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STRATEGIES FOR PROMOTING SUSTAINABLE AQUACULTURE IN ARID AND SEMI-ARID AREAS – A REVIEW

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Abstract

Starvation and malnutrition are one of the most destructive problems faced by the poor and needy in the world. With the world population expected to increase by 9.7 billion by 2050, there are growing concerns about the long-term sustainability of many existing food production systems to meet future needs for food. Aquaculture is one of the important sources of food supply, the development of which is of great importance as an important weapon in the global fight against malnutrition and poverty, especially in developing countries and arid and semi-arid regions of the world. In recent decades, aquaculture has dominated all sectors of livestock production in terms of growth and increasingly contributes to food security, poverty reduction, job creation and sources of income. It is important to follow sustainable development goals to increase aquaculture production. Climate change is currently affecting food security through increasing temperature and decreasing rainfall, especially in arid and semi-arid regions. Food security is a global concern and access to affordable, nutritious, safe and properly cultivated food is one of the most important issues globally. The main emphasis in the development of aquaculture in arid and semi-arid areas is the use of new technologies based on water saving, such as biofloc technology (BFT), integrated multi-trophic aquaculture system (IMTA) and recirculating aquaculture systems (RAS). In this study, the importance of aquaculture as a sustainable source of food production in arid and semi-arid regions is discussed.

Key words: aquaculture, food security, sustainable development, circular economy, climate change

Rapid expansion and intensification of cultivated lands are being driven by the growth of the global population and rising food demand (Naylor et al., 2021; Golden et al., 2021). According to the United Nations Convention to Combat Desertification and the United Nations University, Institute for Water, Environment and Health (UNU-INWEH), these factors, along with increasing evapotranspiration and a decrease in rainfall, may also be contributing to desertification (UNCCD, 2007). Water is essential for human subsistence in arid and semi-arid desert regions. Farmers who practice dryland farming are especially affected by this. During the rainy season, the farmers usually sow seeds of barley, wheat, or other basic grains. In the months following the rainy season, grains are harvested and stored if there is sufficient rainfall (over 200–400 mm). Agricultural residues and weeds are used as forage to feed cows and sheep, providing the farmer and his family with meat and milk as important sources of animal protein (Avnimelech et al., 2019). In years with less rainfall, yields may not be sufficient to support a family's subsistence needs in agricultural crops and pastures, especially, when a series of droughts occurs. Sequences of dry years are more common than before due to global climate change (Godde et al., 2021), leading to critical geopolitical developments. Therefore, in dry regions, aquaculture can provide animal protein, which is counterintuitive (IPCC, 2022). With modern technologies and alternative energy sources, aquaculture in deserts and arid lands has been growing steadily over the past decade, enabling water to be exploited more efficiently and effectively in these places of extremes, for irrigation of crops and fish production (Crespi and Lovatelli, 2011 a; Reid et al., 2019).

In regions where other types of intensive animal husbandry are expensive or impossible, aquaculture has become increasingly important in supplying fish protein to the growing human population (FAO, 2011). Conventional agriculture and intensive livestock practices are severely hampered in arid and semi-arid regions because of the habitat and climate, particularly the reduced annual rainfall (Cowan et al., 2022). The concept of desert fish farming was developed in 1963–1965 and tested experimentally, showing that marine or brackish waters could be used to raise fish successfully (Fishelson and Loya, 1969; Crespi and Lovatelli, 2011 b). High mineral content in these waters, along with high ambient temperatures and solar radiation, result in a food base that is suitable and favorable to fish (Pruginin et al., 1988; Crespi, 2009). As a result of increasing competition for land and water use in a wide range of economic activities, aqua-

culture operations are expanding to new frontiers like exposed and offshore seas, or inhospitable regions like deserts and arid lands, where modern and responsible aquaculture practices can be used better (Chadwick et al., 2016; Pueppke et al., 2020).

Economic development, employment, and trade are all related to aquaculture and fishing. The fisheries and aquaculture sector are rapidly changing due to the growing demand for fish and other aquatic foods and are estimated to provide livelihoods for around 600 million people. It is expected that consumption will increase due to rising incomes, urbanization, changes in post-harvest practices, and distribution, as well as dietary trends focusing on better health and nutrition. Approximately 21 percent of the sector's employees were women, according to the latest data. For equitable and sustainable development, building resilience is essential (FAO, 2022 a). Due to the global decline in catches, projected population growth, and increased demand for aquaculture products, it must be developed to meet the future demand for fish. In most instances, aquaculture provides high-quality animal protein, lipids, and other essential nutrients at an affordable price. Therefore, the aim of this review is to highlight the significance of aquaculture as a sustainable means of addressing the growing global concern of food insecurity, particularly in developing countries and arid and semi-arid regions of the world. With the world population projected to increase by 9.7 billion by 2050, there are concerns about the long-term sustainability of conventional food production systems, making the development of aquaculture an important weapon in the fight against malnutrition and poverty. The study emphasizes the need to follow sustainable development goals to increase aquaculture production, especially in regions where climate change is impacting food security. The study also focuses on the importance of using new technologies, such as biofloc technology, integrated multi-trophic aquaculture system, and recirculating aquaculture systems to promote water efficiency in arid and semi-arid regions. Overall, the study seeks to underscore the importance of aquaculture as a sustainable means of promoting food security, poverty reduction, job creation, and income sources, particularly in regions facing the challenge of food insecurity.

