Potential of Sustainable Aquaculture to Overcome the Declining Fishery Resources in Malaysian Waters

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Abstract

The fisheries sector in Malaysia is important for food security and the national economy. However, fish populations in Malaysian waters, especially the capture fisheries, are gradually declining due to overexploitation, climate change, poor water quality, and habitat destruction. As a result, aquaculture has emerged as an important solution to address the depletion of fish stocks in Malaysia. Aquaculture not only reduces the pressure on wild fish populations, but it also contributes to economic growth and sustainability. This review offers an overview of the current state of aquaculture in Malaysia, noting existing strengths in areas such as wastewater management policies, zonation for aquaculture activities, established practices, and successful research projects. Despite these foundations, the industry faces numerous challenges including a lack of biosecurity measures, spatial constraints, resource dependency, and technological lag. In response, this review highlights the concerted efforts needed to address these challenges, with a focus on implementing robust aquaculture biosecurity, improving aquafeed management, and promoting further research and development. This review also aims to guide the path toward sustainable aquaculture practices, emphasising the critical aspects of assimilative capacity and research and technological advancement. The adoption of these innovative practices and technologies presents a clear pathway for Malaysia to enhance the efficiency and long-term sustainability of its aquaculture sector.

Keywords: aquaculture development, aquaculture biosecurity, aquafeed, assimilative capacity, health management

Introduction

The fisheries sector in Malaysia plays a pivotal role in ensuring food security and economic stability. Besides being a major source of animal protein for the growing population, the fishing industry is important in reducing hunger and meeting nutritional needs across the country (Harun et al., 2023). This industry is essential for maintaining livelihoods in addition to promoting economic growth. It has made a significant economic contribution to the country and supported rural development by generating jobs in fishing and coastal areas (SEAFDEC, 2022; Sin & Yew, 2016). The fishing industry has a significant economic impact on Malaysia, shown by the 0.7 % share of the country's gross domestic product that it contributes to (Department of Fisheries Malaysia [DOFM], 2024). Furthermore, the industry contributes to Malaysia's export revenue and engages in international trade (Harun et al., 2023). Because of its diverse significance, Malaysia's fisheries industry needs to implement sustainable practices to maintain its beneficial effects on the country's economy and food security.

However, the alarming decline in the number of fishes in Malaysian waters has recently gained more attention. Trawling surveys conducted by the fisheries department in 2016 reported that the country's demersal fish stocks have decreased by 88 % since the 1960s (Siva, 2021). This decline is not confined to marine fish alone, it extends to freshwater ecosystems as well. A sharp depletion of iconic species like the arowana fish are also reported in lakes and rivers (Medipally et al., 2016). A thorough analysis that revealed a startling low rate of fisheries production along the Kelantan and Galas rivers highlighted the severity of this problem even further (Radhi et al., 2017). The depletion of both marine and freshwater fishes signals a pressing issue that requires immediate attention from both the government and the population.

Globally, aquaculture emerges as a crucial and effective strategy in overcoming the challenges posed by the decline in fish stocks (Bogmans & van Soest, 2022; Boyd et al., 2022). By reducing the pressure on wild fish populations, aquaculture contributes significantly to conservation efforts and helps maintain ecological balance in aquatic ecosystems (Overton et al., 2024). This review aims to present a comprehensive overview of the current state of aquaculture in Malaysia, emphasising its pivotal role in addressing the declining fish populations. The review also sheds light on the challenges and opportunities associated with aquaculture development in Malaysia, offering valuable insights for the formulation of effective measures to combat fish decline not only in Malaysia but also in other countries that face the similar challenges. By fostering a deeper understanding of aquaculture's potential, this comprehensive review seeks to pave the way for sustainable and innovative approaches to ensure the long-term health of aquatic ecosystems and global fisheries.

Status of Fish Stocks in Malaysian Waters

Malaysia, endowed with vast seas, rivers, and lakes, possesses one of the world's largest and most diverse fish populations (Arai, 2015). Due to its vast aquatic resources, the country is a maritime powerhouse. A large amount of its fish production is used to meet domestic demand, and it also makes a considerable contribution to the global market through exports (DOFM, 2024). The Department of Fisheries Malaysia (DOFM) serves as a pivotal leader in the development of Malaysia's fisheries sector. The fisheries sector in Malaysia encompasses three major sub-sectors: capture fisheries, inland fisheries, and aquaculture, each playing a distinctive role in the nation's fisheries production. Capture fisheries are a notable contributor, supplying over 71 % of the total fish production (Fig. 1) (DOFM, 2024). Both coastal and offshore fishing activities are included in this subsector, with pelagic fish dominating the catches over demersal species (DOFM, 2024). While capture fisheries contribute to the majority of fisheries production, the remaining comes from aquaculture. Aquaculture, which includes freshwater, brackish water and seaweed farming, plays a significant role in the increase of fisheries supplies. Seaweed constitutes a major portion of aquaculture production, followed by sea bass (*Lates calcarifer*), catfish (*Siluriformes*), white shrimp (*Penaeus vannamei*), and red tilapia (*Oreochromis* sp.)(DOFM, 2024). On the other hand, inland fisheries, though contributing a smaller portion, are crucial for the diversity they add to the fisheries landscape. Inland water systems such as lakes, reservoirs, and rivers serve as habitats for species like river catfish (*Cephalocassis jatia*), black tilapia (*Oreochromis niloticus*), freshwater giant prawn (*Macrobrachium rosenbergii*), Javanese carp (*Barbonymus gonionotus*), and snakehead (*Channidae*) (DOFM, 2024).

In 2023, Malaysia's fisheries production reached a total of 1.79 million tonnes, with a value of MYR16.5 billion (DOFM, 2024). Capture fisheries constituted the majority at 71.1 %, followed by aquaculture at 28.4 %, while inland fisheries contributed 0.5 % to the overall production. A comparative analysis between 2022 and 2023 reveals a 2.9 % decline in capture fisheries production, a notable 11.6 % decrease in aquaculture production, and a substantial 15.2 % rise in inland

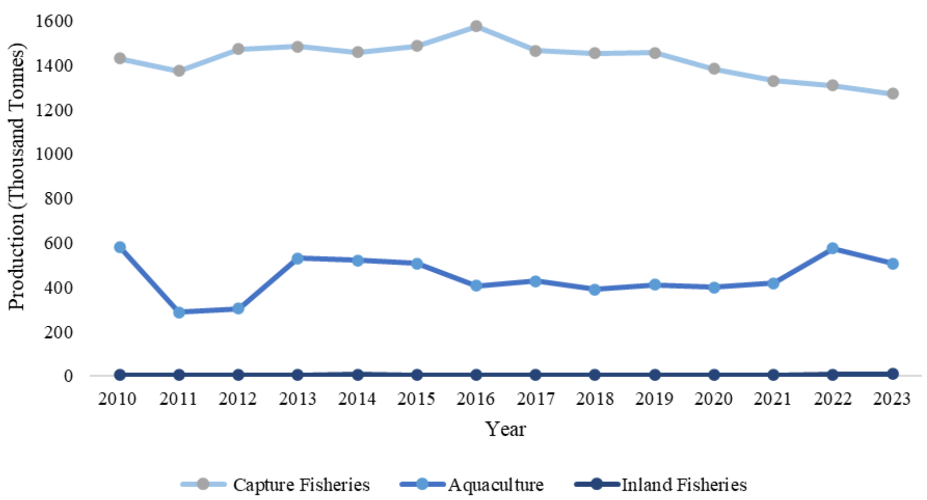

Fig. 1. Fisheries production in Malaysia from 2010 to 2023 (Adapted from Department of Fisheries Malaysia [DOFM], 2024).

fisheries production (DOFM, 2024). Despite these fluctuations, a concerning trend has emerged over the past few years, as the production of capture fisheries continues to decline, reflecting a drop in the amount of fisheries produced per fisherman observed across Malaysia (Rashvinjeet, 2024; The Star, 2023). This decline is particularly noticeable in the pelagic stock, which is being fully exploited and depleted (Hassan, 2015). Previous studies further highlight the issue by demonstrating the poor landings of targeted high-value fish, but an increase in trash fish and squid proportions (Sany et al., 2019).

The demersal stocks in Malaysia are also facing severe exploitation, where alarming statistics were revealed by the DOFM in 2019 (Siva, 2021). The data disclosed a staggering 96 % loss in demersal fish stock over a span of less than six decades, primarily attributed to overfishing (Rashvinjeet, 2024; Siva, 2021). Such overexploitation has terrible consequences, including a damaging effect on fish landings. This is a direct consequence of fishing too rapidly, which prevents juvenile fish from having the chance to develop, reproduce, and maintain the fish population (Jagerroos, 2016). Trawling is one of the destructive fishing methods that puts more pressure on these stocks, leading to overexploitation and rapid depletion (Sin & Yew, 2016; Siow et al., 2020). In addition to the species that are intended for capturing, trawling also catches juvenile sharks, dolphins, sea turtles, and non-commercial fish as well as protected species (Desai & Shambaugh, 2021; Gray & Kennelly, 2018). This practice not only depletes fish stocks but also disturb the delicate balance of marine biodiversity and the food chain (Siow et al., 2020). The exploitation of fisheries resources has reached a critical threshold, according to a warning from WWF Malaysia (Bernama, 2021). Overfishing severely depletes Malaysia's seafood resources and endangers the country's marine ecosystem, so immediate action is required to address it.

The decline in fish populations in Malaysian waters is not solely attributed to overfishing but is also significantly influenced by a reduction in water quality. Various pollutants, including organic contamination from sewage and animal wastes, suspended solids resulting from soil erosion and sedimentation, oil and grease, and heavy metals, are affecting water quality in Malaysian waters (Huang et al., 2018; Omar et al., 2019; Yunus et al., 2020). These pollutants are particularly prevalent in the more developed west coast of Malaysia, characterised by extensive land use, industrialisation, uncontrolled development, mining, and logging activities (Camara et al., 2019; Sany et al., 2019). Additionally, habitat destruction and tourism-related activities in coastal areas contribute to water pollution (Hazri & Noor, 2024; Sany et al., 2019). The runoff from construction stages of tourism and development projects intensifies the damage to the marine ecosystem, as the polluted water may have an impact on the health of aquatic life, especially for those that develop in shallow coastal environments during their early life cycles (Hazri & Noor, 2024; Jagerroos, 2016).

The detrimental effects of climate change are also posing an increasing threat to Malaysia's littoral and marine ecosystems, which are essential to the country's food supply (Shaffril et al., 2017; Solaymani, 2018; Tang, 2019). The physiology and behaviour of aquatic life are being impacted by climate change, primarily through the shifting of water temperatures (Huang et al., 2021). As poikilothermic animals, fish are highly sensitive to ambient water temperature fluctuations, leading to significant impact on their growth, metabolism, food consumption, reproduction and habitat range (Barange et al., 2018; Huang et al., 2021). On top of that, fish's skin integrity and barrier functions are compromised by the high seawater temperatures, making them more vulnerable to infections (Ytteborg et al., 2023). Additionally, the warming seas prompt pelagic fish to migrate to cooler oceanic regions, further reducing the productivity of local marine ecosystems (The Star, 2023). These combined effects resulting in a significant decrease in capture fisheries production, presenting a serious threat to the sustainability of Malaysia's marine resources.

Overall, fishery stocks in Malaysian waters have experienced alarming depletion, primarily attributed to the unregulated overfishing (Rashvinjeet, 2024; Sin & Yew, 2016). The overexploitation of marine resources has led to the severe reduction of crucial fishery populations (Wong & Yong, 2020). Additional factors like habitat destruction, reduced water quality, and climate change exacerbate this immediate crisis (Hazri & Noor, 2024). Due to these challenges occurring simultaneously, Malaysia is vulnerable to the increased dispute among different ocean users over the remaining stocks (Ahmad, 2020). The economic stability of the country is seriously threatened by this scenario, which could lead to lower incomes, compromised food security, and a lower standard of living for the general public (Ahmad, 2020). As a result, aquaculture emerges as a crucial solution for the problems brought forth by Malaysia's declining fish stocks.

Aquaculture in Malaysia: An Overview

The historical development of aquaculture in Malaysia dates back to the 1920s, driven by the nation's abundant land and water resources, which are essential for aquaculture activities (Yusoff, 2015). Aquaculture began with the extensive polyculture of Chinese carps, including the bighead carp (*Hypophthalmichthys nobilis*), silver carp (*Hypophthalmichthys molitrix*), and grass carp (*Ctenopharyngodon idella*) in ex-mining pools. By the mid-1930s, the development of marine shrimp trapping ponds emerged as a significant industry in

Johor (Food and Agriculture Organization [FAO], 2024b). In the early 1940s, the culture of blood cockles (*Tegillarca granosa*) gained prominence (Rosita, 2017). The mid-1950s witnessed the expansion of an extensive culture of freshwater fishes in earthen ponds. Subsequent decades saw notable advancements, including the semi-intensive culture of shrimp and the establishment of floating net cage culture for marine fish, primarily the green grouper (*Epinephelus coioides*), along with the introduction of raft culture for green mussels (*Perna canaliculus*) in the early 1970s (FAO, 2024b). The 1980s marked the emergence of commercial aquaculture, with the establishment of fish and shrimp hatcheries and private feed mills. In the 1990s, the development of commercial-scale integrated shrimp farms, spanning from hatchery operations to processing plants and export facilities, solidified Malaysia's position as a key player in the aquaculture industry (FAO, 2024b).

