Agrociencia

A SUSTAINABLE FUTURE FOR AQUACULTURE: A GLOBAL OVERVIEW WITH A FOCUS ON MEXICO'S POTENTIAL

Karla Jareth **Pérez-Viveros**[1], Javier **Castro-Rosas**[1], José Roberto **Villagómez-Ibarra**[1], Arturo **Cadena-Ramírez**[2], Carlos Alberto **Gómez-Aldapa**[1*]

[1]Universidad Autónoma del Estado de Hidalgo. Instituto de Ciencias Basicas e Ingenieria, Área Academica de Química. Carretera Pachuca-Tulancingo km 4.5, Colonia Carboneras, Mineral de la Reforma, Hidalgo, Mexico. C. P. 42184.

[2]Universidad Politécnica de Pachuca. Posgrado en Biotecnología. Carretera Pachuca-Ciudad Sahagún km 20, Ex-Hacienda de Santa Bárbara, Zempoala, Hidalgo, Mexico. C. P. 43830.

* Author for correspondence: cgomeza@uaeh.edu.mx

Citation: Pérez-Viveros KJ, Castro-Rosas J, Villagómez-Ibarra JR, Cadena-Ramírez A, Gómez-Aldapa CA. 2026. A sustainable future for aquaculture: a global overview with a focus on Mexico's potential.
Agrociencia. https://doi.org/ 10.47163/agrociencia.v60i2.3117

Editor in Chief:
Dr. Fernando C. Gómez Merino

Received: September 21, 2025.
Approved: March 13, 2026.
Published in Agrociencia: March 30, 2026.

ABSTRACT

Currently, aquaculture is a worldwide development activity, with an overall volume of more than 110.2 million Mg live weight and a value of approximately 243 billion USD, contributing more than 60 % of the combined production of aquatic organisms. Among major economic activities, aquaculture has grown more rapidly both internationally and domestically. Asia represents the region with the most extensive development in the cultivation of most species, with China as the dominant producer. However, in terms of growth, some countries in Africa and Latin America, such as Egypt, Nigeria, Chile, and Mexico, are emerging on the world stage. Mexican aquaculture grew by around 70 % from 2013 to 2021, and further growth is expected in the coming years. Despite its importance and growth for human livelihood, aquaculture involves significant water consumption, and its degradation represents a major threat to the future of humanity. Therefore, it is essential to establish clear notions of water quality and sustainable management, monitor social and economic variables, and intensify research on alternatives for water treatment and use control. The present work provides an overview of Mexican aquaculture in the global context, including its importance, concepts related to sustainable management and its alternatives, as well as the development of the industry.

Key words: aquatic ecosystems, pisciculture, water pollution, water resources.

INTRODUCTION

Aquaculture is the economic, social, and cultural activity that consists of the breeding and cultivation of aquatic organisms. Breeding requires human intervention to increase and ensure the production of species with high demand, such as shrimp, catfish, tilapia, and trout (FAO, 1998; Justino *et al*., 2016; Ottinger *et al*., 2016). Populations must be fed and protected from predators in a controlled environment, and their growth must be managed effectively.

Practices differ across regions according to environmental conditions and production systems. In Vietnam, fish are raised using freshwater in paddy fields, while in Ecuador saltwater shrimp are produced in ponds. In Norway and Scotland, cages are used along the coasts for salmon production (Bergheim, 2012; Phuong and Oanh, 2010; Hamilton and Stankwitz, 2012). The most important cultured organisms are freshwater species, which require less water and have lower maintenance costs, including tilapia and carp (Yuan *et al*., 2017).

From a food systems perspective, aquaculture represents a viable alternative for the global food supply. Capture fisheries and aquaculture both contribute to food security and form an integral part of national economies. This activity supports national food security, generates foreign currency, creates employment opportunities in vulnerable areas, and helps alleviate poverty (Tacon and Metian, 2015, 2017). In addition, aquaculture products are rich in animal protein, contributing to the growth and stability of the food system as one of the healthiest food sources. Fish is among the most widely produced food products and represents one of the most important sources of animal protein, accounting for about 17 % of global animal protein consumption. In less developed countries, this proportion may exceed 50 % (Béné *et al*., 2015).

GLOBAL AQUACULTURE PRODUCTION AND TRENDS

Aquaculture has been practiced in a low-technology manner for at least two centuries; however, intensive farming systems comparable to the production of terrestrial animals are much more recent, developing mainly after 1950 (Campbell and Pauly, 2013). In 2016, worldwide production of aquatic organisms totaled around 170.9 million Mg, with a value of approximately 250 billion USD (FAO, 2018; OECD, 2020). Of this amount, just over 110.2 million Mg came from aquaculture, representing about 64 % of the total production (World Bank Group, 2023). These data show that aquaculture is a major contributor to global food security, a trend expected to continue (Little *et al*., 2018; Ottinger *et al*., 2016).