Aquaculture

Food and nutrition will continue to be provided by fisheries and aquaculture at record levels in the future. In 2020, fisheries and aquaculture produced 214 million tonnes, including 178 million tonnes of aquatic animals and 36 million tonnes of algae, largely due to the growth of aquaculture in Asia. The amount intended for human consumption (excluding algae) was 20.2 kg per capita, more than double the average of 9.9 kg per capita in the 1960s. The primary sector employed 58.5 million people. About 600 million livelihoods depend at least partially on fisheries and aquaculture, including subsistence and secondary sector workers. As a result of the outbreak of COVID-19, the international trade of fisheries and aquaculture products generated around USD 151 billion in 2020, down from USD 165 billion in 2018. Global aquaculture production reached a record 122.6 million tonnes in 2020 (for detail see Table 1), valued at USD 281.5 billion. There were 87.5 million tonnes of aquatic animals, and 35.1 million tonnes of algae. Despite a decrease in Egypt and Nigeria, global aquaculture production grew in all regions except Africa in 2020 (Kaleem and Sabi, 2021), driven by expansions in Chile, China, and Norway. From 2019 to 2020, the rest of Africa experienced growth of 14.5%. By 2020, Asia produces 91.6 percent of the world's aquaculture (Figure 1). The growth of aquaculture has often been at the expense of the environment (Keshavarzifard et al., 2020; Sharifinia et al., 2015; Yeganeh et al., 2020). Considering that the aquaculture industry has a great potential to feed and nourish the growing world population, so its development should be sustainable (Khanjani et al., 2022 e, f; Sharifinia et al., 2023). Over the next decade, aquaculture is projected to grow by 1–2 percent annually as the world's population grows to 9.7 billion by 2050. Increasing consumer demand for fish as a healthy and nutritious alternative to other red and white meat will also contribute to this growth. Therefore, aquaculture is essential to meeting the future food security needs of the world with 3 billion people relying on wild-caught and farmed seafood as a primary source of protein. Many people find aquaculture products to be a healthy, nutritious, accessible, and affordable source of protein (Cowan et al., 2022). It is possible to make a significant contribution to the economic prosperity of local communities within some of the world's poorest countries through aquaculture, if the right conditions and species are chosen. Therefore, aquaculture could be a sustainable and efficient way to produce animal protein under certain circumstances. Various forms of aquaculture are practiced on every continent. A variety of organisms can be cultivated in freshwater or saltwater, either in their native environment or in tanks, ponds, or raceways on land. The majority of aquaculture operations focus on a single species, such as carp and tilapia in freshwater and salmon and bivalve mollusks (e.g. clams, oysters, mussels) in marine environments. Other forms, such as multi-trophic aquaculture, where multiple species are cultivated together to resemble a natural ecosystem more closely, provide ecosystem services like nutrient cycling and refuge habitat like a natural system while maintaining food production for multiple species (Correia et al., 2020). "Blue growth" initiatives often mention aquaculture as a possible solution to food insecurity, as well as a major contributor to environmentally sustainable seafood development (Belton et al., 2020; Henriksson et al., 2021). Many aspects of aquaculture development, including the siting of farms, the allocation of space, farming practices, and its role in addressing global food insecurity, are not in agreement among governments, environmentalists, academicians, fishermen, and aquatic farmers (Tigchelaar et al., 2021). World aquaculture production of aquatic animals by major producers and major culture species are shown in Figu-

res 2, 3 and Table 2. Over the next decade, aquaculture is expected to grow faster than capture fisheries. Animal aquaculture production reached 87.5 million tonnes in 2020, 6 percent higher than in 2018. In contrast, capture fisheries production fell to 90.3 million tonnes, a 4.0 percent decline from the previous three years. There was a reduction in capture fisheries production mainly due to the COVID-19 pandemic, which severely disrupted fishing activities, market access, and sales, as well as anchoveta, catches naturally fluctuating (FAO, 2022 b). As part of a food systems approach, aquaculture should not be viewed as a substitute for capture fisheries, but as a complement to them, each sector contributing to livelihoods, employment, and nutrition in distinct ways.

Food security with aquaculture in arid and semi-arid regions

Arid and semi-arid regions are characterized by low rainfall and high evaporation rates, resulting in limited water availability and challenging environmental conditions for agriculture and food production (Huang et al., 2017; Reynolds et al., 2007). These regions cover approximately one-third of the Earth's land surface and are home to more than two billion people worldwide, many of whom are dependent on agriculture and livestock production for their livelihoods (FAO, 2021). Productivity in arid and semi-arid regions is limited by the availability and quality of water resources, as well as by factors such as soil fertility and nutrient availability. In general, the primary production in these regions is dominated by drought-resistant crops such as millet, sorghum, and maize, as well as by pastoral livestock production (Huang et al., 2017; McCord et al., 2015; Mizyed, 2013). However, these production systems are often vulnerable to environmental shocks such as droughts, floods, and pests, which can have significant impacts on food security and livelihoods in these regions. One of the key challenges facing arid and semi-arid regions is the limited availability of water resources, which is exacerbated by climate change and population growth. As a result, there is a need to develop innovative water management strategies and technologies that can help to increase water use efficiency and reduce water losses. For example, rainwater harvesting, drip irrigation, and precision agriculture can all help to improve water management in these regions (Huang et al., 2017). Another challenge is the degradation of natural resources such as soil and water, which can have negative impacts on agricultural productivity and biodiversity. To address this challenge, there is a need for sustainable land and water management practices that can help to restore degraded ecosystems and improve the resilience of agricultural systems (Huang et al., 2017). Despite these challenges, there are also several perspectives and opportunities for improving productivity and food security in arid and semi-arid regions. For example, there is growing interest in the use of climate-resilient crops and livestock breeds that can better adapt to changing environmental conditions. Additionally, the adoption of innovative technologies such as precision agriculture, remote sensing, and big data can help to improve productivity and reduce the environmental impact of agriculture in these regions (Huang et al., 2017; Khosla et al., 2008; McLennon et al., 2021).