Over the last decades, aquaculture has been increasingly being promoted in Malaysia as a key driver of economic growth, poised to become the future economic main pillar. With a production target set at 2.55 million metric tonnes by 2030, aquaculture plays a pivotal role in meeting this ambitious goal (DOFM, 2024). Aquaculture is essential to achieving the ambitious goal of 2.55 million metric tonnes of production by 2030 (DOFM, 2024). Malaysia's aquaculture industry is highly dependent on demand from both domestic and foreign markets (Waiho et al., 2020). Although the majority of industry activity is driven by local consumption, Malaysia's participation in international trade highlights the country's potential for development and expansion in the global aquaculture market. As of 2023, freshwater aquaculture made up 22 % of production, while brackish water and seaweed accounted for 33 % and 45 %, respectively (DOFM, 2024) (Fig. 2). Key freshwater aquaculture species include red tilapia (*Oreochromis* sp.), black tilapia (*Oreochromis niloticus*), catfish (*Siluriformes*), and bighead carp (*Hypophthalmichthys nobilis*), which are recognised as important contributors to the sector (Table 1). Marine aquaculture encompasses a diverse array of species, including finfish like barramundi (*Lates calcarifer*), milkfish (*Chanos chanos*), and crustaceans such as black tiger shrimp (*Penaeus monodon*) and white leg

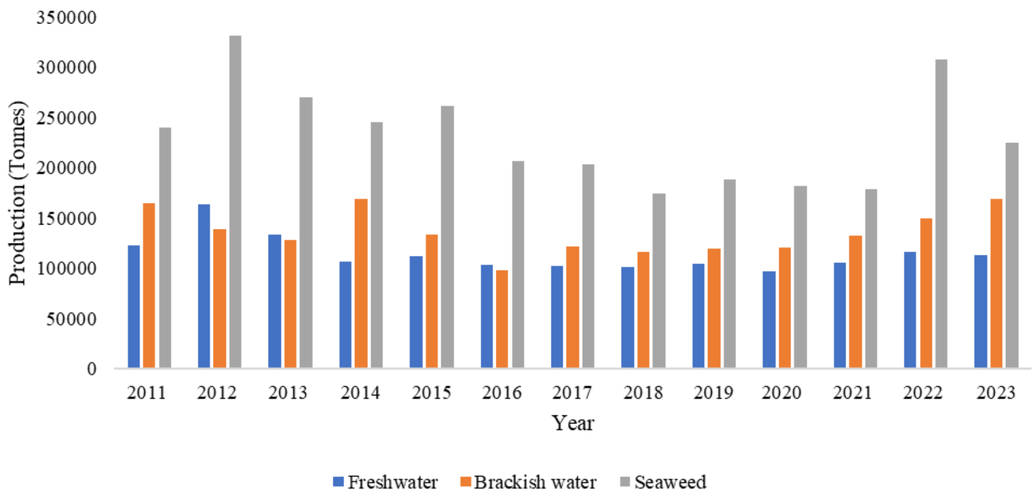

Fig. 2. Aquaculture production in Malaysia from 2011 to 2023 (Adapted from Department of Fisheries Malaysia [DOFM], 2024).

Table 1. Status of Malaysian aquaculture in 2023: Production, economic value, key species and production systems.

	Total production (metric tonnes)	Value (MYR)	Key species cultivated	Production systems
Freshwater	113,070	1.0 billion	Catfish, black tilapia, red tilapia, bighead carp	Earthen ponds, concrete tanks, canvas tanks
Brackish water	168,719	3.3 billion	Barramundi, milkfish, tiger shrimp, white leg shrimp	Floating net cages, inshore cages, tanks, pond culture
Seaweed	225,077	100 million	Seaweed	Raft culture, floating line method

Adapted from Department of Fisheries Malaysia [DOFM], 2024).
USD1.0 = MYR4.56 (2023).

shrimp (*Litopenaeus vannamei*), bivalves like cockle (*Tegillarca granosa*), mussel (*Perna viridis*), and oyster (*Crassostrea belcheri*), as well as seaweed (*Sargassum* spp.) (DOFM, 2024). In Malaysia, both marine and freshwater fish species are cultivated using various methods, including ponds, cages, tanks, and enclosures. Of these, cages have become the most popular breeding system due to the abundance of suitable water bodies such as rivers, lakes, and seawaters (DOFM, 2024).

In the year 2020, the COVID-19 pandemic significantly disrupted aquaculture activities in Malaysia, primarily due to reduced workforce availability, a drop in demand, and challenges in adhering to required sanitary measures (Waiho et al., 2020). Due mostly to logistical problems during the pandemic, aquaculture production faced challenges like temporary closures of fish mills and a decrease in the supply of animal feed (Azra et al., 2021; Waiho et al., 2020). The enforcement of movement control orders (MCOs) further exacerbated supply chain disruptions by restricting importations and distribution of fish and feed due to international and domestic travel restrictions and lockdowns (FAO, 2020a). To ensure food security and economic growth, the aquaculture sector was permitted to resume normal operations in 2021. Consequently, aquaculture production experienced a decline in 2020 but rebounded in 2021, surpassing production levels from 2019 (DOFM, 2023). Despite the pandemic's adverse effects, aquaculture demonstrated resilience, outpacing capture fisheries growth in recent years. This trend suggests that aquaculture is steadily emerging as a key economic driver, indicating its potential for long-term expansion and development in Malaysia.

Significance of Aquaculture in Addressing Declining Fish Stocks

Malaysia stands out as the highest per capita seafood consumer in Southeast Asia, with an average consumption of 44.7 kg per capita in 2023 (FAO, 2020b; DOFM, 2024). Fish, chosen as the primary animal protein in the diet, fulfils 60–70 % of the total national protein intake (Jeevanaraj et al., 2019). The demand for fish is predicted to increase in the upcoming years due to its importance as a source of nutrition and the population's steady increase (Yusoff, 2015). However, annual fish landings have not kept pace with population demand projections, suggesting that marine catch fisheries alone may be challenging to sustain the country's increasing per capita fish consumption trend (Harun et al., 2023). The reduction in fisheries production could have adverse social and economic consequences (Yusoff, 2015). As a result, aquaculture has become crucial to supplying the world's expanding food demand, especially since marine capture fisheries face constraints in meeting the rising consumption needs (Dauda et al., 2018; FAO, 2022).

Globally, the growth of aquaculture production has been the primary driver of the expansion of total aquatic food production since the late 1980s, especially for Asian countries (FAO, 2022). While capture fisheries production has remained relatively stagnant since the end of the 1990s (Fig. 3), the increase in aquatic food consumption has largely been facilitated by the significant rise in aquaculture production (FAO, 2024a). Looking ahead, the sustainable expansion of aquaculture is essential to bridge the gap in global demand for aquatic foods (Gephart et al., 2020). Beyond addressing the supply-demand gap for aquatic food, aquaculture plays a pivotal role in the economic development of developing countries by creating new sources of income and employment opportunities (FAO, 2024b). As such, the continued growth and sustainable development of aquaculture are important for ensuring food security, fostering economic growth, and improving livelihoods, especially in the developing countries (Pradeepkiran, 2019).

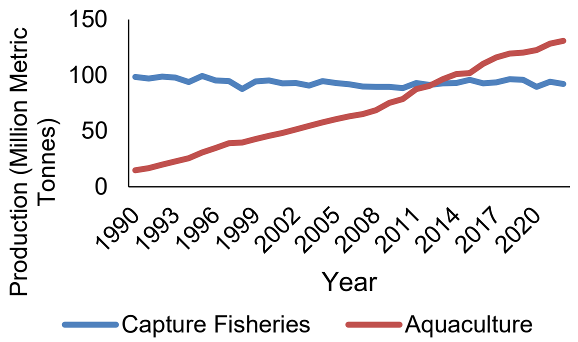

Fig. 3. Global aquaculture and capture fisheries production trend from 1990 to 2022 (Adapted from Food and Agriculture Organization [FAO], 2024a).

In Malaysia, aquaculture has been identified as a strategic industry capable of meeting both local demand and trade purposes for high-value protein resources. The declining levels of wild fish catch have further propelled the growth of the aquaculture sector in Malaysia, as it alleviates pressure on capture fisheries (Anderson et al., 2017; Yusoff, 2015). Recognising the need to reduce overdependence on inshore fisheries, fishery authorities have actively encouraged fishers to diversify into aquaculture (Wong & Yong, 2020). Since 2010, Malaysia has increasingly recognised the significance of aquaculture production as an essential component of efforts to develop its natural resources, conserve the wild fish populations and achieve developed nation status (Kurniawan et al., 2021a). Moreover, aquaculture has emerged as a significant pillar in Malaysian national food security, as outlined in the National Agrofood Policy 2021–2030 (NAP 2.0), thereby narrowing the gap between the supply and demand of food fish in the country (Samah & Kamaruddin, 2015).

Over the past 15 years, aquaculture in Malaysia has undergone remarkable improvements in techniques, cultured species, and its contribution to national income (Kurniawan et al., 2021a). In 2024, about 20,963 fish farmers and culturists participated actively in the aquaculture sector (DOFM, 2024). Aquaculture serves as a vital source of income in addition to traditional fishing activities, especially in Malaysian coastal communities where a large proportion of the population falls into the Bottom 40 % (B40) income group (Ibrahim et al., 2018; Ng et al., 2018). With many fishermen experiencing a decline in fishing frequency due to reduced catches, aquaculture has become a dependable alternative source of income (Jagerroos, 2016). Aquaculture not only provides employment and career development opportunities but also uplifts the living standards of rural populations (Samah & Kamaruddin, 2015). Recognised as a key driver of economic activities, Malaysia's National Key Economic Area (NKEA) places a strong emphasis on the aquaculture industry (Jumatli & Ismail, 2021). Sixteen agro-food Entry Point Projects (EPP) under the NKEA focus on aquaculture are receiving prioritised government support to transform the sector from traditional small-scale production to a large-scale business industry (Yusoff, 2015). The sector successfully produced high-value commodities to meet local demands and export them to overseas markets. These commodities include high-value fishes like Napoleon wrasse, grouper, stonefish, sashimi tuna, snapper, shrimp, and selected species of molluscs (FAO, 2024b).

SWOT Analysis of Aquaculture Development in Malaysia

Over the past few decades, Malaysia's aquaculture industry has grown rapidly and dynamically, making a substantial economic contribution to the country. However, the industry faces numerous challenges that impede its future development and sustainability (Tan et al., 2024). Key challenges include the spread of diseases among aquatic organisms, environmental pollution from aquaculture activities, limited land space for expansion, labour shortages, high operational costs, a scarcity of expertise, and inadequate financial support from the government (Fathi et al, 2018b; Tan et al., 2024). Despite these challenges, the importance of aquaculture in addressing declining fish stocks and ensuring food security in Malaysia cannot be overstated. Both the Malaysian government and private industry are actively working to overcome these challenges and promote the development of the aquaculture sector. The SWOT analysis for developing the aquaculture sector in Malaysia are outlined in Table 2, highlighting the concerted efforts to address existing challenges.

Table 2. SWOT analysis of potential of aquaculture development in Malaysia.

Strengths	Weaknesses
Existing technological knowledge: Base of knowledge in systems like RAS, aquaponics, and bio-coagulants.	Spatial constraints: Limited availability of suitable land and water resources for expansion.
Policy and regulations: Enhancement of Fisheries Act 1985 and implementation of Environmental Quality Act 1974 (EQA74).	Health management: Lack of implementation of proper biosecurity measures on farms.
Site selection: Space utilisation improved via Aquaculture Industrial Zone (AIZ) and Integrated Cage Aquaculture (i-CAGE) programmes.	Resource dependency: High dependence on expensive fishmeal for feed.
Research advancement: Success of Genetic Improvement of Farmed Tilapia (GIFT) project and development of vaccines, epizootiology reports, and R&D innovations.	
Established practices: Frameworks like Good Aquaculture Practice (GAP) are available for adoption.	Technological lag: Limited application and adoption of new available technologies (AI, IoT).
Opportunities	**Threats**
Technological advancement: Can adopt AI, IoT, image processing, and GIS to improve efficiency and monitoring.	Climate change: External environmental changes can threaten stock health and farm viability.
Innovation in feed: Research into alternative, sustainable feed ingredients can reduce costs and environmental footprint.	Public perception: Negative consumer perception due to environmental concerns, antibiotic use or insect-based feed can affect market acceptance.
Policy support: Opportunity for government support through better zoning, funding for R&D, and promoting integrated farming.	Global competition: Competition from other protein sources or from more efficient aquaculture industries in other countries.
Health management: Shift to the application of vaccines and immunostimulants.	Economic volatility: Fluctuating prices of inputs like fishmeal and energy can threaten economic sustainability.