Since 2011, production of aquatic organisms from capture fisheries has remained relatively stable, averaging close to 93 million Mg per year. In contrast, aquaculture production increased by about 48 million Mg during the same period, representing growth of approximately 78 % (World Bank Group, 2013; FAO, 2018). The Asian continent has made the most significant advances in aquaculture development, with China leading production at nearly 64 million Mg in 2021. Other major producing countries include Indonesia, India, Vietnam, Bangladesh, the Philippines, Korea, Egypt, Norway, and Japan, each producing around one million Mg (World Bank Group, 2023). Among the main groups contributing to aquaculture production, fish account for 54.091 million Mg (49.08 %), crustaceans for 7.862 million Mg (7.13 %), mollusks for 17.139 million Mg (15.55 %), and aquatic plants for 30.139 million Mg (27.35 %). Other organisms, including frogs and invertebrates, contribute approximately 939 thousand Mg (0.85 %) to total production (FAO, 2018).

Of the combined global production of approximately 171 million Mg of aquatic organisms from fisheries and aquaculture, about 88 % is used for direct human consumption. The remaining portion is processed into fishmeal and fish oil for applications such as livestock feed, aquaculture feed, industrial products, and pharmaceutical uses (Gjedrem *et al*., 2012; FAO, 2018). The dependence of aquaculture and terrestrial animal production on fishmeal represents an important sustainability concern. In 2021, fishmeal production totaled about 24 million Mg, of which around 5 million Mg were used for non-food purposes. Consequently, the development of alternative protein sources for aquaculture feeds and other animal production systems has become increasingly necessary (Hua *et al*., 2019).

Fishmeal remains a key input in aquaculture feed formulations (Olsen and Hasan, 2012) and is one of the most expensive commercial protein ingredients because of its complex composition of proteins, fatty acids, minerals, and vitamins, as well as its balanced profile of essential amino acids (Hardy, 2010). However, the growing demand for aquaculture products has intensified efforts to develop alternative feed ingredients that maintain fish health and nutritional quality. Research in this area often focuses on locally available resources adapted to regional production systems and species requirements. Feed typically represents about 60 % of operating costs within the aquaculture production chain (Han *et al*., 2016; Hardy, 2010; Olsen and Hasan, 2012).

ALTERNATIVE PROTEIN SOURCES FOR AQUACULTURE FEED

Studies on the use of fish silage and shrimp waste indicate that these preparations can replace up to 75 % of fishmeal while maintaining beneficial effects on fry and providing a profitable alternative (Goddard and Perret, 2005; Madage *et al*., 2015). However, silage is prone to fermentation due to the lack of preservatives, which can affect its quality. Feed acidity has also been associated with poor fish acceptance, as it may suppress appetite. The use of fish meal produced from *Gambusia affinis* or *Atherina boyeri* has allowed the replacement of up to 50 % of commercially used fishmeal without affecting feed efficiency, and this substitution has been supported by economic analyses (Abdelghany, 2003; Gümüş, 2010).

Use of terrestrial animal proteins

Substituting fishmeal with terrestrial animal proteins has been explored using by-products such as food residues, blood, feathers, meat, and bone (Hernández *et al*., 2010; Hu *et al*., 2013). However, these proteins often present inadequate amino acid profiles, containing low levels of essential amino acids such as lysine, isoleucine, and methionine that are required by aquatic species (Liaqat *et al*., 2017). When these deficiencies are corrected through supplementation, such alternative protein sources can replace up to 75 % of fishmeal and remain cost-effective. Nevertheless, their efficiency is still debated because of the need for additional supplements (Hua *et al*., 2019).

Use of vegetable proteins

Oil plants

Among plant protein sources, soybean meal stands out due to its high protein content and relatively complete amino acid profile. However, it shows deficiencies in methionine, lysine, and cysteine. Soybean meal also contains antinutritional factors such as trypsin inhibitors, antivitamins, and lectins like phytohemagglutinin (Bai *et al*., 2015). These compounds can be reduced or eliminated through heat treatment. With proper processing, soybean meal has shown good performance in partial substitutions of fishmeal of up to 75 %. The success of substitution depends on the species, growth stage, and minimum nutritional requirements, as well as mineral availability in soybean meal.

Cottonseed meal is another alternative widely used in tropical and subtropical regions because of its high protein content and low cost (Sun *et al*., 2015; Teves and Ragaza, 2016). However, protein content and quality vary depending on seed management and processing methods, ranging from 26–54 %. In addition, cottonseed meal has relatively low levels of cysteine and lysine, although substitution efficiencies from 50 % to complete assimilation in aquatic species have been reported (Nehete *et al*., 2013).

Aquatic plants

Among aquatic plants, duckweed has been highlighted as a potential plant protein source, with crude protein levels reaching up to 45 %. It also presents a suitable amino acid and mineral profile and has been used as the sole nutrient source in some production systems. Nevertheless, optimal performance is generally achieved with substitution rates around 50 %, allowing good growth without adverse effects while remaining economically viable. Other aquatic plants, including ferns, have also demonstrated positive results when combined with duckweed, particularly during the fry stage (Nakphet *et al*., 2016; Hasan, 2017).

