & Schipper, L. A. (2019). Bacteria and virus removal in denitrifying bioreactors: Effects of media type and age. *Ecological Engineering*, *138*, 46–53.

Raworth, K. (2017). *Doughnut economics: Seven ways to think like a 21st-century economist*. Chelsea Green Publishing.

Reid, G. K., Forster, I., Cross, S., Pace, S., Balfry, S., & Dumas, A. (2017). Growth and diet digestibility of cultured sablefish Anoplopoma fimbria: Implications for nutrient waste production and integrated multi-trophic aquaculture. *Aquaculture*, *470*, 223–229.

Reid, G. K., Gurney-Smith, H. J., Marcogliese, D. J., Knowler, D., Benfey, T., Garber, A. F., Forster, I., Chopin, T., Brewer-Dalton, K., Moccia, R. D., Flaherty, M., Smith, C. T., & De Silva, S. (2019). Climate change and aquaculture: Considering biological response and resources. *Aquaculture Environment Interactions*, *11*, 569–602.

Reverter, M., Tapissier-Bontemps, N., Sarter, S., Sasal, P., & Caruso, D. (2021). Moving towards more sustainable aquaculture practices: A meta-analysis on the potential of plant-enriched diets to improve fish growth, immunity and disease resistance. *Reviews in Aquaculture*, *13*, 537–555.

Rowley, A. F., Cross, M. E., Culloty, S. C., Lynch, S. A., Mackenzie, C. L., Morgan, E., O'Riordan, R. M., Robins, P. E., Smith, A. L., Thrupp, T. J., Vogan, C. L., Wootton, E. C., & Malham, S. K. (2014). The potential impact of climate change on the infectious diseases of commercially important shellfish populations in the Irish Sea - a review. *ICES Journal of Marine Science*, *71*, 741–759.

Salazar, C., Jaime, M., Figueroa, Y., & Fuentes, R. (2018). Innovation in small-scale aquaculture in Chile. *Aquaculture Economics and Management*, *22*, 151–167.

Samuel-Fitwi, B., Nagel, F., Meyer, S., Schroeder, J., & Schulz, C. (2013). Comparative life cycle assessment (LCA) of raising rainbow trout (Oncorhynchus mykiss) in different production systems. *Aquacultural Engineering*, *54*, 85–92.

Santelices, B. (1999). A conceptual framework for marine agronomy. *Hydrobiologia*, *398–399*, 15–23.

Sarkis, S., Karney, R., & Creswell, R. L. (2021). Design and construction considerations for a molluscan hatchery. In S. E. Shumway (Ed.), *Molluscan shellfish aquaculture: A practical guide*. 5 M Publications In press.

Schneider, O., Sereti, V., Eding, E., & Verreth, J. (2005). Analysis of nutrient flows in integrated intensive aquaculture systems. *Aquacultural Engineering*, *32*, 379–401.

Shinn, A. P., Pratoomyot, J., Griffiths, D., Trong, T. Q., Vu, N. T., Jiravanichpaisal, P., & Briggs, M. (2018). Asian shrimp production and the economic costs of disease. *Asian Fisheries Science*, *31*, 29–58.

Shumway, S. (2021). *Molluscan shellfish aquaculture: A practical guide*. 5m Publishing.