Environmental concerns

The intensive use of water in aquaculture systems results in the generation of substantial amounts of wastewater (Kurniawan et al., 2021a). Particularly in man-made ponds used for brackish water and freshwater cultures, the wastewater produced contains a lot of pollutants, including high concentrations of organic matter, nutrients such as nitrogenous and phosphorus compounds, proteins, hormones, and biomass residues (Dauda et al., 2019; Huang et al., 2018; John et al., 2020). Significant environmental concerns are raised by this effluent pollution because it may have a detrimental effect on water quality. The issue of aquaculture effluent pollution is not confined to specific regions but is a global challenge. However, tropical and subtropical areas, like Malaysia, require special attention due to the existence of sensitive ecosystems such as coral reefs and associated communities that are already under threat from factors like global warming and ocean acidification (Hozumi et al., 2018). It is anticipated that the aquaculture industry in Malaysia will contribute into the rise in wastewater generation, particularly as in-land culture systems proliferate. It is estimated that by the year 2030, the aquaculture sector in Malaysia will generate approximately 7.519 km^3 of wastewater (Kurniawan et al., 2021a). This highlights the urgent need for Malaysia to develop an efficient wastewater management system.

In Malaysia, flow-through systems and pond systems continue to dominate aquaculture (FAO, 2024b). Despite being widely used, flow-through systems can be expensive to operate because of the high flow rate of weakly concentrated effluents (Ahmad et al., 2021). On the other hand, pond systems lack specific provisions for nitrogen removal except for the accelerated removal of solids and water containing dissolved nutrients from the culture system (Ahmad et al., 2021). Furthermore, many small-scale aquaculture operations in Malaysia do not possess wastewater treatment plants, leading to direct discharge of untreated wastewater into surface water bodies (Kurniawan et al., 2021a). This practice is not sustainable long-term and raises serious environmental concerns. To address these issues, specific technological interventions are required to treat wastewater from the aquaculture sector.

Over the past decades, recirculating aquaculture systems (RAS) have garnered increasing attention due to their potential as water-saving tools (Kurniawan et al., 2021a). By effectively recycling the majority of the water through a variety of components, RAS systems are made to use the least amount of water possible (Ahmed & Turchini, 2021). Fish are raised intensively in rearing tanks in this system, and the water is subsequently drained into a filtration system made up of physical filters (Ahmad et al., 2022). Subsequently, the water is biologically treated, such as by anaerobic digestion, to reduce organic sludge production further (Ahmad et al., 2022). The water is then cycled back into the rearing tanks after being disinfected with ozone or ultraviolet light. The advantages of RAS are manifold, including reduced water consumption, improved sludge management, and minimised pollution, making it a more popular technique for sustainable aquaculture practices (Ahmed & Turchini, 2021; Fudge et al., 2023).

Currently, research on zero-waste technology is also gaining attention with the objective of generating techniques for waste recovery to produce natural fertilisers that are an alternative to conventional counterparts (Loh et al., 2023). For instance, bio-coagulants and constructed wetlands are being explored for treating aquaculture wastewater effectively (Kurniawan et al., 2020). Coagulants extracted from plants and fungi are utilised to recover solid waste without compromising the water quality (Alnawajha et al., 2022; Iber et al., 2021; Nasir et al., 2019), resulting in the production of biodegradable sludge rich in nutrients that can serve as soil conditioners or fertilisers (Bakar et al., 2021). Residual pollutants in the form of soluble organic materials with abundant nutrients are further treated using floating plants in constructed wetlands (Kurniawan et al., 2021b). These floating plants extract soluble nutrients and can be utilised as feedstocks for fish breeding. By producing treated effluent free from solids and soluble ions, this process helps to reduce environmental impact and promote sustainable environments by recycling and reusing the wastewater for fish farming (Kurniawan et al., 2021a).

Policy and regulatory frameworks

In addition to its benefits, the growth of aquaculture often brings about adverse environmental impacts, including the destruction of wetlands and mangroves and the decline in biodiversity of natural fish populations (Tengku Hashim et al., 2021). The significant increase in fish production requires the conversion of land for aquaculture sites. This conversion causes coastal ecosystems such as lakes, mangroves, coastal wetlands, and agricultural lands to be transformed into aquaculture farms, resulting in habitat destruction (Anderson et al., 2017; Isa et al., 2021). Brackish water fish farming, in particular, is associated with the destruction of mangrove forests and coastal biodiversity (Suzuki, 2021). These unsustainable management practices in aquaculture have significantly reduced mangrove areas, with approximately 30 % (1.66 million hectares) lost in Southeast Asia (Tengku Hashim et al., 2021). Furthermore, over-pumping groundwater in freshwater fish farming may adversely affect land subsidence (Suzuki, 2021). Land is needed for aquaculture expansion, but acquiring land can be difficult due to competition from other economic activities (FAO, 2024b).

To address the land scarcity issue and prevent uncontrolled expansion of aquaculture sites, the DOFM has launched the Aquaculture Industrial Zone (AIZ) Program (FAO, 2024; Jumatli & Ismail, 2021). Under this program, specific zones are designated by state governments to allocate both land and water bodies for commercial-scale aquaculture projects (FAO, 2024b). The goal is to ensure sufficient land is available for the expansion of aquaculture activities. As part of this program, 49 zones have been identified throughout Malaysia, catering to the cultivation of various aquatic species with high market value such as tilapia, groupers, shrimps, catfish, mussels, and seaweed (FAO, 2024; Yusoff, 2015). Moreover, DOFM has identified suitable areas for downstream activities, including fish seed production, feed mills, fish processing plants, and other supporting industries (Yusoff, 2015). Another innovative initiative by the DOFM is the Integrated Cage Aquaculture (i-CAGE) program, that aims to address the challenges posed by limited land availability for pond culture (Iliyasu et al., 2016). For the purpose of freshwater cage aquaculture operations, this program locates sizable bodies of water, including rivers, lakes, dams, reservoirs, and abandoned former mining pools. The i-CAGE approach involves the cultivation of a variety of species, including shrimp, prawn, tilapia, catfish, and carp, within the same water body (Iliyasu et al., 2016; Lola et al., 2017). A key focus of this initiative is to optimise waste or by-product utilisation efficiency, whereby waste generated by one species is converted into a valuable input for another (Mohd Khatib & Jais, 2021). By adopting this integrated farming system, space utilisation is improved and the environmental impact is minimised (Lola et al., 2017; Mohd Khatib & Jais, 2021).

The DOFM has also been actively promoting aquaponics in the country. In the rearing system, aquaponics combines hydroponic planting with aquaculture operations (Okomoda et al., 2023). The idea is to grow plants in a hydroponic system by recycling wastewater from aquaculture that has been enriched with nutrients (Okomoda et al., 2023). In this symbiotic system, plants act as biological filters, absorbing nutrients from the aquaculture wastewater, thereby reducing the need for additional filtration for water quality management in fish rearing (Yavuzcan Yildiz et al., 2017). Aquaponics can be used to increase the efficiency of using land and water resources, simplify pollution control techniques, improve product quality, and raise food safety standards (Anjur et al., 2020). On top of that, the DOFM has developed comprehensive guidelines known as Good Aquaculture Practice – Aquaculture Farm (GAqP) for each aquaculture system with the goal of promoting sustainable and best practices in the sector (Jumatli & Ismail, 2021). Following these recommendations is essential for producing fresh, high-quality fish and is also vital for fostering consumer trust and confidence in the security and dependability of the food supply (Leng et al., 2020). Furthermore, compliance with GAqP standards enhances the competitiveness of Malaysian agricultural products in the global market by meeting international quality and safety standards (Jumatli & Ismail, 2021; Leng et al., 2020).

The Department of Environment has made significant progress under the Environmental Quality Act 1974 (EQA74) to address the various environmental issues related to aquaculture, including eutrophication, water pollution, and microplastic contamination from wastewater discharge (Qi et al., 2019; Tengku Hashim et al., 2021). This act establishes regulations that are enforced to control emissions and discharge from the aquaculture sector, ensuring that they remain within acceptable limits (Witus & Vun, 2016). This legislative framework plays a crucial role in safeguarding the environment against irresponsible practices in the aquaculture industry. Furthermore, Environmental Impact Assessments (EIA) are required for specified aquaculture developments, providing developers with a systematic way to evaluate and lessen any potential environmental effects (Witus & Vun, 2016). Through the implementation of regulatory mechanisms and environmental impact assessments, Malaysia seeks to encourage responsible and environmentally sustainable growth in its aquaculture industry while minimising adverse environmental effects.

Health management

The rapid expansion of aquaculture globally has led to significant disease outbreaks within the sector (Bouwmeester et al., 2021; Fathi, 2018b). Waterborne pathogens, particularly infectious ones, have found the perfect environment for replication and spread within both extensive and intensive aquaculture farming systems (Thiang et al., 2021; Waiho et al., 2021). Compared to wild populations, these settings provide more favourable conditions for the spread of disease because fish are raised in close quarters and at high densities (Suzuki, 2021). For instance, the aquaculture sector has suffered catastrophic losses as a result of the introduction of new fish diseases like Tilapia Lake Virus (TiLV) and Early Mortality Syndrome (EMS) (Mohd et al., 2017; Thiang et al., 2021). Additionally, the combination of stressful conditions arising from high stocking densities and deteriorating environmental conditions due to climate change has intensified the occurrence and severity of diseases (Naylor et al., 2021). In Malaysia, the major diseases affecting aquaculture include TiLV, Streptococcosis, and Vibriosis in fish, as well as acute hepatopancreatic necrosis disease (AHPND) and *Enterocytozoon hepatopenaei* (EHP) in shrimp (Mustafa et al., 2021). If these diseases are not treated, they may cause significant losses in stock, interfere with the functioning of aquaculture facilities, and hinder the expansion of the industry overall (Suzuki, 2021; Wong & Yong, 2020).

Antibiotics are widely used in the aquaculture sector as preventative or therapeutic measures to treat and prevent bacterial diseases. Nevertheless, there is a severe lack of comprehensive legislation, regulatory surveillance, and monitoring mechanisms governing the use of antibiotics in aquaculture in many Southeast Asian countries, including Malaysia (Chuah et al., 2016). Although Malaysia has prohibited the use of nitrofurans and chloramphenicol in aquaculture farming, residues of these antibiotics continue to be detected in seafood, where the US Food and Drug Administration (FDA) has documented 44 cases of antibiotic residues in seafood between 2009 and 2018 (Food and Drug Administration [FDA], 2018). Moreover, the lack of standards for acceptable antibiotic discharge concentrations from wastewater effluents in developing countries has led to the direct release of antibiotics, antibiotic-resistant bacteria, and antibiotic-resistant genes into the environment (Sasikaladevi et al., 2020). This irresponsible release contributes to the proliferation of antimicrobial resistance and reduction of the effectiveness of the antibiotics, thereby heightening the risk of transmission (Thiang et al., 2021).

Immunostimulants and vaccines are increasingly being recognised as alternatives to antibiotics and chemotherapeutants in aquaculture practices (Razak et al., 2019; Vijayaram et al., 2023). Immunostimulants, in particular, have garnered more attention in recent years owing to their cost-effectiveness, efficacy, non-resistance forming-nature, and eco-friendliness (Anjur et al., 2021; Raman, 2017). Examples of widely used immunostimulants in aquaculture include beta-glucan (Ching et al., 2021; Khanjani et al., 2022a), chitosan (Kamilya & Khan, 2020; Mohan et al., 2023), herbal extracts (Dev et al., 2024), vitamins and minerals (Vijayaram et al., 2023). These compounds have demonstrated the ability to enhance the immunity of aquatic animals by modulating the gut microbiota and activating both the innate and adaptive immune responses (Ching et al., 2021; Thépot et al., 2021). The major advantage of immunostimulants is that they come from natural sources, which minimises the risk of harmful side effects when administered to aquatic species (Ali et al., 2022). As such, their application in aquaculture is widely advocated. On the other hand, despite vaccines having great potential for mitigating disease spread in aquaculture, only a small number of farms and hatcheries in Malaysia have adopted vaccines (Ridzuan et al., 2022). Currently, the Malaysian government has licensed three imported aquatic vaccines (Ridzuan et al., 2022). High manufacturing costs, lengthy registration procedures, and a lack of technical knowledge are some of the reasons why local vaccine production is lacking (Ridzuan et al., 2022). Despite these challenges, the potential benefits of immunostimulants and vaccines in aquaculture highlight the importance of continued research and development efforts in this field.