Legumes

Legumes are commonly used as partial substitutes for cereals in aquaculture feed. For example, *Leucaena* can contribute up to 30 % of the protein in feed mixtures. Beans and corn are also used as alternative ingredients, although many legumes present variable amino acid profiles (Laining and Kristanto, 2015). They are often deficient in essential amino acids such as arginine, isoleucine, methionine, and threonine. Additionally, antinutritional compounds such as mimosine, a non-protein amino acid that can be toxic, must be considered. Some plant ingredients, including cassava and corn, have shown favorable results during the fry stage, with substitution levels of up to 25 and 100 %, respectively, producing satisfactory growth. However, the presence of phytic acid in these plants can reduce mineral bioavailability, particularly when feed formulations are already deficient in one or more minerals (de Silva, 2012).

Use of unicellular organisms

Microorganisms such as algae, fungi, bacteria, cyanobacteria, and yeasts are gaining attention as alternative protein sources in semi-intensive and intensive aquaculture feeding systems because they can simplify production and reduce costs (Maisashvili *et al*., 2015; Wang *et al*., 2019). These microorganisms can utilize carbon sources such as wheat or rice bran, helping optimize production systems with relatively inexpensive inputs. Unicellular proteins therefore represent a promising group of microbial resources that promote growth while also providing environmental benefits, as some bacteria contribute to reducing ammonia concentrations in aquaculture systems (Guedes *et al*., 2015).

GLOBAL RISKS AND CHALLENGES

Monitoring in aquaculture production systems

Monitoring in aquaculture facilities should provide the information needed to support decision-making based on reference data, production levels, area limits, and environmental impacts. Accurate and periodic monitoring at sectional scales is required to achieve this (Mulema and García, 2019; Simbeye *et al*., 2014). However, implementing such monitoring, particularly through cartography-based methods, remains challenging due to the high cost and limited availability of appropriate systems, as well as insufficient financing, infrastructure, and trained personnel (Ferreira *et al*., 2020).

To address these limitations, the Food and Agriculture Organization has promoted initiatives focused especially on developing regions. One proposed approach is the development of cost-effective technologies capable of generating inventories of cultivable species and supporting management systems. These technologies could enable sustainable management and assist licensing processes by identifying unregistered or illegal facilities. They can also provide information for site selection and for evaluating farm evolution in relation to surrounding ecosystems, helping prevent environmental damage (Soininen *et al*., 2019). In this context, global positioning systems are essential for recording the location of aquaculture facilities and facilitating the integration of geographic information systems and spatial analyses (Mulema and García, 2019; Ferreira *et al*., 2020).

Social challenges in aquaculture

Low-quality employment is frequently associated with low productivity, and its causes vary depending on local contexts. In aquaculture, producers often face challenges such as limited access to formal education, which restricts the availability of services and hinders the adoption of advanced technologies and access to demanding markets (Carlarne and Depledge, 2019; Ngajilo and Jeebhay, 2019). In addition, inadequate fish handling and poor capture, processing, and storage facilities contribute to high post-capture losses, reducing overall production yields (Song and Soliman, 2019).

In Mexico, families lacking alternative employment opportunities often accept low wages and poor working conditions within aquaculture operations. Continuous industry expansion may also lead to overexploitation of resources, environmental degradation, and risks to the livelihoods of communities dependent on aquaculture. Addressing the shortage of decent work requires improving access to education and training, adopting new technologies, and enhancing fish handling, capture, processing, and storage infrastructure. These measures can increase productivity while supporting the sustainability of the sector and the communities that depend on it (Espinosa-Romero *et al*., 2017).

Workers in the aquaculture and fisheries sectors often belong to vulnerable social groups and face hazardous working conditions. Although these activities represent an essential source of income for low-income populations, social protection mechanisms are frequently limited or absent (Watterson, 2018). In many countries, workers rely on informal or minimal protection, and integration into formal social security systems remains difficult. As a result, workers and their families face environmental, social, physical, and economic risks, often intensified by factors such as migration, sexually transmitted diseases, gender violence, and substance abuse (Ahmed and Thompson, 2019).

Beyond resource overexploitation, the occupation itself is considered highly dangerous. Each year, approximately 24 000 workers experience illness, injury, or death due to long working hours and fatigue. Insufficient enforcement of occupational safety regulations further increases these risks. Strengthening social protection through improved access to healthcare, education, training programs, and occupational health and safety regulations is therefore essential. Such measures help protect workers' rights while supporting the long-term sustainability of the aquaculture sector and the well-being of dependent communities (Ahmed and Thompson, 2019; Soininen *et al*., 2019).