Shumway, S. E. (1990). A review of the effects of algal blooms on shellfish and aquaculture. *Journal of the World Aquaculture Society*, *21*, 65–104.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Shumway, S. E. (2011). *Shellfish aquaculture and the environment*. John Wiley & Sons.
Silva, C., Ferreira, J. G., Bricker, S. B., DelValls, T. A., Martín-Díaz, M. L., & Yáñez, E. (2011). Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments. *Aquaculture*, *318*, 444–457.
Song, X., Liu, Y., Pettersen, J. B., Brandão, M., Ma, X., Røberg, S., & Frostell, B. (2019). Life cycle assessment of recirculating aquaculture systems: A case of Atlantic salmon farming in China. *Journal of Industrial Ecology*, *23*, 1077–1086.
Stentiford, G. D., Neil, D. M., Peeler, E. J., Shields, J. D., Small, H. J., Flegel, T. W., Vlak, J. M., Jones, B., Morado, F., Moss, S., Lotz, J., Bartholomay, L., Behringer, D. C., Hauton, C., & Lightner, D. V. (2012). Disease will limit future food supply from the global crustacean fishery and aquaculture sectors. *Journal of Invertebrate Pathology*, *110*, 141–157.
Stokstad, E. (2020). Tomorrow's catch. *Science*, *370*, 902–905.
Subasinghe, R., Arthur, J., Bartley, D., De Silva, S., Halwart, M., Hishamunda, N., Mohan, C., & Sorgeloos, P. (2013). Proceedings of the Global Conference on Aquaculture 2010. Farming the waters for people and food, Proceedings of the Global Conference on Aquaculture 2010. Farming the waters for people and food. FAO/NACA.
Tacon, A. G. J. (2020). Trends in global aquaculture and Aquafeed production: 2000–2017. *Reviews in Fisheries Science and Aquaculture*, *28*, 43–56.
Thilsted, S. H., Thorne-Lyman, A., Webb, P., Bogard, J. R., Subasinghe, R., Phillips, M. J., & Allison, E. H. (2016). Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy*, *61*, 126–131.
Timmons, M. B., Guerdat, T., Vinci, B. J., & United States. Department of, A., Northeastern Regional Aquaculture, C. (2018). *Recirculating aquaculture* (4th ed.). Ithaca Publishing Company LLC.
Tinh, T. H., Koppenol, T., Hai, T. N., Verreth, J. A. J., & Verdegem, M. C. J. (2021). Effects of carbohydrate sources on a biofloc nursery system for whiteleg shrimp (Litopenaeus vannamei). *Aquaculture*, *531*, 735795.
Trainer, V. L., Moore, S. K., Hallegraeff, G., Kudela, R. M., Clement, A., Mardones, J. I., & Cochlan, W. P. (2020). Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. *Harmful Algae*, *91*, 101591.
Troell, M., Halling, C., Neori, A., Chopin, T., Buschmann, A., Kautsky, N., & Yarish, C. (2003). Integrated mariculture: Asking the right questions. *Aquaculture*, *226*, 69–90.
Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A. H., & Fang, J.-G. (2009). Ecological engineering in aquaculture—Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture*, *297*, 1–9.
Troell, M., Metian, M., Beveridge, M., Verdegem, M., & Deutsch, L. (2014). Comment on 'Water footprint of marine protein consumption-aquaculture's link to agriculture'. *Environmental Research Letters*, *9*, 4.
Troell, M., Naylor, R. L., Metian, M., Beveridge, M., Tyedmers, P. H., Folke, C., Arrow, K. J., Barrett, S., Crépin, A. S., Ehrlich, P. R., Gren, A., Kautsky, N., Levin, S. A., Nyborg, K., Österblom, H., Polasky, S., Scheffer, M., Walker, B. H., Xepapadeas, T., & De Zeeuw, A. (2014). Does aquaculture add resilience to the global food system? *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 13257–13263.
Tucker, C., & Hargreaves, J. (2012). Ponds. In J. H. Tidwell (Ed.), *Aquaculture Production Systems* (pp. 191–244). John Wiley & Sons, Inc.
Uccello, E., Kauffmann, D., Calo, M., & Streissel, M. (2017). *Nutrition-sensitive agriculture and food systems in practice: Options for intervention*. FAO.
Usandizaga, S., Buschmann, A. H., Camus, C., Kappes, J. L., Arnaud-Haond, S., Mauger, S., Valero, M., & Guillemin, M. L. (2020). Better off alone? Compared performance of monoclonal and polyclonal stands of a cultivated red alga growth. *Evolutionary Applications*, *13*, 905–917.
Valero, M., Guillemin, M. L., Destombe, C., Jacquemin, B., Gachon, C. M. M., Badis, Y., Buschmann, A. H., Camus, C., & Faugeron, S. (2017). Perspectives on domestication research for sustainable seaweed aquaculture. *Perspectives in Phycology*, *4*, 33–46.
Van Rijn, J. (2013). Waste treatment in recirculating aquaculture systems. *Aquacultural Engineering*, *53*, 49–56.
Van Zanten, H. H. E., Van Ittersum, M. K., & De Boer, I. J. M. (2019). The role of farm animals in a circular food system. *Global Food Security*, *21*, 18–22.
Verdegem, M. C. J., & Bosma, R. H. (2009). Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. *Water Policy*, *11*, 52–68.
Verdegem, M. C. J., Bosma, R. H., & Verreth, J. A. J. (2006). Reducing water use for animal production through aquaculture. *International Journal of Water Resources Development*, *22*, 101–113.
Verdegem, M. C. J., Yossa, R., Chary, K. T., Schrama, J. W., Beveridge, M. C. M., & Marwaha, N. (2021). Sustainable and accessible fish feeds for small-scale fish farmers. CGIAR Research Program on Fish Agri-Food Systems. Program Brief: FISH-2021-06.
Vielma, J., Kankainen, M., & Setälä, J. (2022). *Current status of recirculation aquaculture systems (RAS) and their profitability and competitiveness in the Baltic Sea area, natural resources and bioeconomy studies 75/2022* (p. 28). Natural Resources Institute Finland.