Progressive management pathway for aquaculture biosecurity

To enhance national aquaculture biosecurity, Malaysia has made substantial progress to implement Progressive Management Pathway for Aquaculture Biosecurity (PMP/AB). PMP/AB is a FAO initiative designed to strengthen national aquaculture biosecurity management through risk-based approaches and public-private partnerships (Cottier-Cook et al., 2022; FAO, 2023). The country's efforts align strongly with the PMP/AB's objectives, primarily through the implementation of its National Fish Health Strategy (NFHSM) 2018–2022 (DOFM, 2016). This plan was supported by the FAO's Technical Cooperation Programme project TCP/MAL/3501: "Strengthening Aquaculture Biosecurity Capacity of the Department of Fisheries Malaysia". The initiative focused on key areas such as developing alternatives to antimicrobials, creating vaccines, and fostering research and development in disease diagnostics and control (DOFM, 2016). A central achievement of this program is the work of the National Fish Health Research Center (NaFisH), which successfully delivered significant outputs, including the development of three vaccines, eight epizootiology reports on various aquatic pathogens, and eleven R&D innovations (Institute Penyelidikan Perikanan [IPP], 2024; Kua et al., 2024).

Malaysia continues to prioritise aquaculture biosecurity and disease prevention through strengthening the legal framework by preparing amendments to the Fisheries Act 1985 (Media Selangor, 2024). These amendments aim to enhance biosecurity protocols and improve the regulation of the aquaculture sector, including Monitoring, Control, and Surveillance (MCS) and Fisheries Impact Assessment (FIA) (Media Selangor, 2024). For early disease detection, Malaysia employs a tiered diagnostic system. Initial on-site screening at farms is conducted using tools like the Shrimp Health On-site Spotter (SHOS-Spotter), with further validation through laboratory-based polymerase chain reaction (PCR) tests (Kua et al., 2024). However, the implementation of PCR on farms can be challenging due to the need for specialised equipment and technical expertise (Chiew et al., 2019). More accessible alternative techniques, such as lateral flow devices (LFD) and loop-mediated isothermal amplification (LAMP), are gaining attention for their ease of use and portability (Chiew et al., 2019). Besides disease monitoring, daily observation of fish health is considered essential in aquaculture practices, and it is acknowledged as a critical requirement for farms seeking certification under the myGAP Fisheries Biosecurity Certification Scheme Programme (DOFM, 2021; Manap & Pauzi, 2020). Additionally, DOFM actively encourages aquaculture to adopt best practices, including the responsible use of antibiotics (Noordin et al., 2020). This initiative aligns with the Malaysian Action Plan on Antimicrobial Resistance (MyAP-AMR) 2022–2026 and involves continuous protocol monitoring and improvement to ensure responsible antibiotic management (Natrah et al., 2025).

Aquafeed management

In Malaysia, the type of feed used in aquaculture depends on the species being farmed. For marine fish, especially carnivorous species like groupers and seabass, the main feed given are the chopped trash fish (Mok et al., 2021). Although imported pelleted feed is used, particularly for shrimp farming, its high cost and limited availability make it less common for fish (Obi et al., 2025). For freshwater species like tilapia and catfish, farmers commonly use formulated dry fish pellets (Kartika et al., 2022; Sakinah et al., 2024). In the early larval stages of both fish and crustaceans, live feed such as artemia, rotifers, and copepods is essential (Syukri et al., 2022). According to a 2019 industry report, Malaysia's aquafeed demand was estimated at 80,000 tonnes for fish feed, 105,000 tonnes for shrimp feed, and 50,000 tonnes for marine fish feed (Merican, 2021). More recent data from 2023 indicates a shift in these trends, with shrimp feed consumption decreasing while the demand for marine fish feed rose significantly (Aquaculture Asia Pacific [AAP], 2024).

Overall, the aquaculture sector depends on a combination of live and formulated feeds. However, there is a growing preference for formulated options due to the high cost and limitations of live feed production, though live feed remains essential for specific early-life stages in aquaculture (Syukri et al., 2022). To address rising costs and enhance sustainability, Malaysia's aquaculture industry is increasingly adopting novel ingredients in aquafeed. This involves a strategic shift away from traditional marine-based resources and toward more plant-based alternatives and farm-made feed solutions (Kari et al., 2023a).

Necessity of novel ingredients to replace unsustainable fishmeal

As aquaculture continues to expand globally, the demand for fishmeal, which is primarily made from unwanted marine trash fish, has witnessed a concurrent rise (Suzuki, 2021). However, the growing dependence on fishmeal from marine trash fish poses a significant sustainability challenge for the aquaculture sector in long term (Wong & Yong, 2020). Since marine proteins and oils are crucial parts of the diet of cultured fish, the increased demand for fishmeal puts wild stocks under more fishing pressure, endangering the sustainability of associated capture fisheries (Boyd et al., 2022). This phenomenon is frequently called the "fishmeal trap" (Anderson et al., 2017). On top of that, the rapid expansion of aquaculture and the elevated prices of trash fish may encourage non-targeted fisheries, leading to detrimental impacts on marine resources (Bogmans & van Soest, 2022). Consequently, resolving this issue requires a concerted effort to create sustainable and alternative aquaculture feed sources (Suzuki, 2021).

The rising cost of fish oil and fishmeal has compelled Malaysia's aquafeed industry to look for substitute ingredients for feed formulations (Macusi et al., 2023; Manaf & Omar, 2015). Various studies have investigated the feasibility of replacing fishmeal and fish oil with novel ingredients such as fisheries by-products, poultry by-products, black soldier fly larvae, field cricket, microalgae, palm oil, and soybean oil (Hairuddin et al., 2020; Hanan et al., 2022; Macusi et al., 2023; Sakinah et al., 2024). These investigations have primarily focused on freshwater species such as African catfish (*Clarias gariepinus*), red hybrid tilapia (*Oreochromis* sp.), jade perch (*Scortum barcoo*), and Siamese fighting fish (*Betta splendens*) (Hanan et al., 2022; Kari et al., 2020; Kari et al., 2023b; Zainorahim et al., 2024). Among the novel ingredients in aquaculture feed, insect meal is gaining global recognition, including in Malaysia. It has emerged as a successful alternative to traditional fishmeal due to its nutritional benefits and environmental sustainability (Nogales-Mérida et al., 2019; Van Huis, 2020). Common insect species used for this purpose include the black soldier fly, mealworms, crickets, and the domesticated silkworm (Raghuvaran et al., 2024). To date, extensive research into incorporating insect meal into fish diets has yielded promising results. Studies on various species, including catfish (*Ictalurus punctatus*), tilapia (*Oreochromis niloticus*), carp (*Cyprinus carpio*), guppy (*Poecilia reticulata*), and juvenile whiteleg shrimp (*Litopenaeus vannamei*), have evaluated a range of inclusion levels (Fan et al., 2023; Peh et al., 2021; Perera & Bhujel, 2022; Perera et al., 2025; Zhou et al., 2018). These studies consistently show that insect meal can be included without negatively impacting growth performance or other physiological responses. Beyond its nutritional advantages, insect meal also offers potential cost benefits. A cost-benefit analysis indicated that replacing fishmeal with soldier termite meal can be economically sustainable (Nephale et al., 2024). Additionally, research efforts have explored the utilisation of mathematical software to precisely determine the optimal combination of feed ingredients, ensuring that the dietary requirements of the fish are met while minimising production costs (Sakinah et al., 2024). By lowering reliance on costly and limited resources, these initiatives seek to alleviate the financial hardships aquaculture farmers face while promoting sustainability in the sector.

In Malaysia, several companies are actively converting organic waste into high-value protein and oil through insect farming, providing a sustainable alternative for the aquaculture sector. The commercial viability of this industry is demonstrated by the approval from the Ministry of Agriculture for Malaysian companies to export insect-based products to European markets for use in pet food, aquaculture, and livestock feed (Aquaculture Magazine, 2021; The Fish Site, 2023). However, the widespread adoption of insect meal mainly depends on market acceptance. While global studies on consumer behaviour show moderate acceptance of insect protein in aquaculture, research in Malaysia remains limited (Mulazzani et al., 2023).

Furthermore, a farmer's willingness to use insect-based feed is strongly influenced by their perception of its nutritional value, their familiarity with its use, and their overall awareness of the product's benefits (Ssepuuya et al., 2019).

Despite their promise as sustainable alternatives to fishmeal, the application of insect meals presents several challenges. A primary obstacle is the difficulty in achieving complete fishmeal replacement without adversely affecting growth performance in certain fish species and life stages (Gougbedji et al., 2022). Reported issues include hepatic steatosis at higher inclusion levels, reduced digestibility in some species, and the presence of anti-nutritional factors (Caligiani et al., 2018; Eggink et al., 2022; Zarantoniello et al., 2019). Therefore, it is necessary to determine species-specific optimal inclusion rates and employ processing techniques like defatting (Gougbedji et al., 2022; Zhao et al., 2023). Concurrently, research into how insect meal influences gut microbiota is essential to maximise benefits and prevent adverse effects (Kalemi et al., 2025).

Further concerns involve safety and quality control. Insects, such as black soldier fly larvae reared on organic waste, can bioaccumulate heavy metals from their substrate, creating a potential pathway for these hazardous elements to enter the human food chain (Addeo et al., 2024). Hence, it is necessary to implement strict regulations and quality control measures to govern the growing substrates, ensuring both safety and consistent quality.

Research and development initiatives

Aquaculture research in Malaysia encounters several challenges that impede its progress, including limited financial resources, inadequate expertise, and less optimal structure for cutting edge research (Fathi et al., 2018b; Jumatli & Ismail, 2021). Furthermore, aquaculture production has grown unevenly across species, with some species being easier to farm than others (FAO, 2022). In Malaysia, applied aquaculture research is primarily conducted by the FRI, along with contributions from universities and stakeholders (DOFM, 2015). The FRI operates three research centres focusing on brackish water, freshwater, and marine species. Research efforts predominantly concentrate on areas such as gonadal maturation, breeding techniques, seed production, nutrition, fish diseases, and production technologies in both pond and cage systems (FAO, 2024b). Researchers are also striving to develop fish species that are larger, faster-growing, have low feed conversion ratios, and exhibit tolerance to adverse environmental conditions like high stocking density and low oxygen levels (Pradeepkiran, 2019).

The application of biotechnology and genetics in the fisheries sector has shown promise in improving the survival and health of cultivated stocks while reducing disease transmission (Pradeepkiran, 2019). For instance, tilapia aquaculture can become more profitable and sustainable through the use of DNA marker-assisted selection programmes, like those carried out at the FRI Glami Lemi (Mohamad et al., 2021). Additionally, the Malaysian government has provided support for projects like Genetic Improvement of Farmed Tilapia (GIFT) project, which seeks to develop a genetically improved strain of red hybrid tilapia through selective breeding methods with characteristics like high survivability, uniform red coloration, and suitability for various aquaculture systems (Mohamad et al., 2021). With the support and efforts by government, researchers and stakeholders, aquatic research can continue to develop in Malaysia.

Technological advancement in aquaculture

The development of the aquaculture sector in Malaysia also faces challenges, including a lack of technical knowledge, low farmer educational attainment, and poor infrastructure (Iliyasu et al., 2016). The lack of interaction and communication between farmers and the DOFM exacerbates these problems (Fathi et al., 2018a). Farmers often do not have access to the tools needed to monitor water quality and fish health, both of which are essential for successful fish farming (Suzuki & Hoang Nam, 2018). To address these challenges, the application of advanced information technology (IT) solutions, such as computerised models, artificial intelligence (AI), internet of things (IoT), image processing, and geographic information system (GIS), is essential (Manan et al., 2023; O'donncha & Grant, 2019). These technologies can significantly enhance the management of aquaculture by enabling farmers to optimise their operations and ensure sustainable practices with better tools and data.

However, IoT technology is still very new and has a limited acceptance level in Malaysia (Khairi, 2018; MOSTI, 2015). For site selection and in-situ water quality monitoring, the DOFM continues to rely on traditional techniques (Bandira et al., 2021). Nonetheless, a growing number of projects and studies are encouraging the application of new technologies in modern aquaculture. For instance, the GIS-based multi-criteria evaluation (MCE) employs remote sensing and land use data to determine the best locations for inland aquaculture farms (Bandira et al., 2021). Satellite data could monitor water levels and water quality (Sabjan et al., 2022). Additionally, real-time monitoring of water quality parameters like temperature, pH, alkalinity, and nitrate levels is made possible by the integration of IoT into aquaculture (Rastegari et al., 2023). The application of IoT has revolutionised the aquaculture sector by enabling less human intervention and more precise monitoring (Gupta et al., 2022). This technology reduces mortality rates and increases profitability by allowing faster detection of contamination and early treatment (Lim & Majid, 2021; Rastegari et al., 2023). With IoT solutions, farmers can explore new methods to boost production while maintaining affordability and sustainability in the supply chain (Khairi, 2018).