Climate change

Climate change represents a major global challenge, requiring aquaculture systems to develop adaptive strategies capable of addressing its impacts, variability, and associated risks. Key factors include warming of water bodies, sea-level rise, ocean acidification, and changes in weather patterns that may result in extreme events (Falconer *et al*., 2020). Climate change poses significant risks to aquaculture systems. Increased atmospheric CO_2 levels and the resulting acidification of water bodies can affect the physiology of many species, influencing growth, reproduction, and product quality.

At the same time, global warming may create certain opportunities, such as increased growth rates and expanded geographic ranges for some cultured species. Research on sensitive fish species across life stages (from embryo to adulthood) has shown that temperature variation influences growth, disease susceptibility, spawning time, and mortality rates at different developmental stages (Dubey *et al*., 2017). Metabolic changes associated with these environmental shifts may also generate significant economic impacts. Adaptation will likely require modifications to aquaculture infrastructure and the development of more specific and nutritionally adequate feed formulations (Bhuiyan *et al*., 2018; Steeves and Filgueira, 2019).

Species vulnerability

Assessing the vulnerability of species and environmental systems in aquaculture often involves classifying farms according to geographic location (continental, coastal, or arid tropical environments) as well as production density and intensity (Navas *et al*., 2011). Even within the same region, farms may differ in technological capacity and production systems, which can increase vulnerability for producers, particularly regarding supply limitations. Reducing these vulnerabilities requires the adoption of improved local practices and advanced technologies (Islam *et al*., 2019). Potential strategies include the use of new biological strains, such as catfish varieties adapted to salinity conditions, and improvements in harvesting methods to ensure product quality. Additional technological approaches may involve water-recycling systems and innovations that enhance fish health and feed efficiency (Rickard *et al*., 2020; Yogev *et al*., 2020).

Sustainability through organization

Many fishers and fish farmers operate small-scale systems without formal contracts, which limits organization within the sector and reduces opportunities for policy development. Dependence on intermediaries within the value chain further affects producers, as these actors often control market access and influence the economic viability of primary production (Valenti *et al*., 2018). Addressing these issues requires context-specific interventions that strengthen communication and coordination among stakeholders (Davies *et al*., 2019). Developing simple, sustainable, and inclusive value chains, particularly at small scales, can help prevent sector overcapacity and reduce economic, environmental, and social disruptions. Currently, an important concern within the production chain involves the generation of by-products and the continued reliance on fishmeal and fish oil, which may place additional pressure on wild fish populations and other aquatic species (Carlarne and Depledge, 2019; Dubey *et al*., 2017).

AQUACULTURE IN MEXICO

Water has played a crucial role in human settlement and societal development throughout history. Its uses range from domestic consumption to livestock watering, irrigation, aquaculture, power generation, navigation, and recreation. In aquaculture, water availability is essential, and Mexico's altitudinal profile creates a wide diversity of climatic conditions and ecosystems that support the development of the aquaculture sector (Oyarzabal, 2000). However, the successful expansion of the industry also depends on the efficient application of technologies and on processes of innovation, modernization, and productive reconversion (FAO, 2013). In Mexico, fish farming was formally established at the end of the 19th century when the Ministry of Development initiated the construction of a fish nursery in Ocoyoacac, State of Mexico, using a batch of 500 000 rainbow trout (*Oncorhynchus mykiss*) fry imported from the United States.

Regional development of Mexican aquaculture

Mexico is divided into five regions as part of the "Diagnosis and Regional Planning of Fisheries and Aquaculture" initiative, designed to promote sustainable and integrated development of this economically and socially important sector. Region I, the Pacific North, includes Baja California, Baja California Sur, Sonora, Sinaloa, and Nayarit. In 2021, this region produced 195 705.71 Mg of live weight, with Sonora and Sinaloa each contributing about 39 % of the total production. Region II, the Central and South Pacific Zone, comprises Chiapas, Jalisco, Colima, Michoacán, Oaxaca, and Guerrero. In 2021, this region generated 34 599.87 Mg in live weight, with Jalisco leading production with 37 %.

Region III, the Northern Gulf of Mexico Zone, includes Veracruz and Tamaulipas. Veracruz dominated production in this region, accounting for 86 % of the total 3182.55 Mg produced. Region IV, known as the Gulf of Southern Mexico and Caribbean Sea region, includes Quintana Roo, Yucatán, Tabasco, and Campeche. Aquaculture production in this region reached 14 718.68 Mg of live weight, with Tabasco contributing 82 % of the total. Region V corresponds to the landlocked states, which do not have coastal aquaculture systems and rely mainly on inland water production. This region produced 1406.8 Mg of live weight, with the State of Mexico contributing 34 % of the total production.

In 2021, aquaculture production in Mexico reached 249 613.71 Mg. A notable limitation of the industry is its strong dependence on shrimp and mojarras, mainly produced through crossbreeding systems. To ensure sustainable use of marine, brackish, and inland water resources, diversification of cultured species is necessary. Other species considered in Mexican aquaculture include freshwater fish such as robalo, bass, and catfish; marine fish such as snapper, sea bream, red snapper, sea bass, horse mackerel, and tuna; mollusks such as clams, abalone, and snails; freshwater crustaceans such as freshwater lobster and shrimp; and other groups including ornamental fish (CONAPESCA, 2020).