Table 1. World aquaculture production and average annual growth rate (FAO, 2020 b)

All aquaculture	1990–2000	2000–2010	2010–2020	2015–2020
Starting annual output (MT)	17.3	43.0	77.9	104.0
Ending year's annual output (MT)	43.0	77.9	122.6	122.6
Accumulated increase in annual output (MT)	25.7	34.9	44.6	18.6
Overall increase	149%	81%	57%	18%
Average annual growth rate	9.5%	6.1%	4.6%	3.3%

MT = Million tonnes; All aquaculture = Aquatic animals + Algae.

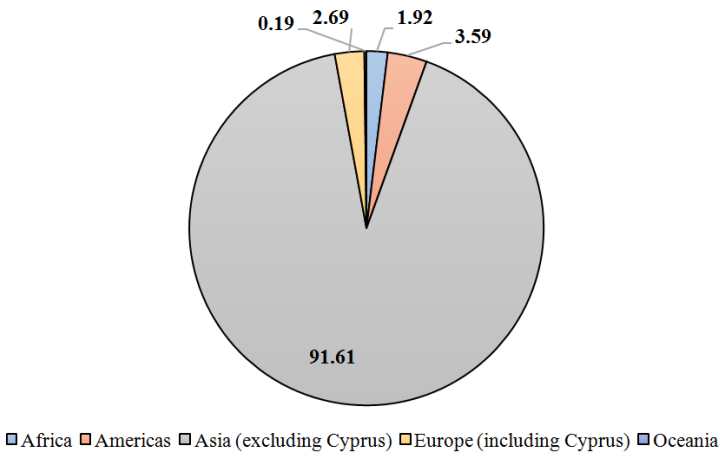


Figure 1. World aquaculture production by region (%)

Table 2. World production of major aquaculture species (FAO, 2020 b)

Species		2000	2005	2010	2015	2020
		TT	TT	TT	TT	TT
English name	Scientific name					
Finfishin inland aquaculture						
Grass carp	*Ctenopharyngodon idellus*	2976.5	3396.6	4213.1	5315.0	5791.5
Silver carp	*Hypophthalmichthys molitrix*	3034.7	3690.0	3972.0	4713.6	4896.6
Nile tilapia	*Oreochromis niloticus*	1003.5	1726.6	2657.7	4050.7	4514.6
Common carp	*Cyprinus carpio*	2410.4	2666.3	3331.0	4025.8	4236.3
Catla	*Catla catla*	602.3	1317.5	2526.4	2313.4	3540.3
Bighead carp	*Hypophthalmichthys nobilis*	1438.9	1929.5	2513.6	3109.1	3187.2
	Carassius spp.	1198.5	1798.2	2137.8	2644.1	2748.6
Striped catfish	*Pangasianodon hypophthalmus*	113.2	411.2	1749.4	2083.2	2520.4
Roho labeo	*Labeo rohita*	733.9	1435.9	1133.2	1785.3	2484.8
Rainbow trout	*Oncorhynchus mykiss*	495.7	562	752.4	750.6	959.6
Black carp	*Mylopharyngodon piceus*	149.0	280.7	409.5	541.2	695.5
Finfishin marine and coastal aquaculture						
Atlantic salmon	*Salmo salar*	895.7	1266.6	1433.8	2380.2	2719.6
Milkfish	*Chanos chanos*	429.7	542.9	750.5	1012.3	1167.8
Mullets nei, Mugilidae		92.4	173.7	102.7	129.2	291.2
Gilthead seabream	*Sparus aurata*	87.3	110.8	142.3	168.8	282.1
Large yellow croaker	*Larimichthys croceus*	0.00	60.9	83.3	142.4	254.1
Rainbow trout	*Oncorhynchus mykiss*	155.3	202.0	287.7	204.1	220.1
Japanese seabass	*Lateolabrax japonicus*	0.6	79.6	104.8	120.6	196.9
Pompano	*Trachinotus ovatus*	0.00	0.00	80.0	110.0	160.0
Japanese amberjack	*Seriola quinqueradiata*	136.8	159.7	138.9	140.3	137.1
Nile tilapia	*O. niloticus*	1.6	5.3	20.3	49.8	10.7
Barramundi	*Lates calcarifer*	18.1	27.0	52.7	68.7	105.8
Crustaceans						
Whiteleg shrimp	*Penaeus vannamei*	154.5	1678.4	2648.5	3803.6	5812.2
Red swamp crawfish	*Procambarus clarkii*	9.9	114.3	599.3	723.1	2469.0
Chinese mitten crab	*Eriocheir sinensis*	202.5	378.4	572.4	747.4	775.9
Giant tiger prawn	*Penaeus monodon*	631.0	665.5	562.9	735.2	717.1
Giant river prawn	*Macrobrachium rosenbergii*	130.7	195.9	193.1	202.5	294.0
Indo-Pacific swamp crab	*Scylla serrata*	10.7	11.7	37.0	83.6	248.8
Molluscs						
Cupped oysters	*Crassostrea* spp.	2922.6	3377.5	3570.7	4408.3	5450.3
Japanese carpet shell	*Ruditapes philippinarum*	1504.3	2590.8	3500.2	3880.2	4266.2
Scallops nei, Pectinidae		811.5	906.3	1366.6	1710.1	1746.4
Sea mussels, Mytilidae		719.8	834.1	871.4	1055.8	1108.3
Constricted tagelus	*Sinonovacula constricta*	487.7	624.4	693.3	760.2	860.3
Pacific cupped oyster	*Magallana gigas*	617.7	686.7	640.7	576.5	610.3
Algae						
Japanese kelp	*Laminaria japonica*	5380.9	5699.1	6525.6	10313.7	12469.8
Eucheuma seaweeds	*Eucheuma* spp.	214.3	983.9	3472.6	10182.1	8129.4
Gracilaria seaweeds	*Gracilaria* spp.	55.5	933.2	1657.1	3767.0	5180.4
Wakame	*Undaria pinnatifida*	311.1	2439.7	1505.1	2215.6	2810.6
Nori	*Porphyra* spp.	424.9	703.1	1040.7	1109.9	2220.2