Recommendations for Sustainable Aquaculture Development

Although aquaculture has advanced significantly over the past decades, there's more to be done to improve its profitability and sustainability (FAO, 2020b). Increasing attention is being devoted in raising awareness of environmental issues caused by improper aquaculture practices and implementing approaches to minimise the aquaculture's environmental footprint (Boyd et al., 2020). This focus is in line with the Sustainable Development Goal (SDG) 2, which aims to achieve food security, and SDG 14, which seeks to conserve marine resources for sustainable development (United Nations [UN], 2015). The main goal of sustainable aquaculture is to guarantee a steady supply of farmed aquatic organisms for human consumption without endangering the existing ecosystems. Strategies for sustainable aquaculture development were proposed in the aspects of assimilative capacity and research and technological advancement.

Assimilative capacity

The concept of assimilative capacity is fundamental to achieving sustainable aquaculture. This approach involves designing systems where the environment can naturally absorb or recycle nutrients and wastes, thereby allowing for increased production without causing ecological degradation (Fisher et al., 2023). Concurrently, the careful monitoring and management of carrying capacity are essential to prevent over-intensification and irreversible harm to aquatic ecosystems (Weitzman & Filgueira, 2020). Applying these approaches across both freshwater and marine systems is critical for mitigating ecological risks and supporting sustainable production.

Freshwater aquaculture

In Malaysia, freshwater aquaculture is predominantly conducted in ponds, tanks, and cages. A significant challenge in these systems, especially those with limited water exchange, is nutrient pollution from accumulated metabolic wastes and uneaten feed (Munguti et al., 2021). The decomposition of this organic matter elevates the biochemical oxygen demand (BOD), depleting dissolved oxygen and potentially harming cultured stock (Munguti et al., 2021; Tom et al., 2021). Furthermore, the release of excess nutrients, particularly nitrogen and phosphorus, can lead to eutrophication and harmful algal blooms in downstream water bodies, compromising ecosystem health (Tom et al., 2021). Therefore, enhancing the waste assimilation capacity of these aquaculture systems is critical for sustainability. This can be achieved through source reduction via improved feed management practices to minimise waste output, and biological treatment using aquatic plants, filter feeders, or engineered biofloc systems to process nutrients within the system (Dauda et al., 2019; Karimanzira, 2025).

Effective waste management in aquaculture begins with source reduction, primarily through improved feed strategies such as using high-quality diets and preventing overfeeding (Dauda et al., 2019). The integration of advanced technology is pivotal to this approach. The hunger status of cultured fish can be tracked with underwater sensors that are connected to the internet. This allows for precise feeding to optimise feed utilisation and reduce waste (Li et al., 2020; Zhou et al., 2019). Furthermore, the IoT facilitates comprehensive environmental management through real-time monitoring of critical water parameters such as dissolved oxygen, pH, pollutant concentrations, and temperature (Rather et al., 2024; Su et al., 2020; Yue & Shen, 2022). This approach allows farmers to intelligently regulate stocking densities in accordance with the waterbody's carrying capacity, ensuring that production is optimised within sustainable ecological limits. Ultimately, the synergy between strategic source reduction and digital innovation is key to enhancing both operational efficiency and environmental sustainability.

Integrated multi-trophic aquaculture (IMTA) offers a sustainable model for freshwater systems by co-cultivating species from different trophic levels to create a balanced, synergistic ecosystem (Azhar & Memis, 2023). This approach recycles nutrients, mitigates eutrophication risks, and improves overall water quality. For instance, incorporating aquatic plants like duckweed with fish allows the plants to utilise dissolved inorganic wastes, while filter-feeding species, such as freshwater snails, can consume organic particulate waste (Kibria & Haque, 2018; Paolacci et al., 2022). Innovative applications demonstrate the versatility of this concept. Studies highlight modified RAS that integrate wetland filters, aquaponics, or microalgae symbiosis to optimise nutrient uptake (Tom et al., 2021). Similarly, traditional earthen pond systems can be transformed into IMTA operations. Kibria and Haque (2018) successfully combined carp culture with inorganic-extractive aquatic plants and organic-extractive snails, the latter also being used as a feed source for carnivorous catfish reared in cages within the pond. By converting waste from one species into inputs for another, IMTA enhances environmental sustainability through efficient nutrient cycling.

Another biological treatment is biofloc technology. This technology operates on the principle of recycling waste nutrients, particularly nitrogen, into microbial biomass, which can be directly utilised as a feed supplement for aquatic animals or processed into feed ingredients (Bossier & Ekasari, 2017). By absorbing inorganic nitrogen from aquaculture wastewater, biofloc technology enhances water quality while providing a nutritious food source that improves feed utilisation efficiency (Khanjani & Sharifinia, 2020). This technology is therefore a low-cost and sustainable choice for aquaculture development since it provides minimal water exchange and decreased feed intake (El-Sayed, 2021). Biofloc systems are particularly effective for culturing species such as penaeid shrimp and tilapia (Boyd et al., 2020). Additionally, biofloc technology can be successfully incorporated into other food production systems, fostering integrated systems that are both highly productive and sustainable (Bossier & Ekasari, 2017). This integration promotes a more sustainable approach to aquaculture and food production in general by supporting the objective of producing more food and feed from the same area with fewer inputs (Khanjani et al., 2022b).

Marine and coastal aquaculture

Unlike enclosed freshwater systems, marine cages and coastal ponds discharge effluents directly into open ecosystems (Wang et al., 2020). The release of nutrient-rich waste from these systems poses a significant environmental risk, including the degradation of sensitive benthic habitats, the triggering of harmful algal blooms, and reduce biodiversity when the area's natural assimilation capacity is overwhelmed (Quimpo et al., 2020). Specific issues include the high organic load from shrimp pond effluents, which can contribute to the degradation of vital mangrove forests (Hua et al., 2024). Furthermore, the expansion of coastal aquaculture is often constrained by spatial competition with other stakeholders, including tourism, fisheries, and conservation areas (Alsaleh & Wang, 2025).

A fundamental solution to mitigate these impacts is strategic site selection and spatial planning (Fisher et al., 2023; Petrosillo et al., 2023). Hydrodynamic modelling can be utilised to identify locations with optimal natural water flow and energy. High-energy sites with strong currents effectively disperse and dilute waste particles, enhancing the environment's natural assimilation capacity and reducing localised accumulation beneath cages (Petrosillo et al., 2023). For this approach to be successful on a broad scale, aquaculture development must adhere to a comprehensive integrated coastal zone management plan. This ensures that farms are situated in ecologically suitable areas that can sustain production while balancing the needs of other coastal users and conserving overall ecosystem health (Perillo et al., 2021).

Integrated multi-trophic aquaculture also presents a transformative method for marine and coastal systems by co-cultivating fed species with extractive species like seaweeds and bivalve molluscs (Meitei et al., 2025). This creates a more circular and sustainable system where the extractive species utilise dissolved inorganic nutrients and organic particulate waste from the fed species, simultaneously mitigating environmental impact and diversifying marketable output (Rusco et al., 2024; Yang et al., 2025). The benefits of IMTA extend beyond waste reduction to enhance the entire farming system. By improving water quality and potentially reducing pathogen loads, IMTA fosters a healthier environment (Rusco et al., 2024; Ghosh et al., 2025). This is evidenced by studies showing enhanced growth, stronger non-specific immune responses, and glycolipid metabolism in the hybrid grouper within IMTA systems (Zhang et al., 2022). The combination of improved animal welfare and a reduced ecological footprint translates into significant economic and market advantages, making IMTA an effective strategy for sustainable marine aquaculture.

Effective management of assimilative capacity in aquaculture also involved establishment of clear Environmental Quality Standards (EQS) and farm effluent standards specific to aquaculture waters (Kingsbury et al., 2024). Concurrently, the implementation of robust environmental monitoring systems is critical for tracking potential impacts and ensuring compliance with these standards (Zhang et al., 2023). At the farm level, the universal adoption of good aquaculture practices is necessary. This includes measures such as the regular removal of accumulated sediments beneath cages using submersible pumps and the proper collection and treatment of sludge from ponds and tanks (DOFM, 2022). All effluent must be treated in accordance with regulations, such as Malaysia's Environmental Quality (Industrial Effluents) Regulations 2009 (Mokhtar et al., 2024). For instance, shrimp farms can significantly reduce their nutrient load by integrating effluent treatment systems such as settling ponds, biofilters, and mangrove buffer zones, to purify water before its discharge into the environment (Iber & Kasan, 2021). With these approaches, the environmental concerns induced by aquaculture activities can be minimised.

Research and technological advancement

Aquatic research has advanced in various dimensions due to current multi-omics approaches, including genomics, transcriptomics, proteomics, and metabolomics (Natnan et al., 2021a). These approaches, together with reliable databases and advancements in bioinformatic analysis, have facilitated the identification of potential molecular biomarkers, including genes, mRNAs, proteins, and metabolites, in numerous fish disease studies (Natnan et al., 2021b). Moreover, the integration of multi-omics data analysis provides a comprehensive understanding of the molecular mechanisms of the fish immune system, encompassing gene expression, protein expression, and metabolite production (Nam et al., 2023). The study of pathogen-host interactions and mechanisms in aquatic organisms has also significantly benefited from these omics approaches (Liu et al., 2024). Furthermore, fish disease prevention and control can be achieved through the development of vaccines and immunostimulants using high-throughput data from various omics levels (Natnan et al., 2021b). Omics approaches are also employed to study the effects of incorporating essential feed additives in fish diets to enhance growth and boost immune responses (Rasmussen et al., 2022).

Furthermore, genetic improvement of farmed species is a powerful strategy to enhance aquaculture production and reduce its environmental impact (Gratacap et al., 2019). Aquatic organisms can be genetically modified to increase growth rates and cost-effectiveness while using less feed, land, and water per unit of production. Additionally, genetic improvement can increase resistance of aquatic organisms to environmental stressors and pathogens, enhance broodstock quality, and provide better control over reproduction (Yue & Shen, 2022). Rapid advancement of economic traits in aquaculture species is made possible by methods like genomic selection and genome editing (Yue & Shen, 2022). Genomic selection, utilising single-nucleotide polymorphisms, is increasingly applied to a wide range of aquaculture species to optimise selective breeding and speed up genetic improvement (Shen & Yue, 2019). Moreover, genome editing with CRISPR/Cas technology can expedite genetic improvements when the specific genes targeted for editing are identified (Gratacap et al., 2019).

Nanotechnology has emerged as an innovative and promising tool in various aspects of aquaculture, including fish nutrition, biotechnology, genetics, reproduction, pathology, and environmental quality maintenance (Sarkar et al., 2022; Shah & Mraz, 2020). In aquatic systems, semiconductor nanoparticles, nanoscale iron, and nanocomposites are currently employed to break down contaminants and lower treatment expenses (Sarkar et al., 2022). When added to fish diets at the microscale, nanoparticles can also act as immunomodulators and growth promoters, improving the general health and growth rates of the fish (Abu-Elala et al., 2021; El-Naggar et al., 2021; Izquierdo et al., 2017). Moreover, advancements in nanotechnology, such as nanomedicine, nano-vaccine delivery, and nanoparticle-based gene therapy, offer promising solutions for fish disease control and health management (Nasr-Eldahan et al., 2021; Rather et al., 2022; Shaalan et al., 2016). These innovations not only improve the efficiency of treatments but also contribute to the sustainable development of the aquaculture industry by ensuring healthier and more resilient fish populations.

Additionally, the use of protein-protein interaction (PPI) networks in aquaculture has the potential to significantly advance the understanding of the pathogenesis of fish diseases and enhance the identification and treatment of these diseases in aquaculture species (Waiho et al., 2021). Protein-protein interaction networks can be applied to various aspects of fish disease management, including the identification of biomarkers, prediction of disease mechanisms, comprehension of host-pathogen interactions, understanding of pathogen co-infection dynamics, and the development of potential vaccines and treatments (Li et al., 2021; Rosilan et al., 2023; Waiho et al., 2021; Wang et al., 2022). Overall, these approaches not only improve disease management and increase aquaculture production but also contribute to the better management and sustainability of the aquaculture industry. These approaches, together with the collaborative effort uniting government agency, academic institutions, and the private sector, Malaysia can strive for higher stages of implementation for the PMP/AB.

Energy-intensive operations such as aeration, recirculation, and temperature control are common in aquaculture farms (Chary et al., 2024). To enhance sustainability, farms should aim to minimise energy consumption, reduce reliance on fossil fuels, and lower greenhouse gas emissions by transitioning to renewable energy sources (Lal et al., 2024). Aquaculture operations can benefit from steady and reliable power from wind, solar, and wave energy (Chary et al., 2024). For instance, solar-powered oxygen generators, integrated with water electrolysis and fuel cells, create a more sustainable system by producing oxygen for fish and using hydrogen as a clean fuel to generate electricity and store solar energy for future use (Erdemir & Dincer, 2024). Additionally, ocean waves can be captured by wave energy converters to supply offshore aquaculture with energy (Clemente et al., 2023). Compared to traditional energy sources, renewable energy infrastructure can save money over time, even though the initial investment may be high (Lal et al., 2024).