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

von Ahnen, M., Pedersen, P. B., & Dalsgaard, J. (2018). Performance of full-scale woodchip bioreactors treating effluents from commercial RAS. *Aquacultural Engineering*, *83*, 130–137.
Wang, Q., Ding, H., Tao, Z., & Ma, D. (2018). Crayfish (Procambarus clarkii) cultivation in China: A decade of unprecedented development, aquaculture in China. In J.F. Gui, Q. Tang, Z. Li, J. Liu, & S.S. De Silva (Eds.), *Aquaculture in China*, 317–337. Wiley Blackwell.
Wang, X., Olsen, L. M., Reitan, K. I., & Olsen, Y. (2012). Discharge of nutrient wastes from salmon farms: Environmental effects, and potential for integrated multi-trophic aquaculture. *Aquaculture Environment Interactions*, *2*, 267–283.
Watson, D., Shumway, S., & Whitlatch, R. (2009). Biofouling and the shellfish industry. In S. Shumway, & G. E. Rodrick (Eds.), *Shellfish Safety and Quality*. Woodhead Publishing Limited, 317–337.
Weitzman, J. (2019). Applying the ecosystem services concept to aquaculture: A review of approaches, definitions, and uses. *Ecosystem Services*, *35*, 194–206.
Wells, M. L., Potin, P., Craigie, J. S., Raven, J. A., Merchant, S. S., Helliwell, K. E., Smith, A. G., Camire, M. E., & Brawley, S. H. (2017). Algae as nutritional and functional food sources: Revisiting our understanding. *Journal of Applied Phycology*, *29*, 949–982.
Wilfart, A., Prudhomme, J., Blancheton, J. P., & Aubin, J. (2013). LCA and emergy accounting of aquaculture systems: Towards ecological intensification. *Journal of Environmental Management*, *121*, 96–109.
Wongkiew, S., Hu, Z., Chandran, K., Lee, J. W., & Khanal, S. K. (2017). Nitrogen transformations in aquaponic systems: A review. *Aquacultural Engineering*, *76*, 9–19.
Xiao, R., Wei, Y., An, D., Li, D., Ta, X., Wu, Y., & Ren, Q. (2019). A review on the research status and development trend of equipment in water treatment processes of recirculating aquaculture systems. *Reviews in Aquaculture*, *11*, 863–895.
Xiao, X., Agusti, S., Lin, F., Li, K., Pan, Y., Yu, Y., Zheng, Y., Wu, J., & Duarte, C. M. (2017). Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. *Scientific Reports*, *7*, 46613.
Xiao, X., Agustí, S., Yu, Y., Huang, Y., Chen, W., Hu, J., Li, C., Li, K., Wei, F., Lu, Y., Xu, C., Chen, Z., Liu, S., Zeng, J., Wu, J., & Duarte, C. M. (2021). Seaweed farms provide refugia from ocean acidification. *The Science of the Total Environment*, *776*, 145192.
Yadav, A., Noori, M. T., Biswas, A., & Min, B. (2023). A concise review on the recent developments in the internet of things (IoT)-based smart aquaculture practices. *Reviews in Fisheries Science & Aquaculture*, *31*, 103–118.
Yang, P., Zhang, Y., Yang, H., Guo, Q., Lai, D. Y. F., Zhao, G., Li, L., & Tong, C. (2020). Ebullition was a major pathway of methane emissions from the aquaculture ponds in Southeast China. *Water Research*, *184*, 116176.
Yang, Y., Chai, Z., Wang, Q., Chen, W., He, Z., & Jiang, S. (2015). Cultivation of seaweed Gracilaria in Chinese coastal waters and its contribution to environmental improvements. *Algal Research*, *9*, 236–244.
Yi, Y., & Fitzsimmons, K. (2004). Survey of tilapia-shrimp polyculture in Thailand. In R. Harris, I. Courter, & H. Egna (Eds.), *Twenty-first annual technical report*. Oregon State University.
Zhang, J., Zhang, X., Zhou, Y., Han, Q., Wang, X., Song, C., Wang, S., & Zhao, S. (2023). Occurrence, distribution and risk assessment of antibiotics at various aquaculture stages in typical aquaculture areas surrounding the Yellow Sea. *Journal of Environmental Sciences (China)*, *126*, 621–632.
Zhang, Y., Bleeker, A., & Liu, J. (2015). Nutrient discharge from China's aquaculture industry and associated environmental impacts. *Environmental Research Letters*, *10*, 045002.
Zhou, C., Xu, D., Lin, K., Sun, C., & Yang, X. (2018). Intelligent feeding control methods in aquaculture with an emphasis on fish: A review. *Reviews in Aquaculture*, *10*, 975–993.

How to cite this article: Verdegem, M., Buschmann, A. H., Latt, U. W., Dalsgaard, A. J. T., & Lovatelli, A. (2023). The contribution of aquaculture systems to global aquaculture production. *Journal of the World Aquaculture Society*, *54*(2), 206–250. https://doi.org/10.1111/jwas.12963

17497345, 2023, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12963 by Wageningen University and Research Bibliotheek, Wiley Online Library on [28/08/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License