TT = Thousand tonnes, live weight.

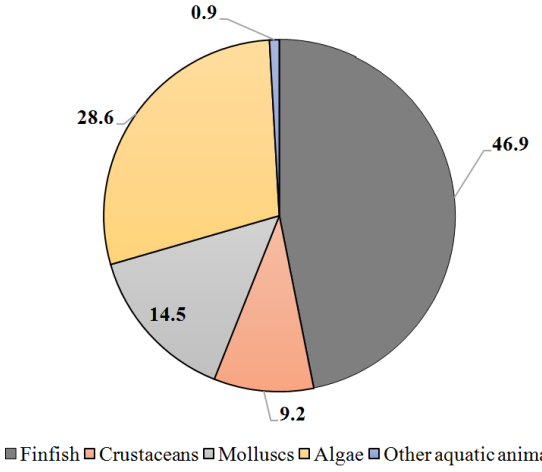


Figure 2. Total aquaculture production in the world by main groups, 2020 (%)

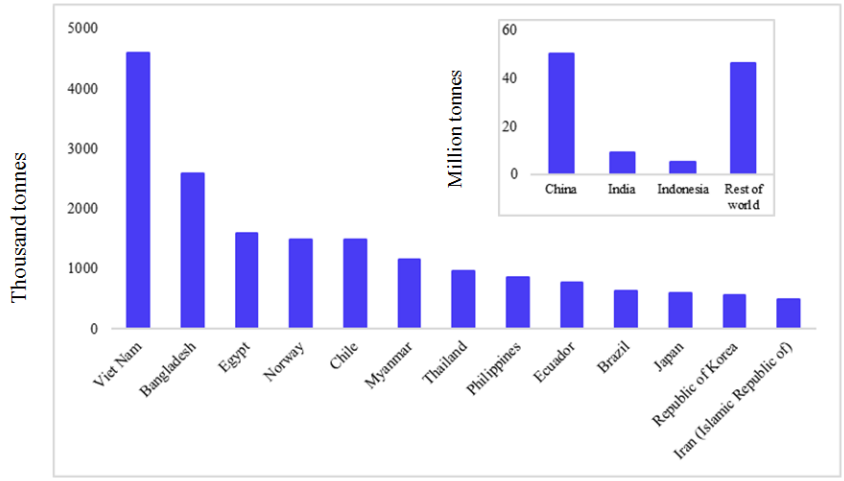


Figure 3. World aquaculture production of aquatic animals by major producers, in 2020

Aquatic food consumption has significantly increased and is projected to continue due to rising incomes, urbanization, and changes in dietary habits (Naylor et al., 2021; FAO, 2022 b). Despite supporting millions of lives and livelihoods, many small-scale producers, especially women, face precarious working conditions and gender-based constraints (FAO, 2021). Food insecurity affects 2.37 billion people globally, with developing and low-income regions being particularly affected by food system inequalities and insecurity, which are also exacerbated by climate change (Global Health 50/50 and International Food Policy Research Institute, 2021; Tigchelaar et al., 2021). These regions are responsible for greenhouse gas emissions and are most likely to be affected by food insecurity and climate change. Climate change threatens access to food and traditional ways of life in some regions and affects the distribution and abundance of aquatic foods, which have historically been economically, socially, and culturally important (Reid et al., 2019; Golden et al., 2021).

Aquaculture is one possible solution to address global food security issues, as it creates jobs, reduces greenhouse gas emissions, and makes aquatic products more affordable for consumers (Gephart et al., 2021; Golden et al., 2021; Belton et al., 2018). The aquaculture of bivalve, forage fish, and seaweed emits fewer greenhouse gases than land-based aquaculture (Gephart et al., 2021; Golden et al., 2021).

To develop the aquaculture industry in arid and semi-arid regions, sustainable aquaculture practices should be followed, and partnerships should be strengthened to generate and share knowledge, information, and technology. Innovation, research, and development in aquaculture should be invested in, and open and transparent communication about sustainable aquaculture should be created. To ensure equitable and just access to nutritious food, power imbalances related to gender, ethnicity/race, migration status, and (dis)ability in all food systems should be addressed. Opportunities exist to support equity and justice, including enhancing women's and in-

digenous access to employment and benefits within the sector (Costello et al., 2020; FAO, 2022 a).

Small-scale land-based aquatic farming systems are more likely to provide food and livelihoods to many low- and middle-income people globally. Science and policy should focus on socially responsible, sustainable, and resilient aquaculture developments that can withstand climate change impacts (Belton et al., 2018; Cowan et al., 2022).