During the 1990s, social, political, economic, and environmental factors contributed to the expansion of aquaculture activity in Mexico. Legal reforms and federal government support programs strengthened value chains by promoting more structured projects and improving the availability of socio-economic and environmental data. Despite these advances, the aquaculture sector still faces challenges in achieving full sustainability. Greater investment in science and technology is required, together with the promotion of a culture that values the balance between economic development and environmental protection. Although value chains have improved, bureaucratic barriers continue to limit stronger collaboration among producers, researchers, and government institutions.

Risks associated with aquaculture in Mexico

Like any productive sector, aquaculture in Mexico faces several risks that may affect its sustainability and profitability.

Disease outbreaks. Aquaculture facilities are vulnerable to disease outbreaks that can cause major production losses and affect the health and welfare of fish and shellfish. Diseases can spread rapidly through water, particularly in systems with high stocking densities, and can be difficult to control.

Environmental impacts. Improper management of aquaculture systems may generate negative environmental effects. Overcrowding, excessive feed use, and waste discharge can cause eutrophication and water quality degradation, affecting surrounding ecosystems and reducing production efficiency. Certain practices may also affect wild fish populations and natural habitats.

Economic risks. Aquaculture requires substantial investments in infrastructure, technology, and labor. Fluctuations in market demand, price volatility, and production risks, such as disease outbreaks or extreme weather events, can generate significant financial losses for producers and companies.

Regulatory compliance. Aquaculture activities in Mexico are subject to national and international regulations related to food safety, environmental protection, and animal welfare. Failure to comply with these regulations may result in penalties, production restrictions, or reputational damage.

Climate change. Climate change represents an additional risk for aquaculture production, including changes in temperature, precipitation patterns, sea-level rise, and the occurrence of extreme weather events.

To reduce these risks, aquaculture producers can implement best management practices such as regular monitoring and water quality testing, biosecurity protocols, and environmental impact assessments. In addition, diversification of production systems and increased investment in research and development can improve resilience and adaptability to changing environmental and market conditions.

CONCLUSIONS

Aquaculture is a sector characterized by constant change and growing demand. Although aquaculture production in Mexico has progressed steadily, national demand for seafood continues to increase. These trends require optimization across the value chain and the adoption of more efficient practices, including technological innovation in equipment and feed products adapted to different socio-economic contexts and cultured species. Such innovations can promote sustainable practices and balanced growth in the industry.

Mexico has several advantages that could position it among the leading countries in global aquaculture production, particularly in the cultivation of freshwater and shrimp species. Favorable climatic conditions in many regions support the production of species of commercial interest, including native species with characteristics suitable for aquaculture. These conditions provide an opportunity to expand production and supply seafood to major consumer markets. To support the growth and sustainability of the aquaculture industry, the federal administration should establish legislation that recognizes aquaculture as an activity independent from fisheries. State governments should adopt similar frameworks and implement long-term policies to ensure the continued development of the sector beyond individual government administrations.

REFERENCES

Abdelghany AE. 2003. Partial and complete replacement of fish meal with gambusia meal in diets for red tilapia '*Oreochromis niloticus* × *O. mossambicus*.' Aquaculture Nutrition 9 (3): 145–154. https://doi.org/10.1046/j.1365-2095.2003.00234.x

Ahmed N, Thompson S. 2019. The blue dimensions of aquaculture: A global synthesis. Science of The Total Environment 652: 851–861. https://doi.org/10.1016/j.scitotenv.2018.10.163

Bai SC, Katya K, Yun H. 2015. Additives in aquafeed. *In* Feed and Feeding Practices in Aquaculture. Woodhead Publishing: Sawston, UK, pp: 171–202. https://doi.org/10.1016/b978-0-08-100506-4.00007-6

Béné C, Barange M, Subasinghe R, Pinstrup-Anderson P, Merino G, Hemre GI, Williams M. 2015. Feedig 9 billion by 2050 – Putting fish back on the menu. Food Security 7 (2): 261–274. https://doi.org/10.1007/s12571-015-0427-z

Bergheim A. 2012. Recent growth trend and challenges in the Norwegian aquaculture industry. Latin American Journal of Aquatic Research 40 (3): 800–807.