Conclusion

In conclusion, this review highlights the significant role of aquaculture in addressing the decline of fish populations in Malaysian waters. Although aquaculture represents an effective solution to alleviate pressure on wild fish stocks and promote economic growth, there are also disadvantages of current aquaculture practices that might not benefit its purposes. Despite the challenges such as a lack of biosecurity measures, spatial constraints, inadequate aquaculture research, and the need for advanced technologies, the opportunities for sustainable aquaculture development are substantial. By adopting innovative practices and integrating new technologies, Malaysia can enhance the efficiency and sustainability of its aquaculture industry. This comprehensive understanding and strategic approach can serve as a model for other nations facing similar challenges, contributing to the global effort to ensure the long-term health of aquatic ecosystems and the sustainability of fisheries worldwide.

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References

Abu-Elala, N. M., Shaalan, M., Ali, S. E., & Younis, N. A. (2021). Immune responses and protective efficacy of diet supplementation with selenium nanoparticles against cadmium toxicity in *Oreochromis niloticus*. *Aquaculture Research*, *52*(8), 3677–3686. https://doi.org/10.1111/are.15212

Addeo, N. F., Scivicco, M., Vozzo, S., Bovera, F., Asiry, K. A., Alqurashi, S., Cacciola, N. A., & Severino, L. (2024). Mineral profile and heavy metals bioaccumulation in black soldier fly (*Hermetia illucens*, L.) larvae and frass across diverse organic substrates. *Italian Journal of Animal Science*, *23*(1), 179–188. https://doi.org/10.1080/1828051X.2024.2302845

Ahmad, A. (2020). *Overview of the comparison of commercial pelagic species fisheries management in Malaysia and Oregon, United States* [Undergraduate thesis, Oregon State University]. Oregon State University ScholarsArchive. https://ir.library.oregonstate.edu/concern/undergraduate_thesis_or_projects/44558m69n

Ahmad, A., Abdullah, S. R. S., Hasan, H. A., Othman, A. R., & Ismail, N. I. (2021). Aquaculture industry: Supply and demand, best practices, effluent and its current issues and treatment technology. *Journal of Environmental Management*, *287*, Article 112271. https://doi.org/10.1016/j.jenvman.2021.112271

Ahmad, A. L., Chin, J. Y., Harun, M. H. Z. M., & Low, S. C. (2022). Environmental impacts and imperative technologies towards sustainable treatment of aquaculture wastewater: A review. *Journal of Water Process Engineering*, *46*, Article 102553. https://doi.org/10.1016/j.jwpe.2021.102553

Ahmed, N., & Turchini, G. M. (2021). Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. *Journal of Cleaner Production*, *297*, Article 126604. https://doi.org/10.1016/j.jclepro.2021.126604

Ali, M. F. Z., Nakahara, S., Otsu, Y., Ido, A., Miura, C., & Miura, T. (2022). Effects of functional polysaccharide from silkworm as an immunostimulant on transcriptional profiling and disease resistance in fish. *Journal of Insects as Food and Feed*, *8*(11), 1221–1233. https://doi.org/10.3920/JIFF2021.0108

Alnawajha, M. M., Kurniawan, S. B., Imron, M. F., Abdullah, S. R. S., Hasan, H. A., & Othman, A. R. (2022). Plant-based coagulants/flocculants: characteristics, mechanisms, and possible utilization in treating aquaculture effluent and benefiting from the recovered nutrients. *Environmental Science and Pollution Research*, *29*(39), 58430–58453. https://doi.org/10.1007/s11356-022-21631-x

Alsaleh, M., & Wang, X. (2025). Aquaculture growth and coastal tourism development in the context sustainable blue economy. *Sustainable Development*, *33*(2), 2030–2046. https://doi.org/10.1002/sd.3224

Anderson, J. L., Asche, F., Garlock, T., & Chu, J. (2017). Aquaculture: its role in the future of food. In *World Agricultural Resources and Food Security* (Frontiers of Economics and Globalization, Vol. 17, pp. 70–90). Emerald Publishing Limited. https://doi.org/10.1108/S1574-871520170000017011

Anjur, N., Sabran, S. F., Daud, H. M., & Othman, N. Z. (2021). An update on the ornamental fish industry in Malaysia: *Aeromonas hydrophila*-associated disease and its treatment control. *Veterinary World*, *14*(5), 1143–1152. https://doi.org/10.14202/vetworld.2021.1143-1152

Anjur, N., Samsuri, M. S., Arif, T. A. M., & Halim, Z. A. A. (2020). Potential of aquaponic system for the growth and production of strawberry (*Fragaria* sp.). *In 3rd ICA Research Symposium (ICARS) 2020*, 22.

Aquaculture Asia Pacific. (2024, October 22). *Aquafeeds in 2023: A market slowdown*. https://aquaasiapac.com/2024/10/22/aquafeeds-in-2023-a-market-slowdown/

Aquaculture Magazine. (2021, March 4). *Nutrition technologies opens a new industrial-scale insect protein factory in Malaysia*. https://aquaculturemag.com/2021/03/04/nutrition-technologies-opens-a-new-industrial-scale-insect-protein-factory-in-malaysia/

Arai, T. (2015). Diversity and conservation of coral reef fishes in the Malaysian South China Sea. *Reviews in Fish Biology and Fisheries*, *25*, 85–101. https://doi.org/10.1007/s11160-014-9371-9

Azhar, M., & Memiş, D. (2023). Application of the IMTA (integrated multi-trophic aquaculture) system in freshwater, brackish and marine aquaculture. *Aquatic Sciences and Engineering*, *38*(2), 101–121. https://doi.org/10.26650/ASE20231252136

Azra, M. N., Kasan, N. A., Othman, R., Noor, G. A. G. R., Mazelan, S., Jamari, Z. B., ... Ikhwanuddin, M. (2021). Impact of COVID-19 on aquaculture sector in Malaysia: Findings from the first national survey. *Aquaculture Reports*, *19*, Article 100568. https://doi.org/10.1016/j.aqrep.2020.100568

Bakar, S. N. H. A., Hasan, H. A., Abdullah, S. R. S., Kasan, N. A., Muhamad, M. H., & Kurniawan, S. B. (2021). A review of the production process of bacteria-based polymeric flocculants. *Journal of Water Process Engineering*, *40*, Article 101915. https://doi.org/10.1016/j.jwpe.2021.101915

Bandira, P. N. A., Mahamud, M. A., Samat, N., Tan, M. L., & Chan, N. W. (2021). GIS-based multi-criteria evaluation for potential inland aquaculture site selection in the George Town Conurbation, Malaysia. *Land*, *10*(11), Article 1174. https://doi.org/10.3390/land10111174

Barange, M., Bahri, T., Beveridge, M. C., Cochrane, K. L., Funge-Smith, S., & Poulain, F. (2018). Impacts of climate change on fisheries and aquaculture. *United Nations' Food and Agriculture Organization*, *12*(4), 628–635.

Bernama. (2021, November 23). Tackle overfishing to halt depletion of resources - WWF Malaysia. *New Straits Times*. https://www.nst.com.my/news/nation/2021/11/747865/tackle-overfishing-halt-depletion-resources-wwf-malaysia

Bogmans, C. W., & van Soest, D. (2022). Can global aquaculture growth help to conserve wild fish stocks? Theory and empirical analysis. *Natural Resource Modeling*, *35*(1), e12323. https://doi.org/10.1111/nrm.12323

Bossier, P., & Ekasari, J. (2017). Biofloc technology application in aquaculture to support sustainable development goals. *Microbial Biotechnology*, *10*(5), 1012–1016. https://doi.org/10.1111/1751-7915.12836

Bouwmeester, M. M., Goedknegt, M. A., Poulin, R., & Thieltges, D. W. (2021). Collateral diseases: aquaculture impacts on wildlife infections. *Journal of Applied Ecology*, *58*(3), 453–464. https://doi.org/10.1111/1365-2664.13775

Boyd, C. E., D'Abramo, L. R., Glencross, B. D., Huyben, D. C., Juarez, L. M., Lockwood, G. S., ... Valenti, W. C. (2020). Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. *Journal of the World Aquaculture Society*, *51*(3), 578–633. https://doi.org/10.1111/jwas.12714

Boyd, C. E., McNevin, A. A., & Davis, R. P. (2022). The contribution of fisheries and aquaculture to the global protein supply. *Food Security*, *14*(3), 805–827. https://doi.org/10.1007/s12571-021-01246-9

Caligiani, A., Marseglia, A., Leni, G., Baldassarre, S., Maistrello, L., Dossena, A., & Sforza, S. (2018). Composition of black soldier fly prepupae and systematic approaches for extraction and fractionation of proteins, lipids and chitin. *Food Research International*, *105*, 812–820. https://doi.org/10.1016/j.foodres.2017.12.012

Camara, M., Jamil, N. R., & Abdullah, A. F. B. (2019). Impact of land uses on water quality in Malaysia: a review. *Ecological Processes*, *8*(1), 1–10. https://doi.org/10.1186/s13717-019-0164-x

Chary, K., van Riel, A. J., Muscat, A., Wilfart, A., Harchaoui, S., Verdegem, M., ... Wiegertjes, G. F. (2024). Transforming sustainable aquaculture by applying circularity principles. *Reviews in Aquaculture*, *16*(2), 656–673. https://doi.org/10.1111/raq.12860

Chiew, I. K. M., Salter, A. M., & Lim, Y. S. (2019). The significance of major viral and bacterial diseases in Malaysian aquaculture industry. *Pertanika Journal of Tropical Agricultural Science*, *42*(3), 1005–1022. http://www.pertanika.upm.edu.my/Pertanika%20PAPERS/JTAS%20Vol.%2042%20(3)%20Aug.%202019/10%20JTAS-1591-2018.pdf

Ching, J. J., Shuib, A. S., Abdul Majid, N., & Mohd Taufek, N. (2021). Immunomodulatory activity of β-glucans in fish: Relationship between β-glucan administration parameters and immune response induced. *Aquaculture Research*, *52*(5), 1824–1845. https://doi.org/10.1111/are.15086

Chuah, L. O., Effarizah, M. E., Goni, A. M., & Rusul, G. (2016). Antibiotic application and emergence of multiple antibiotic resistance (MAR) in global catfish aquaculture. *Current Environmental Health Reports*, *3*, 118–127. https://doi.org/10.1007/s40572-016-0091-2

Clemente, D., Rosa-Santos, P., Ferradosa, T., & Taveira-Pinto, F. (2023). Wave energy conversion energizing offshore aquaculture: Prospects along the Portuguese coastline. *Renewable Energy*, *204*, 347–358. https://doi.org/10.1016/j.renene.2023.01.009

Cottier-Cook, E. J., Cabarubias, J. P., Brakel, J., Brodie, J., Buschmann, A. H., Campbell, I., Critchley, A. T., Hewitt, C. L., Huang, J., Hurtado, A. Q., & Kambey, C. S. (2022). A new progressive management pathway for improving seaweed biosecurity. *Nature Communications*, *13*(1), Article 7401. https://doi.org/10.1038/s41467-022-34783-8

Dauda, A. B., Ajadi, A., Tola-Fabunmi, A. S., & Akinwole, A. O. (2019). Waste production in aquaculture: Sources, components and managements in different culture systems. *Aquaculture and Fisheries*, *4*(3), 81–88. https://doi.org/10.1016/j.aaf.2018.10.002

Dauda, A. B., Natrah, I., Karim, M. M., Kamarudin, M. S., & Bichi, A. H. (2018). African catfish aquaculture in Malaysia and Nigeria: Status, trends and prospects. *Fisheries and Aquaculture Journal*, *9*, 1–5. https://doi.org/10.4172/2150-3508.1000237

Department of Fisheries Malaysia. (2015). *National plan of action for the management of fishing capacity in Malaysia*. https://www.dof.gov.my/dof2/resources/user_1/UploadFile/Penerbitan/Senarai%20Penerbitan/NPOA.pdf

Department of Fisheries Malaysia. (2016). *National fish health strategy Malaysia 2018 – 2022*. http://dx.doi.org/10.13140/RG.2.2.20022.45128

Department of Fisheries Malaysia. (2021). *Certification scheme (Biosecurity)*. https://www.dof.gov.my/en/services/certification-scheme/

Department of Fisheries Malaysia. (2022). *DOF/SIRIM 3:2022. Code of good aquaculture practices for marine finfish farming*. https://www.dof.gov.my/wp-content/uploads/2022/11/DOF-SIRIM-3-2022-COP-Marine-Finfish-Farming.pdf

Department of Fisheries Malaysia. (2023). *Malaysia annual fisheries statistics 2022*. https://www.dof.gov.my/en/resources/fisheries-statistics-i/