Aquatic food systems offer powerful solutions to meet food security and environmental sustainability goals through blue transformation. FAO is committed to sustaining growth and innovation in aquatic food systems by providing legal, policy, and technical frameworks. Blue transformation aims to boost the role of aquatic food systems in feeding the world's growing population sustainably, leaving no one behind, especially those communities that depend on these sectors, through climate- and environment-friendly policies and practices, as well as technological innovations (Belton et al. 2020; Cottrell et al., 2021; FAO, 2022 b).

To achieve the United Nations 2030 Agenda, commitment from both public and private sectors is crucial, especially in the wake of the COVID-19 pandemic, which has reversed previously favorable trends. Governments, the private sector, and civil society need to commit to blue transformation to maximize the opportunities offered by fisheries and aquaculture. Sustainable aquaculture expansion and intensification, effective fisheries management, and upgrading of aquatic value chains are key objectives of blue transformation (Cottrell et al., 2021; FAO, 2022 b). Public-private partnerships are needed to enhance equitable access to lucrative markets, reduce food loss and waste, and increase availability and improve access to aquatic foods. National food security and nutrition strategies must include aquatic foods, along with initiatives to improve consumer awareness of their benefits.

Aquaculture in arid and semi-arid regions

Aquatic animal production for direct human consumption surpassed 157 million tonnes in 2020, despite the COVID-19 pandemic. The proportion of animal proteins consumed from aquatic foods reached 23 percent in lower-middle-income countries, and over 50 percent in parts of Asia and Africa in 2019. Seventy percent of the world's fisheries and aquaculture production of aquatic animals was produced by Asian countries in 2020, followed by countries in the Americas, Europe, Africa, and Oceania. Among the top fisheries producers were China, Indonesia, Peru, the Russian Federation, the United States, India, and Vietnam, respectively (Enciso-Lopez and García-Trejo, 2019; FAO, 2022 a).

Approximately one-fifth of the earth's surface is covered by arid lands (Smith et al., 2008). Climate change and desertification are expected to increase salinization and desertification of agricultural lands, according to the World Meteorological Organization. Dry lands are characterized by inhospitable temperatures, inaccessible terrain, and a scarcity of sweet water, which makes them difficult to inhabit (Cabrera-González et al., 2022). It is generally recognized, however, that arid lands have a great deal of potential for development. It is possible to use desert aquaculture technology for commercial, as well as small-scale affordable aquaculture initiatives by cultivating organisms that can tolerate the salt content prevalent in arid land and saline groundwater sources. Around the world, seawater is used to farm marine fish and plants. As well, a similar initiative to use desert saline or brackish water for fish farming was launched in 1963–1965 and tested experimentally, demonstrating that such water was capable of rearing fish. Because of the high mineral content in this water, along with the high ambient temperatures and solar radiation, fish have a suitable and favorable food base. Scientists have been working on developing technologies suitable for fish farming since then and, as of today, many countries have developed successful models for producing fish in brackish or saline water beneath deserts (Crespi and Lovatelli, 2011 a). It is important to manage water well in these systems – including recycling and saving – and to introduce modern aquaculture technologies such as recirculating aquaculture systems (RAS) (Martins et al., 2010), integrated multitrophic aquaculture (IMTA) (Khanjani et al., 2022 d), aquaponics (Kotzen et al., 2019), biofloc (Khanjani et al., 2023 b, c), and aquamimicry (Khanjani et al., 2022 a).

In arid regions, other commercially important and valuable organisms can also be produced, which are tolerant of high salt concentrations and high temperatures. Examples include shrimp, seaweed, microalgae, and live foods (copepods, artemia). These days, fish farming in deserts and arid lands is considered a lucrative business. Such fish farming has been developed in many countries, making their lands arable and productive. Some examples are the USA, South Africa, Mexico, Qatar, Saudi Arabia, Egypt, Kazakhstan, and the central regions of Iran (Suloma and Ogata, 2006; Kaleem and Sabi, 2021; Graham et al., 2022; Soleimani-Sardo and Khanjani, 2022).

Climate change threatens to cause more droughts in already arid and semi-arid regions of the world and threatens the livelihoods and well-being of hundreds of millions of people. In the near future, it will not be possible to heal global climate change, but we should do all we can to minimize the risks of water scarcity (IPCC, 2022; Cabrera-González et al., 2022). This can be accomplished through the use of efficient irrigation methods, wastewater recycling, collecting drainage and flash flood water, and improving low-cost desalination technologies. One of the most important activities in this direction is the development of aquaculture. The main protein source for people living in dry areas is livestock, mostly cows and sheep, whose existence is dependent on the growth of forage every year. During droughts and repeated droughts, rainfed pasture is not available to support the animals, and there are not enough water impoundments

to supply drinking water. For subsistence farmers, these conditions result in a severe lack of animal protein and massive cattle mortality.

Aquaculture can provide animal protein in dry regions, which seems counterintuitive. It appears that fish farming in ponds requires large amounts of water for production, mostly due to evaporation, infiltration, and drainage losses (Kaleem and Sabi, 2021). According to Verdegem et al. (2006), ponds lose about 3.5 m of water per year as a result of evaporation and infiltration. There is a potential evaporation of 2–3 meters per year from ponds in deserts. An extensive fish pond with an annual fish production of 1 t/ha will consume 35 m^3 of water per kilogram of fish, a huge amount of water that cannot be obtained under arid conditions; however, with increased intensity, water consumption can be greatly reduced. There is a common production level of about 1 t/ha/year, but biofloc ponds and recirculating systems can produce 100–1000 t/ha/year. Under arid conditions, investing less than 100 L of possibly low-quality water is feasible to obtain 1 kg fish (0.1 m^3/kg). By intensifying production, water is saved in limited and possibly zero water exchange systems such as biofloc technology (BFT; Khanjani et al., 2021; 2022 b, c; Khanjani and Sharifinia, 2022), RAS (Timmons and Ebeling, 2007) and aquaponics (Rakocy et al., 2016, Kotzen et al., 2019).