Bhuiyan MA, Jabeen M, Zaman K, Khan A, Ahmad J, Hishan SS. 2018. The impact of climate change and energy resources on biodiversity loss: Evidence from a panel of selected Asian countries. Renewable Energy 117: 324–340. https://doi.org/10.1016/j.renene.2017.10.054

Campbell B, Pauly D. 2013. Mariculture: A global analysis of production trends since 1950. Marine Policy 39: 94–100. https://doi.org/10.1016/j.marpol.2012.10.009

Carlarne C, Depledge MH. 2019. Climate change, environmental health, and human rights. *In* Encyclopedia of Environmental Health (Second edition). Elsevier: Amsterdam, Netherlands, pp: 653–660. https://doi.org/10.1016/b978-0-12-409548-9.11689-6

CONAPESCA (Comisión Nacional de Acuacultura y Pesca). 2020. Acuasesor. Gobierno de México. Secretaría de Agricultura y Desarrollo Rural. Comisión Nacional de Acuacultura y Pesca. Ciudad de México, México. https://acuasesor.conapesca.gob.mx/index.php (Retrieved: June 2020).

Davies IP, Carranza V, Froehlich HE, Gentry RR, Kareiva P, Halpern BS. 2019. Governance of marine aquaculture: Pitfalls, potential, and pathways forward. Marine Policy 104: 29–36. https://doi.org/10.1016/j.marpol.2019.02.054

de Silva SS. 2012. Aquaculture: A newly emergent food production sector—and perspectives of its impacts on biodiversity and conservation. Biodiversity and Conservation 21 (12): 3187–3220. https://doi.org/10.1007/s10531-012-0360-9

Dubey SK, Trivedi RK, Chand BK, Mandal B, Rout SK. 2017. Farmers' perceptions of climate change, impacts on freshwater aquaculture and adaptation strategies in climatic change hotspots: A case of the Indian Sundarban delta. Environmental Development 21: 38–51. https://doi.org/10.1016/j.envdev.2016.12.002

Espinosa-Romero MJ, Torre J, Zepeda JA, Solana FJV, Fulton S. 2017. Civil society contributions to the implementation of the small-scale fisheries guidelines in Mexico. *In* Jentoft S, Chuenpagdee R, Barragán-Paladines M, Franz N. (eds.), The Small-Scale Fisheries Guidelines. Springer: Cham, Switzerland. https://doi.org/10.1007/978-3-319-55074-9_20

Falconer L, Hjøllo SS, Telfer TC, McAdam BJ, Hermansen Ø, Ytteborg E. 2020. The importance of calibrating climate change projections to local conditions at aquaculture sites. Aquaculture 514: 734487. https://doi.org/10.1016/j.aquaculture.2019.734487

FAO (Food and Agriculture Organization of the United Nations). 1998. Rural aquaculture: Overview and framework for country reviews (XF1999084549). Bangkok, Thailand. https://www.fao.org/4/x6941e/x6941e00.htm#Contents (Retrieved: June 2025).

FAO (Food and Agriculture Organization of the United Nations). 2013. National aquaculture sector overview, Mexico. Mexico City, Mexico. https://www.fao.org/fishery/en/countrysector/naso_mexico (Retrieved: August 2025).

FAO (Food and Agriculture Organization of the United Nations). 2018. The state of world fisheries and aquaculture 2018 – Meeting the sustainable development goals. Rome, Italy. https://openknowledge.fao.org/handle/20.500.14283/i9540en (Retrieved: August 2025).

Ferreira RG, Ferreira JG, Boogert FJ, Corner RA, Nunes JP, Grant J, Johansen J, Dewey WF. 2020. A multimetric investor index for aquaculture: Application to the European Union and Norway. Aquaculture 516: 734600. https://doi.org/10.1016/j.aquaculture.2019.734600

Gjedrem T, Robinson N, Rye M. 2012. The importance of selective breeding in aquaculture to meet future demands for animal protein: A review. Aquaculture 350–353: 117–129. https://doi.org/10.1016/j.aquaculture.2012.04.008

Goddard JS, Perret JSM. 2005. Co-drying fish silage for use in aquafeeds. Animal Feed Science and Technology 118 (3–4): 337–342. https://doi.org/10.1016/j.anifeedsci.2004.11.004

Guedes AC, Sousa-Pinto I, Malcata FX. 2015. Application of microalgae protein to aquafeed. *In* Handbook of Marine Microalgae. Academic Press: Cambridge, MA, USA, pp: 93–125. https://doi.org/10.1016/b978-0-12-800776-1.00008-x

Gümüş E. 2010. Fatty acid composition of fry mirror carp (*Cyprinus carpio*) fed graded levels of sand smelt (*Atherina boyeri*) meal. Asian-Australasian Journal of Animal Sciences 24 (2): 264–271. https://doi.org/10.5713/ajas.2011.10223

Hamilton SE, Stankwitz C. 2012. Examining the relationship between international aid and mangrove deforestation in coastal Ecuador from 1970 to 2006. Journal of Land Use Science 7 (2): 177–202. https://doi.org/10.1080/1747423x.2010.550694

Han D, Shan X, Zhang W, Chen Y, Wang Q, Li Z, Zhang G, Xu P, Li J, Xie S, *et al*. 2016. A revisit to fishmeal usage and associated consequences in Chinese aquaculture. Reviews in Aquaculture 10 (2): 493–507. https://doi.org/10.1111/raq.12183

Hardy RW. 2010. Utilization of plant proteins in fish diets: Effects of global demand and supplies of fishmeal. Aquaculture Research 41 (5): 770–776. https://doi.org/10.1111/j.1365-2109.2009.02349.x

Hasan MR. 2017. Feeding global aquaculture growth. FAO Aquaculture Newsletter 56 (2). Rome, Italy.