Department of Fisheries Malaysia. (2024). *Malaysia annual fisheries statistics 2023*. https://www.dof.gov.my/en/resources/fisheries-statistics-i/

Desai, R. M., & Shambaugh, G. E. (2021). Measuring the global impact of destructive and illegal fishing on maritime piracy: A spatial analysis. *PLOS ONE*, *16*(2), e0246835. https://doi.org/10.1371/journal.pone.0246835

Dev, A. K., Thakur, R., & Yadav, S. (2024). Deciphering the importance of herbal immunostimulants in aquaculture, using citation network analysis: A futuristic sustainable approach. *Comparative Immunology Reports*, *6*, Article 200129. https://doi.org/10.1016/j.cirep.2023.200129

Eggink, K. M., Pedersen, P. B., Lund, I., & Dalsgaard, J. (2022). Chitin digestibility and intestinal exochitinase activity in Nile tilapia and rainbow trout fed different black soldier fly larvae meal size fractions. *Aquaculture Research*, *53*(16), 5536–5546. https://doi.org/10.1111/are.16035

El-Naggar, M., Salaah, S., El-Shabaka, H., Abd El-Rahman, F., Khalil, M., & Suloma, A. (2021). Efficacy of dietary chitosan and chitosan nanoparticles supplementation on health status of Nile tilapia, *Oreochromis niloticus* (L.). *Aquaculture Reports*, *19*, Article 100628. https://doi.org/10.1016/j.aqrep.2021.100628

El-Sayed, A. F. M. (2021). Use of biofloc technology in shrimp aquaculture: a comprehensive review, with emphasis on the last decade. *Reviews in Aquaculture*, *13*(1), 676–705. https://doi.org/10.1111/raq.12494

Erdemir, D., & Dincer, I. (2024). Development of renewable energy based green hydrogen and oxygen production and electricity generation systems for sustainable aquaculture. *Journal of Cleaner Production*, *434*, Article 140081. https://doi.org/10.1016/j.jclepro.2023.140081

Fan, K., Liu, H., Pei, Z., Brown, P. B., & Huang, Y. (2023). A study of the potential effect of dietary fishmeal replacement with cricket meal (*Gryllus bimaculatus*) on growth performance, blood health, liver antioxidant activities, intestinal microbiota and immune-related gene expression of juvenile channel catfish. *Animal Feed Science and Technology*, *295*, Article 115542. https://doi.org/10.1016/j.anifeedsci.2022.115542

Fathi, S., Harun, A. N., Rambat, S., Nawi, M. N. M., & Haron, N. A. (2018a). Development of a mobile aquaculture management systems for performance monitoring of aquaculture players. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, *10*(1-11), 113–117. https://jtec.utem.edu.my/jtec/article/view/3858

Fathi, S., Rahim, Z. A., Rambat, S., & Tukiran, N. (2018b). A review of Malaysian aquaculture industries: Issues and challenges. *Innovation and Management*, 1694.

Fisher, J., Angel, D., Callier, M., Cheney, D., Filgueira, R., Hudson, B., ... Byron, C. J. (2023). Ecological carrying capacity in mariculture: Consideration and application in geographic strategies and policy. *Marine Policy*, *150*, Article 105516. https://doi.org/10.1016/j.marpol.2023.105516

Food and Agriculture Organization of the United Nations. (2020a). *The impact of COVID-19 on fisheries and aquaculture: A global assessment from the perspective of regional fishery bodies* (pp. 1–38). http://www.fao.org/3/ca9279en/CA9279EN.pdf

Food and Agriculture Organization of the United Nations. (2020b). *The state of world fisheries and aquaculture 2020: Sustainability in action*. https://openknowledge.fao.org/handle/20.500.14283/ca9229en

Food and Agriculture Organization of the United Nations. (2022). *The state of world fisheries and aquaculture 2022: Towards blue transformation*. https://doi.org/10.4060/cc0461en

Food and Agriculture Organization of the United Nations. (2023). *The progressive management pathway for aquaculture biosecurity: Guidelines for application*. https://www.fao.org/3/cc6858en/cc6858en.pdf

Food and Agriculture Organization of the United Nations. (2024a). *In brief to The State of World Fisheries and Aquaculture 2024: Blue transformation in action*. https://doi.org/10.4060/cd0690en

Food and Agriculture Organization of the United Nations. (2024b). *Fisheries and aquaculture: National Aquaculture Sector Overview (Malaysia)* (Text by M. Hashim). https://www.fao.org/fishery/en/countrysector/naso_malaysia

Food and Drug Administration. (2018). *US Food and Drug Administration import refusals report*. https://www.fda.gov/industry/fda-import-process/import-refusals#listrefusals

Fudge, M., Higgins, V., Vince, J., & Rajaguru, R. (2023). Social acceptability and the development of commercial RAS aquaculture. *Aquaculture*, *568*, Article 739295. https://doi.org/10.1016/j.aquaculture.2023.739295

Gephart, J. A., Golden, C. D., Asche, F., Belton, B., Brugere, C., Froehlich, H. E., ... Allison, E. H. (2020). Scenarios for global aquaculture and its role in human nutrition. *Reviews in Fisheries Science & Aquaculture*, *29*(1), 122–138. https://doi.org/10.1080/23308249.2020.1782342

Ghosh, A. K., Hasanuzzaman, A. F. M., Islam, S. S., Sarower, M. G., Mistry, S. K., Arafat, S. T., & Huq, K. A. (2025). Integrated multi-trophic aquaculture (IMTA): enhancing growth, production, immunological responses, and environmental management in aquaculture. *Aquaculture International*, *33*(5), Article 336. https://doi.org/10.1007/s10499-025-02021-9

Gougbedji, A., Detilleux, J., Lalèyè, P. A., Francis, F., & Caparros Megido, R. (2022). Can insect meal replace fishmeal? A meta-analysis of the effects of black soldier fly on fish growth performances and nutritional values. *Animals*, *12*(13), Article 1700. https://doi.org/10.3390/ani12131700

Gratacap, R. L., Wargelius, A., Edvardsen, R. B., & Houston, R. D. (2019). Potential of genome editing to improve aquaculture breeding and production. *Trends in Genetics*, *35*(9), 672–684. https://doi.org/10.1016/j.tig.2019.06.006

Gray, C. A., & Kennelly, S. J. (2018). Bycatches of endangered, threatened and protected species in marine fisheries. *Reviews in Fish Biology and Fisheries*, *28*(3), 521–541. https://doi.org/10.1007/s11160-018-9520-7

Gupta, S., Gupta, A., & Hasija, Y. (2022). Transforming IoT in aquaculture: A cloud solution. In *AI, Edge and IoT-based Smart Agriculture* (pp. 517–531). Academic Press. https://doi.org/10.1016/B978-0-12-823694-9.00020-7

Hairuddin, N. D., Talip, B. A., Zing, N. Z., Radin Mohamed, R. M. S., Al-Gheethi, A. A. S., Muhammad, N., ... Abdullah, S. (2020). Microalgae production in fresh market wastewater and its utilization as a protein substitute in formulated fish feed for *Oreochromis* spp. *Prospects of Fresh Market Wastes Management in Developing Countries*, 77–88. https://doi.org/10.1007/978-3-030-42641-5_5

Hanan, M. Y., Amatul-Samahah, M. A., Jaapar, M. Z., & Mohamad, S. N. (2022). The effects of field cricket (*Gryllus bimaculatus*) meal substitution on growth performance and feed utilization of hybrid red tilapia (*Oreochromis* spp.). *Applied Food Research*, *2*(1), Article 100070. https://doi.org/10.1016/j.afres.2022.100070

Harun, M., Ismail, R., & Sulaiman, N. (2023). Status of fish in food security in Malaysia. *Journal of Advanced Zoology*, *44*(3), 138–155. https://doi.org/10.53555/jaz.v44i3.573

Hasan, R. B. (2015). *Current status of purse seine fisheries in the Southeast Asian region*. Jabatan Perikanan Malaysia. http://hdl.handle.net/20.500.12561/295

Hazri, M. I. N. M., & Noor, N. M. (2024). Fish diversity assessment in the Malaysian Straits: Insights into climate change resilience. *Aquaculture Research*, *2024*(1), Article 3913221. https://doi.org/10.1155/2024/3913221

Hozumi, A., Hong, P. Y., Kaartvedt, S., Røstad, A., & Jones, B. H. (2018). Water quality, seasonality, and trajectory of an aquaculture-wastewater plume in the Red Sea. *Aquaculture Environment Interactions*, *10*, 61–77. https://doi.org/10.3354/aei00254

Hua, H. H., Cremin, E., Van Huynh, D., Long, G., & Renaud, F. G. (2024). Impacts of aquaculture practices on the sustainability of social-ecological systems in coastal zones of the Mekong Delta. *Ocean & Coastal Management*, *258*, Article 107392. https://doi.org/10.1016/j.ocecoaman.2024.107392

Huang, L., Li, M., Ngo, H. H., Guo, W., Xu, W., Du, B., ... Wei, D. (2018). Spectroscopic characteristics of dissolved organic matter from aquaculture wastewater and its interaction mechanism to chlorinated phenol compound. *Journal of Molecular Liquids*, *263*, 422–427. https://doi.org/10.1016/j.molliq.2018.05.025

Huang, M., Ding, L., Wang, J., Ding, C., & Tao, J. (2021). The impacts of climate change on fish growth: A summary of conducted studies and current knowledge. *Ecological Indicators*, *121*, Article 106976. https://doi.org/10.1016/j.ecolind.2020.106976

Iber, B. T., & Kasan, N. A. (2021). Recent advances in shrimp aquaculture wastewater management. *Heliyon*, *7*(11), Article e08283. https://doi.org/10.1016/j.heliyon.2021.e08283

Iber, B. T., Okomoda, V. T., Rozaimah, S. A., & Kasan, N. A. (2021). Eco-friendly approaches to aquaculture wastewater treatment: Assessment of natural coagulants vis-a-vis chitosan. *Bioresource Technology Reports*, *15*, Article 100702. https://doi.org/10.1016/j.biteb.2021.100702

Ibrahim, A. Z., Hassan, K., Kamarudin, R., & Anuar, A. R. (2018). Measuring sustainable livelihood for Malaysia's poor: The sustainable livelihoods index and the B40 group of coastal fishermen in northern Peninsular Malaysia. *LIFEWAYS-International Journal of Society, Development and Environment in the Developing World*, *2*(1), 39–47. http://repo.uum.edu.my/24113/1/IJSDEDW%202%201%202018%2039%2047.pdf

Iliyasu, A., Mohamed, Z. A., Ismail, M. M., Amin, A. M., & Mazuki, H. (2016). Technical efficiency of cage fish farming in Peninsular Malaysia: a stochastic frontier production approach. *Aquaculture Research*, *47*(1), 101–113. https://doi.org/10.1111/are.12474

Institute Penyelidikan Perikanan. (2024). *The National Fish Health Research Center (NaFisH)*. https://fri.dof.gov.my/en/the-national-fish-health-research-centre-nafish/

Isa, S. H., Ramlee, M. N. A., Lola, M. S., Ikhwanuddin, M., Azra, M. N., Abdullah, M. T., ... Ibrahim, Y. (2021). A system dynamics model for analysing the eco-aquaculture system of integrated aquaculture park in Malaysia with policy recommendations. *Environment, Development and Sustainability*, *23*, 511–533. https://doi.org/10.1007/s10668-020-00594-4

Izquierdo, M. S., Ghrab, W., Roo, J., Hamre, K., Hernández-Cruz, C. M., Bernardini, G., ... Saleh, R. (2017). Organic, inorganic and nanoparticles of Se, Zn and Mn in early weaning diets for gilthead seabream (*Sparus aurata*; Linnaeus, 1758). *Aquaculture Research*, *48*(6), 2852–2867. https://doi.org/10.1111/are.13119

Jagerroos, S. (2016). Assessment of living resources in the Straits of Malacca, Malaysia: case study. *Journal of Aquaculture and Marine Biology*, *4*(1), Article 00070. https://doi.org/10.15406/jamb.2016.04.00070

Jeevanaraj, P., Hashim, Z., Elias, S. M., & Aris, A. Z. (2019). Risk of dietary mercury exposure via marine fish ingestion: assessment among potential mothers in Malaysia. *Exposure and Health*, *11*, 227–236. https://doi.org/10.1007/s12403-017-0270-x

John, E. M., Krishnapriya, K., & Sankar, T. V. (2020). Treatment of ammonia and nitrite in aquaculture wastewater by an assembled bacterial consortium. *Aquaculture*, *526*, Article 735390. https://doi.org/10.1016/j.aquaculture.2020.735390

Jumatli, A., & Ismail, M. S. (2021). Promotion of sustainable aquaculture in Malaysia. In *Proceedings of the International Workshop on the Promotion of Sustainable Aquaculture, Aquatic Animal Health, and Resource Enhancement in Southeast Asia* (pp. 31–40). Aquaculture Department, Southeast Asian Fisheries Development Center. http://hdl.handle.net/10862/6253