Some of the plant ingredients used in fish feed require fresh water. Water investment in feed ingredients depends on the type of animal produced (fish or shrimp) and the way plant crops are grown, but approximately 3 m^3 of water is needed to produce 1 kg of fish feed ingredients (Verdegem et al., 2006; Troell et al., 2014). Apart from indirect water consumption, feed is an important part of the total expenses involved and, in most cases, this fraction of the expenses determines the feasibility of growing animals under variable circumstances. Aquaculture development is critically dependent on production costs, especially in dry regions. Defining the weight of feed in animal production (without taking into account its specific cost) is the feed conversion ratio (FCR). Water-living animals float instead of exerting energy against gravity, do not spend energy controlling their body temperature so that it is different from the temperature of the environment, and therefore use less energy than terrestrial livestock, which must exert energy in order to resist gravity and maintain a constant body temperature. FCRs in aquaculture are typically lower than those in terrestrial farming (Fry et al., 2018), with cattle and pigs having FCRs of 6.0–10 and 2.7–5, respectively. Due to effective genetic selection and the use of enclosed temperature-controlled cages, poultry raised for meat has an FCR of 1.7–2.0. In addition, the pond system can be used in some cases to produce natural feed from waste products, either waste products produced by the pond itself or from external wastes, such as home feed residues. It is also possible for the pond biota to metabolize other organic materials to produce microbial biomass (biofloc) and zooplankton (copepods and others) that can supply a portion of the fish with feed and reduce the need for manufactured feed (Khanjani et al., 2022 b; Khanjani et al., 2023 a)

The lack of water for farming fish and other commercially valuable aquatic organisms limits the development of this food production sector (Nenciu et al., 2022). It is also true that underground water is not the only source of water. As well as natural ponds and rivers that may be perennial or seasonal, man-made water retention dams mainly for irrigation and livestock, and small lakes from abandoned open mines, there are also other water bodies. Aquaculture in harsh environmental physical conditions, such as deserts and arid lands, demands that production strategies focus on good water management, which includes use of water-saving and recycling methods. In addition to protecting against strong solar radiations, modern aquaculture technologies like RASs need to be introduced, especially if high density fish farming is feasible economically and technically. As a result, these latter systems usually occupy a relatively small area and produce fish at up to 50 kg/m^3 of water (Kolkovski et al., 2011). Throughout the world, arid lands have long been exploited and utilized, resulting in the development of artificial water reservoirs of various types and sizes, many of which are used for aquaculture. In Kolkovski (2011) review, two salt-tolerant fish species, Japanese meagre or mulloway (*Argyrosomus japonicus*) and rainbow trout (*Oncorynchus mykiss*), have been successfully cultivated in such water bodies (Kolkovski, 2011). Namibia, for example, uses disused mine pits to grow Mozambique tilapia (*Oreochromis mossambicus*) in floating cages, resulting in interesting production results (Mapfumo, 2011). Arid regions are able to produce other commercially important and valuable organisms, tolerant to high salt concentrations and high temperatures, in addition to table fish. The small brine shrimp, *Artemia* sp. and the unicellular green algae, *Dunaliella* sp. are two examples. In Australia, ß-carotene is extracted primarily from *Dunaliella salina*, which is grown in large saline evaporation ponds (Benemann, 2008; Allan et al., 2008). The excessive use of underground, as well as surface water resources in many countries with extensive arid regions has forced many fish farming entrepreneurs and research institutions in developing water-saving strategies, including harvesting runoff water, sharing water from reservoirs with green crops, and utilizing saline water sources unsuitable for human consumption or agriculture (Mires, 2000). Meanwhile, mariculture may be the most efficient way to overcome inland aquaculture water shortages in countries with the opportunity to develop mariculture. Open water mariculture, however, requires a level of investment and modern technology that is certainly not accessible to rural populations in deserts and arid regions. In areas with limited water resources, aquaculture is becoming increasingly attractive due to its integration with agriculture. As a result of such systems, quality fish protein and fresh vegetable products can be produced with less water than if both systems were operated independently (McMurtry et al., 1997; Crespi and

Lovatelli, 2011 b; Yue and Shen, 2022). Additionally, innovative fish/vegetable co-culture systems use fish waste as direct inputs to produce vegetables, constantly recycling the same water (for example, aquaponics) (Vasdravanidis et al., 2022). In addition, recirculating systems are not affected by soil type, use a fraction of the water required by pond culture, and conserve land (Martins et al., 2010). Using water for fish culture improves water efficiency and reduces the cost of water used for fish culture in conventional earthen ponds (Zhang et al., 2011). In certain arid and semiarid zones, microalgal mass production, such as the unicellular green algae and filamentous cyanobacteria *Spirulina*, offers an alternative to conventional agriculture for biomass production, since brackish or saline water is not suitable (Richmond and Preiss, 1980; Crespi and Lovatelli, 2011 b). In Chile's northern regions, which lack water resources and are unsuitable for agriculture, *Spirulina* and other microalgae are available as a novel industrial activity (Ayala and Vargas, 1987; Crespi and Lovatelli, 2011 b). In order to maintain adequate temperatures in the culture medium, polyvinyl chloride-lined raceway ponds are covered with translucent UV-resistant polyethylene film (Habib et al., 2008).