Hernández C, Olvera-Novoa MA, Hardy RW, Hermosillo A, Reyes C, González B. 2010. Complete replacement of fish meal by porcine and poultry by-product meals in practical diets for fingerling Nile tilapia *Oreochromis niloticus*: Digestibility and growth performance. Aquaculture Nutrition 16 (1): 44–53. https://doi.org/10.1111/j.1365-2095.2008.00639.x

Hu L, Yun B, Xue M, Wang J, Wu X, Zheng Y, Han F. 2013. Effects of fish meal quality and fish meal substitution by animal protein blend on growth performance, flesh quality and liver histology of Japanese seabass (*Lateolabrax japonicus*). Aquaculture 372–375, 52–61. https://doi.org/10.1016/j.aquaculture.2012.10.025

Hua K, Cobcroft JM, Cole A, Condon K, Jerry DR, Mangott A, Praeger C, Vucko MJ, Zeng C, Zenger K, Strugnell JM. 2019. The future of aquatic protein: Implications for protein sources in aquaculture diets. One Earth 1 (3): 316–329. https://doi.org/10.1016/j.oneear.2019.10.018

Islam MM, Barman A, Kundu GK, Kabir MA, Paul B. 2019. Vulnerability of inland and coastal aquaculture to climate change: Evidence from a developing country. Aquaculture and Fisheries 4 (5): 183–189. https://doi.org/10.1016/j.aaf.2019.02.007

Justino CI, Duarte KR, Freitas AC, Panteleitchouk TS, Duarte AC, Rocha-Santos TA. 2016. Contaminants in aquaculture: Overview of analytical techniques for their determination. TrAC Trends in Analytical Chemistry 80: 293–310. https://doi.org/10.1016/j.trac.2015.07.014

Laining A, Kristanto AH. 2015. Aquafeed development and utilization of alternative dietary ingredients in aquaculture feed formulations in Indonesia. *In* Catacutan MR, Coloso MR, Acosta BO. (eds.), Development and Use of Alternative Dietary Ingredients or Fish Meal Substitutes in Aquaculture Feed Formulation. Nay Pyi Taw, Myanmar, pp: 3–13).

Liaqat I, Mukhtar B, Malik M, Shah SH, Azzam A, Slahuddin. 2017. Lysine supplementation in fish feed. International Journal of Applied Biology and Forensics 1 (2): 26–31.

Little DC, Young JA, Zhang W, Newton RW, Al Mamun A, Murray FJ. 2018. Sustainable intensification of aquaculture value chains between Asia and Europe: A framework for understanding impacts and challenges. Aquaculture 493: 338–354. https://doi.org/10.1016/j.aquaculture.2017.12.033

Madage SSK, Medis WUD, Sultanbawa Y. 2015. Fish silage as replacement of fishmeal in red tilapia feeds. Journal of Applied Aquaculture 27 (2): 95–106. https://doi.org/10.1080/10454438.2015.1005483

Maisashvili A, Bryant H, Richardson J, Anderson D, Wickersham T, Drewery M. 2015. The values of whole algae and lipid extracted algae meal for aquaculture. Algal Research 9: 133–142. https://doi.org/10.1016/j.algal.2015.03.006

Mulema SA, García AC. 2019. Monitoring of an aquatic environment in aquaculture using a MEWMA chart. Aquaculture 504: 275–280. https://doi.org/10.1016/j.aquaculture.2019.01.019

Nakphet S, Ritchie RJ, Kiriratnikom S. 2016. Aquatic plants for bioremediation in red hybrid tilapia (*Oreochromis niloticus* × *Oreochromis mossambicus*) recirculating aquaculture. Aquaculture International 25 (2): 619–633. https://doi.org/10.1007/s10499-016-0060-7

Navas JM, Telfer TC, Ross LG. 2011. Spatial modeling of environmental vulnerability of marine finfish aquaculture using GIS-based neuro-fuzzy techniques. Marine Pollution Bulletin 62 (8): 1786–1799. https://doi.org/10.1016/j.marpolbul.2011.05.019

Nehete J, Narkhede M, Bhambar R, Gawali S. 2013. Natural proteins: Sources, isolation, characterization and applications. Pharmacognosy Reviews 7 (14): 107. https://doi.org/10.4103/0973-7847.120508

Ngajilo D, Jeebhay MF. 2019. Occupational injuries and diseases in aquaculture – A review of literature. Aquaculture 507: 40–55. https://doi.org/10.1016/j.aquaculture.2019.03.053

OECD (Organisation for Economic Co-operation and Development). 2020. Aquaculture production. OECD Data Explorer. Paris, France. https://data-explorer.oecd.org/ (Retrieved: March 2026).