Despite the climatic conditions in many arid regions making it nearly impossible to obtain enough water (250 mm/year), there are many areas with underground sources of drinking water. Local populations are currently receiving daily rations of water from these sources in some places. These sources of water can be diversified between irrigation, aquaculture, and drinking, depending on a variety of factors (Sharifinia et al., 2017). This technique involves integrating the three activities to maximize productivity while reducing water waste. Some areas have fully integrated these three uses vertically and horizontally. Egypt's rural communities have been successful in integrating these fields into their lives, giving them extensive practice and enabling them to produce and maintain three different crops (fish, green crops and livestock) with the same quantity of water (Sadek et al., 2011), which served as a vector for energy transport from each activity. Surface and underground waters are both available and accessible in all of the above farming systems in arid regions. In spite of this, the choice of a specific farming system remains closely linked to the local conditions, existing infrastructure (such as roads, utilities, feed and seed plants), the level of capital available, the ability to acquire farming technology, and the support of local and central authorities. Developing desert aquaculture, particularly in community-based aquaculture projects, will undoubtedly benefit from institutional support. As well as contributing to local food security, such initiatives can engage young people who would otherwise remain unemployed due to the remoteness of their rural communities. By stocking dams with fish fingerlings, many countries are already supporting fish production strategies (Soleimani-Sardo and Khanjani, 2022).

Suitable species for aquaculture in dry areas

Aquatic ecosystems are comprised of interdependent communities of organisms, collectively known as aquatic life, which rely on each other and their surroundings to thrive (Sharifinia, 2015). It is possible to cultivate a wide variety of organisms in arid conditions, particularly if the technology used is adequate for the proliferation of the farmed species. There are a few general criteria to consider when selecting species to raise in deserts and arid environments. To cope with the water-limited conditions characteristic of these arid regions, the species should be particularly tolerant of hyper-saline waters, have a high tolerance to large temperature fluctuations, and be relatively fast-growing (Treece, 2011). As well as the availability of farm inputs, market value and volume, local consumption and preferences, and dietary habits, species choice is obviously influenced by other factors as well (Crespi and Lovatelli, 2011 b). Currently, the most suitable fish species for water-limited aquaculture systems include the tilapia (*Oreochromis* spp.), barramundi or the Asian seabass (*Lates calcarifer*), Chinese carps – common carp (*Cyprinus carpio*), grass carp (*Ctenopharyngodon idellus*), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*H. nobilis*), mullets (*Mugil cephalus* and *Liza ramada*) and several catfishes species (*Clarias gariepinus* and *Bagrus* spp.) (Troell, 2009; Segovia Quintero, 2011; Sadek, 2011; Soleimani-Sardo and Khanjani, 2022). Tilapias can be raised intensively in monoculture as well as in polyculture systems with other compatible and commercial species, such as carps and mullets (El-Sayed, 2006). In addition to being capable of being farmed in a wide range of salinities, they also have a relatively short production cycle (6 to 8 months to market size). Several countries produce indigenous species of tilapia or hybrids, such as the red tilapia (*O. mossambicus* × *O. niloticus*), which fetch a good market price. A successful example of marine aquaculture production at large commercial scale is the Indian white prawn (*Penaeus indicus*). There has also been successful cultivation of Pacific white shrimp in Iran (Khanjani et al., 2016). Pacific white shrimp is tolerant of salinity variations and is therefore a good candidate for aquaculture under such circumstances. It has been successful to rear European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*) in brackish waters in Egypt (Sadek, 2011; Kaleem and Sabi, 2021). These species, however, require the use of advanced technology and technical skills, which are not always available. Apart from suitable finfish and crustaceans, microalgae and filamentous *Spirulina* are suitable candidates currently being produced in several arid coastal regions (Cai et al., 2017; Rasheed et al., 2022). In order to produce these latter organisms at competitive prices, however, large capital investments and technical skills may be necessary. Also noteworthy is the ornamental fish farming subsector, which has grown at an average annual rate of approximately 14 percent (FAO, 2010). Diversification of species remains a challenge for those countries

wishing to develop desert aquaculture due to the rigid environmental conditions. In order to avoid negative impacts on local species and the environment, non-indigenous species are often identified, selected, and introduced without adequate risk assessments (FAO, 2007).

Circular economy in aquaculture

Like sustainability, circular economies (CEs) lack a consensus definition. It is similar to sustainability, which can be better defined in terms of its opposite – a linear economy – that the circular economy is defined. Rather than the linear economy of "take, make, consume, dispose," a circular economy based on "reduce, reuse, recycle, recover" allows more value to be extracted from resources. A circular economy is defined by the Ellen MacArthur Foundation (2019) as "one that is restorative and regenerative by design and keeps products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles." In this definition, waste and pollution are eliminated, products and materials are used, and natural systems are restored. A recent study presented a set of 5 principles applicable to food and non-food systems to guide biomass use towards a circular bio-economy (Muscat et al., 2021); regenerating and preserving the health of our agroecosystems; avoiding non-essential products and wasting essential ones; prioritizing biomass streams for basic human needs; utilizing and recycling byproducts of agroecosystems; and utilizing renewable energy while minimizing overall energy consumption. A variety of aquatic ecosystems (sea, earthen ponds, rivers, mangroves, paddy fields) can be used for aquaculture, as well as different technologies, ranging from low-tech and low-input systems (e.g., earthen ponds and longlines) to high-tech systems and energy-consuming systems (such as recirculated systems). Aquaculture includes organisms from five different trophic levels (including carnivorous species), which can have very different impacts on feed/food competition, as well as different contributions to food security globally. Additionally, each species produces wastes and byproducts (e.g., feces, uneaten feed, excretion, trimmings, shells, etc.) that can be reused or recycled. Design decisions are crucial since once a designed system is constructed, the implications for resource usage and emissions are largely fixed. IMTA, biofloc, aquaponics, and aquamimicry are relatively recent systems that are based on ecological or regenerative principles (Khanjani et al., 2022 a, d). Recirculating and intensive shrimp farming models allow waste solids to be recovered and used for biogas production. The majority of these systems, however, have not yet developed to the point where they contribute meaningfully to global aquaculture. Circular economies in aquaculture utilize by-products and waste from supply chains to produce food for human consumption. About 35% of the fish meal used in aquaculture comes from trimmings from fish processing. The by-products from the slaughter of terrestrial animals destined for human consumption can also be converted into nutritious meals. By utilizing waste streams as inputs, novel ingredients such as insect and bacterial meals are available. Waste generated during processing can be utilized further downstream in the value chain. The wastes from processing plants are now routinely rendered and incorporated into aqua feeds for animals. Shrimp shell waste can be extracted and used as a thickener in food processing, as biodegradable plastic, and as a pharmaceutical ingredient. Leather products and burn treatments are made from tilapia skins. Shells from bivalve mollusks are collected from processors and restaurants and returned to bay bottoms to mitigate local acidification. Wastes from other economic sectors are being used as resources in aquaculture, in addition to aquaculture wastes. The larvae of black soldier flies are processed into an alternative to fish meal using a variety of organic wastes. It is possible to recover about 50 kg of insect protein and 200 kg of compost from every tonne of organic waste. Aquaculture has historically embraced the principles of circular economy well. There is, however, always room for improvement. Farm managers should explore and evaluate ways to improve resource use efficiency and reduce, reuse, and recover waste at all levels. Considering ways to use aquaculture wastes in other economic sectors, and vice versa, at the regional or value-chain level should be considered. Emissions from aquaculture are relatively small at the global level. Despite their complexity, new creative system designs can produce valuable co-products that enhance aquaculture's profitability and sustainability (Cabrera-González et al., 2022).

BFT, IMTA, and RAS can all be effective in low water areas by conserving water resources, reducing the environmental impact of aquaculture, and increasing economic viability. BFT is particularly suitable for low water areas as it can minimize water exchange and reduce reliance on external protein sources. It can also convert waste into protein-rich feed for aquatic animals. IMTA is useful in low water areas because it can efficiently utilize available resources and create a diverse and resilient system that can adapt to changing environmental conditions. RAS can also conserve water resources and minimize the impact of aquaculture on the environment by reusing water within the system. However, the high costs of constructing and maintaining RAS may limit their adoption in some areas.

Furthering progress

Aquaculture systems have the potential to address the food security and nutritional needs of arid regions, but several challenges must be overcome to fully realize this potential. One of the key challenges is the scarcity of water resources, which limits the feasibility of traditional aquaculture systems. Innovative systems that operate with minimal water usage, such as BFT, IMTA, and RAS, can help conserve water resources and minimize the environmental impact of aquaculture. Another challenge is the limited availability of suitable feed sources,

which can be addressed through research and development of alternative feed sources that can be produced locally using low-cost inputs. These could include microbial-based, insect-based, or locally available plant-based feeds.

To make further progress in the use of aquaculture in arid regions, a multidisciplinary approach involving collaboration among scientists, policymakers, and local communities is essential. This approach should include the development of policies and regulations that promote sustainable aquaculture practices, as well as technical support and capacity building to enable the adoption of innovative aquaculture systems. The adoption of aquaculture in arid regions is expected to increase due to the growing demand for food, the need for sustainable resource management, and the potential for economic development. Innovative aquaculture systems, such as BFT, IMTA, and RAS, offer a sustainable and efficient way to produce aquatic foods, and are likely to become more widespread. Additionally, the development of alternative feed sources and the use of precision aquaculture technologies can help reduce costs and increase productivity. Although the future of aquaculture in arid regions looks promising, continued research and development efforts are necessary to overcome the challenges and fully realize the potential of this sector.

Conclusions

In order to end global hunger and malnutrition, fisheries and aquaculture must grow, but the further transformation is needed to address challenges. Transforming agrifood systems can protect the sustainability of aquatic habitats and biodiversity, as well as ensure the sustainable harvesting of aquatic foods and the livelihoods of those who depend on them. More than ever before, aquatic foods contribute to food security and nutrition. Aquatic foods (excluding algae) have increased at an average rate of 3 percent per year since 1961, nearly twice the rate of annual world population growth – reaching 20.2 kg per capita, more than double the level in the 1960s. It is feasible to produce fish as a basic source of protein for the population of dry regions, especially during periods of drought that are caused by climate change. As compared to conventional aquaculture or conventional terrestrial livestock production, it is possible to produce fish at a water efficiency of about 100 L/kg or less with applying appropriate technology and selection of suitable aquatic species. There is, however, a need for further development, adaptation, training, and guidance. We must adapt the currently known technologies to the conditions of the different areas where dryland aquaculture is practiced. The development of desert and land aquaculture should primarily focus on new technologies based on water conservation, such as BFT, IMTA, RAS, and aquaponics. Additionally, it is necessary to select species that are suitable for proper growth in the above-mentioned systems but are also well-suited to local traditions and preferences. There is also the possibility of using waste materials (or accompanying organisms such as aquatic plants, insects attracted to the water, or suitable zooplankton) as cheap local feed additives. In addition, farmers should be provided with appropriate training, literature, and other means of information.

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Competing interests

The authors declare no competing interests.

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