Olsen RL, Hasan MR. 2012. A limited supply of fishmeal: Impact on future increases in global aquaculture production. Trends in Food Science and Technology 27 (2): 120–128. https://doi.org/10.1016/j.tifs.2012.06.003

Ottinger M, Clauss K, Kuenzer C. 2016. Aquaculture: Relevance, distribution, impacts and spatial assessments – A review. Ocean and Coastal Management 119: 244–266. https://doi.org/10.1016/j.ocecoaman.2015.10.015

Oyarzabal F. 2000. Comentarios a las leyes e instituciones que reglamentan las aguas superficiales de México. Natural Resources Journal 22 (4): 999–1005.

Phuong NT, Oanh DTH. 2010. Striped catfish aquaculture in Vietnam: A decade of unprecedented development. *In* de Silva SS, Davy FB. (eds.), Success Stories in Asian Aquaculture. Springer: Dordrecht, Germany. https://doi.org/10.1007/978-90-481-3087-0_7

Rickard LN, Britwum K, Noblet CL, Evans KS. 2020. Factory-made or farm fresh? Measuring U.S. support for aquaculture as a food technology. Marine Policy 115: 103858. https://doi.org/10.1016/j.marpol.2020.103858

Simbeye DS, Zhao J, Yang S. 2014. Design and deployment of wireless sensor networks for aquaculture monitoring and control based on virtual instruments. Computers and Electronics in Agriculture 102: 31–42. https://doi.org/10.1016/j.compag.2014.01.004

Soininen N, Belinskij A, Similä J, Kortet R. 2019. Too important to fail? Evaluating legal adaptive capacity for increasing coastal and marine aquaculture production in EU-Finland. Marine Policy 110: 103498. https://doi.org/10.1016/j.marpol.2019.04.002

Song AM, Soliman A. 2019. Situating human rights in the context of fishing rights – Contributions and contradictions. Marine Policy 103: 19–26. https://doi.org/10.1016/j.marpol.2019.02.017

Steeves L, Filgueira R. 2019. Stakeholder perceptions of climate change in the context of bivalve aquaculture. Marine Policy 103: 121–129. https://doi.org/10.1016/j.marpol.2019.02.024

Sun H, Tang J, Yao X, Wu Y, Wang X, Liu Y, Lou B. 2015. Partial substitution of fish meal with fermented cottonseed meal in juvenile black sea bream (*Acanthopagrus schlegelii*) diets. Aquaculture 446: 30–36. https://doi.org/10.1016/j.aquaculture.2015.04.020

Tacon AGJ, Metian M. 2015. Feed matters: Satisfying the feed demand of aquaculture. Reviews in Fisheries Science and Aquaculture 23 (1): 1–10. https://doi.org/10.1080/23308249.2014.987209

Tacon AGJ, Metian M. 2017. Food matters: Fish, income, and food supply—A comparative analysis. Reviews in Fisheries Science and Aquaculture 26 (1): 15–28. https://doi.org/10.1080/23308249.2017.1328659

Teves JFC, Ragaza JA. 2016. The quest for indigenous aquafeed ingredients: A review. Reviews in Aquaculture 8 (2): 154–171. https://doi.org/10.1111/raq.12089

Valenti WC, Kimpara JM, Preto BL, Moraes-Valenti P. 2018. Indicators of sustainability to assess aquaculture systems. Ecological Indicators 88: 402–413. https://doi.org/10.1016/j.ecolind.2017.12.068

Wang A, Ran C, Wang Y, Zhang Z, Ding Q, Yang Y, Olsen RE, Ringø E, Bindelle J, Zhou Z. 2019. Use of probiotics in aquaculture of China—A review of the past decade. Fish and Shellfish Immunology 86: 734–755. https://doi.org/10.1016/j.fsi.2018.12.026

Watterson A. 2018. Aquaculture/occupational safety: Towards healthy work. International Collective in Support of Fishworkers: Amsterdam, Netherlands.

World Bank Group. 2013. Fish to 2030: Prospects for fisheries and aquaculture. Agriculture and environmental services discussion paper no. 3. Washington, DC, USA. https://doi.org/10.1596/17579

World Bank Group. 2023. Aquaculture production. Washington, DC, USA. https://data.worldbank.org/indicator/ER.FSH.AQUA.MT (Retrieved: June 2025).

Yogev U, Barnes A, Giladi I, Gross A. 2020. Potential environmental impact resulting from biased fish sampling in intensive aquaculture operations. Science of The Total Environment 707: 135630. https://doi.org/10.1016/j.scitotenv.2019.135630

Yuan Y, Yuan Y, Dai Y, Gong Y. 2017. Economic profitability of tilapia farming in China. Aquaculture International 25 (3): 1253–1264. https://doi.org/10.1007/s10499-017-0111-8