Kalemi, V., Rimoldi, S., Costa, R. S., Basto, A., Monteiro, M., Terova, G., & Valente, L. M. (2025). Replacing fishmeal with an insect meal blend: Implications for intestinal microbiota in European seabass. *Aquaculture Reports*, *43*, Article 102939. https://doi.org/10.1016/j.aqrep.2025.102939

Kamilya, D., & Khan, M. I. R. (2020). Chitin and chitosan as promising immunostimulant for aquaculture. In *Handbook of Chitin and Chitosan* (pp. 761–771). Elsevier. https://doi.org/10.1016/B978-0-12-817966-6.00024-8

Kari, Z. A., Kabir, M. A., Razab, M. K. A. A., Munir, M. B., Lim, P. T., & Wei, L. S. (2020). A replacement of plant protein sources as an alternative of fish meal ingredient for African catfish, *Clarias gariepinus*: A review. *Journal of Tropical Resources and Sustainable Science*, *8*(1), 47–59. http://dx.doi.org/10.47253/jtrss.v8i1.164

Kari, Z. A., Sukri, S. A. M., Rusli, N. D., Mat, K., Mahmud, M. B., Zakaria, N. N. A., Wee, W., Hamid, N. K. A., Kabir, M. A., Ariff, N. S. N. A., & Abidin, S. Z. (2023a). Recent advances, challenges, opportunities, product development and sustainability of main agricultural wastes for the aquaculture feed industry–a review. *Annals of Animal Science*, *23*(1), 25–38. https://doi.org/10.2478/aoas-2022-0082

Kari, Z. A., Téllez-Isaías, G., Hamid, N. K. A., Rusli, N. D., Mat, K., Sukri, S. A. M., Kabir, M. A., Ishak, A. R., Dom, N. C., Abdel-Warith, A. W. A., & Younis, E. M. (2023b). Effect of fish meal substitution with black soldier fly (*Hermetia illucens*) on growth performance, feed stability, blood biochemistry, and liver and gut morphology of siamese fighting fish (*Betta splendens*). *Aquaculture Nutrition*, *2023*, Article 6676953. https://doi.org/10.1155/2023/6676953

Karimanzira, D. (2025). Comprehensive fish feeding management in pond aquaculture based on fish feeding behavior analysis using a vision language model. *Aquaculture Journal*, *5*(3), Article 15. https://doi.org/10.3390/aquacj5030015

Kartika, B., Parson, S. W., Kassim, Z., & Chowdhury, A. J. K. (2022). Overview of halal freshwater aquaculture system: Malaysian perspectives. *Water Conservation and Management*, *6*(1), 01–05. https://doi.org/10.26480/wcm.02.2022.01.05

Khairi, A. K. M. (2018). *Examination of Internet of Things adoption among aquaculturist in Malaysia* [Master's thesis, Universiti Utara Malaysia]. Universiti Utara Malaysia Institutional Repository. https://etd.uum.edu.my/8412/2/s94581_01.pdf

Khanjani, M. H., & Sharifinia, M. (2020). Biofloc technology as a promising tool to improve aquaculture production. *Reviews in Aquaculture*, *12*(3), 1836–1850. https://doi.org/10.1111/raq.12412

Khanjani, M. H., Sharifinia, M., & Ghaedi, G. (2022a). β-glucan as a promising food additive and immunostimulant in aquaculture industry. *Annals of Animal Science*, *22*(3), 817–827. https://doi.org/10.2478/aoas-2021-0083

Khanjani, M. H., Zahedi, S., & Mohammadi, A. (2022b). Integrated multitrophic aquaculture (IMTA) as an environmentally friendly system for sustainable aquaculture: functionality, species, and application of biofloc technology (BFT). *Environmental Science and Pollution Research*, *29*(45), 67513–67531. https://doi.org/10.1007/s11356-022-22371-8

Kibria, A. S. M., & Haque, M. M. (2018). Potentials of integrated multi-trophic aquaculture (IMTA) in freshwater ponds in Bangladesh. *Aquaculture Reports*, *11*, 8–16. https://doi.org/10.1016/j.aqrep.2018.05.004

Kingsbury, M., Marteinson, S., Ryall, E., & Hamoutene, D. (2024). Considerations and data update for the inference of environmental quality standards for two avermectins widely used in salmon aquaculture. *Marine Pollution Bulletin*, *201*, Article 116213. https://doi.org/10.1016/j.marpolbul.2024.116213

Kua, B. C., Noordin, W. N. M., Bakar, P., Othman, A. B., & Yahya, R. A. (2024). Environmentally friendly alternatives to chemicals in aquatic animal health management: Malaysian experiences. *Malaysian Fisheries Journal*, *24*, 1–20.

Kurniawan, S. B., Abdullah, S. R. S., Imron, M. F., Said, N. S. M., Ismail, N. I., Hasan, H. A., ... Purwanti, I. F. (2020). Challenges and opportunities of biocoagulant/bioflocculant application for drinking water and wastewater treatment and its potential for sludge recovery. *International Journal of Environmental Research and Public Health*, *17*(24), Article 9312. https://doi.org/10.3390/ijerph17249312

Kurniawan, S. B., Ahmad, A., Rahim, N. F. M., Said, N. S. M., Alnawajha, M. M., Imron, M. F., ... Hasan, H. A. (2021a). Aquaculture in Malaysia: Water-related environmental challenges and opportunities for cleaner production. *Environmental Technology & Innovation*, *24*, Article 101913. https://doi.org/10.1016/j.eti.2021.101913

Kurniawan, S. B., Ahmad, A., Said, N. S. M., Imron, M. F., Abdullah, S. R. S., Othman, A. R., ... Hasan, H. A. (2021b). Macrophytes as wastewater treatment agents: Nutrient uptake and potential of produced biomass utilization toward circular economy initiatives. *Science of The Total Environment*, *790*, Article 148219. https://doi.org/10.1016/j.scitotenv.2021.148219

Lal, J., Vaishnav, A., Kumar, D., Jana, A., Jayaswal, R., Chakraborty, A., ... Pavankalyan, M. (2024). Emerging innovations in aquaculture: Navigating towards sustainable solutions. *International Journal of Environment and Climate Change*, *14*(7), 83–96. https://doi.org/10.9734/ijecc/2024/v14i74254

Leng, S. T. K., Weng, C. N., Tan, M. L., Wee, S. T., & Samat, N. (2020). Consumer awareness and acceptance of aquaculture practices and products in Penang, Malaysia. *European Proceedings of Social and Behavioural Sciences*, 584–593. https://doi.org/10.15405/epsbs.2020.10.02.68

Li, H., Ma, X., Tang, Y., Wang, D., Zhang, Z., & Liu, Z. (2021). Network-based analysis of virulence factors for uncovering *Aeromonas veronii* pathogenesis. BMC Microbiology, *21*(1), 188. https://doi.org/10.1186/s12866-021-02261-8

Li, D., Wang, Z., Wu, S., Miao, Z., Du, L., & Duan, Y. (2020). Automatic recognition methods of fish feeding behavior in aquaculture: A review. *Aquaculture*, *528*, Article 735508. https://doi.org/10.1016/j.aquaculture.2020.735508

Lim, J. H., & Majid, H. A. (2021). IoT monitoring system for aquaculture farming. *Progress in Engineering Application and Technology*, *2*(1), 567–577. https://doi.org/10.1051/matecconf/202237204009

Liu, L., Zhang, Y., Yuan, M. D., Xiao, D. M., Xu, W. H., Zheng, Q., ... Huang, X. H. (2024). Integrated multi-omics analysis reveals liver metabolic reprogramming by fish iridovirus and antiviral function of alpha-linolenic acid. *Zoological Research*, *45*(3), 565–578. https://doi.org/10.24272/j.issn.2095-8137.2024.028

Loh, C. Y., Koe, A. Z. Y., Lim, W. J., & Ooi, B. S. (2023). Recovery of ammonia and phosphate from aquaculture effluent using a reactive vacuum membrane distillation-vacuum membrane distillation/nanofiltration hybrid system. *Separation and Purification Technology*, *327*, Article 124893. https://doi.org/10.1016/j.seppur.2023.124893

Lola, M. S., Isa, S. H., Ramlee, M. N. A., & Ikhwanuddin, M. (2017). Sustainability of integrated aquaculture development project using system dynamic approach. *Journal of Sustainability Science and Management*, *12*(2), 194–203.

Macusi, E. D., Cayacay, M. A., Borazon, E. Q., Sales, A. C., Habib, A., Fadli, N., & Santos, M. D. (2023). Protein fishmeal replacement in aquaculture: A systematic review and implications on growth and adoption viability. *Sustainability*, *15*(16), Article 12500. https://doi.org/10.3390/su151612500

Manaf, M. S. A., & Omar, A. F. M. (2015). Status and development and use of alternative dietary ingredients in aquaculture feed formulation in Malaysia. In *Development and Use of Alternative Dietary Ingredients or Fish Meal Substitutes in Aquaculture Feed Formulation: Proceedings of the ASEAN Regional Technical Consultation* (pp. 15-22). Aquaculture Department, Southeast Asian Fisheries Development Center.

Manan, H., Jalilah, M., Fauzan, F., Ikhwanuddin, M., Amin-Safwan, A., Abdullah, N. S., ... Kasan, N. A. (2023). Recent developments in aquaculture–A review. *Annals of Animal Science*, *23*(3), 663–680. https://doi.org/10.2478/aoas-2023-0044

Manap, M. G. A., & Pauzi, M. F. A. (2020). myGAP: Malaysia's gift to seafood world. *IOP Conference Series: Earth and Environmental Science*, *414*(1), Article 012012. https://doi.org/10.1088/1755-1315/414/1/012012

Media Selangor. (2024, September 23). *Fisheries Act amendment aims to enhance biosecurity, regulate aquaculture*. https://mediaselangor.com/en/2024/09/234200/fisheries-act-amendment-aims-to-enhance-biosecurity-regulate-aquaculture/

Medipally, S. R., Yusoff, F. M., Sharifhuddin, N., & Shariff, M. (2016). Sustainable aquaculture of Asian arowana--a review. *Journal of Environmental Biology*, *37*(4), 829–838.

Meitei, M. M., Muralidhar, A. P., Syamala, K., Sureesh, S., Biswas, G., Megarajan, S., & Munilkumar, S. (2025). Assessment of filtration capacity of different bivalve species suitable for integrated multi-trophic aquaculture (IMTA) systems vis-à-vis waste valorization for sustainable environment. *Discover Sustainability*, *6*(1), 1–16. https://doi.org/10.1007/s43621-025-01104-0

Merican, Z. (2021, May 5). *Aquafeeds in 2019: Pulled by market demand*. Aquaculture Asia Pacific. https://aquaasiapac.com/2021/05/05/aquafeeds-in-2019-pulled-by-market-demand/

Mohamad, S. N., Noordin, W. N. M., Ismail, N. F., & Hamzah, A. Z. H. A. R. (2021). Red hybrid tilapia (*Oreochromis* spp.) broodstock development programme in Malaysia: Status, challenges and prospects for future development. *Asian Fisheries Science*, *34*, 73–81. https://doi.org/10.33997/j.afs.2021.34.1.008

Mohan, K., Rajan, D. K., Ganesan, A. R., Divya, D., Johansen, J., & Zhang, S. (2023). Chitin, chitosan and chitooligosaccharides as potential growth promoters and immunostimulants in aquaculture: A comprehensive review. *International Journal of Biological Macromolecules*, *253*, Article 126285. https://doi.org/10.1016/j.ijbiomac.2023.126285

Mohd Khatib, M. A., & Jais, A. M. M. (2021). A brief overview of the integrated fish farming of three commercially popular fish species (snakehead, Tilapia and catfish) in Malaysia. *Malaysian Journal of Applied Sciences*, *6*(2), 105–112. https://doi.org/10.37231/myjas.2021.6.2.301

Mohd, F. O. (2017). Transforming the aquaculture industry in Malaysia. *World Aquaculture*, *48*(2), 16–17.

Mok, W. J., Zainia, R. M., Tan, C. P., & Zulkipli, S. Z. (2021). Selected non-essential and trace elements concentration in trash fish and aquafeeds. *Aquaculture, Aquarium, Conservation & Legislation*, *14*(1), 189–196.

Mokhtar, Z., Idris, S. H., Kenway, S., & Pikaar, I. (2024). Analysing the regulatory mechanisms of river pollution in Malaysia. *International Journal of Business, Economics and Law*, *31*(1), 23–37.

MOSTI. (2015). *National Internet of Things (IoT) Strategic Roadmap*. MIMOS. http://mimos.my/iot/National_IoT_Strategic_Roadmap_Book.pdf

Mulazzani, L., Arru, B., Camanzi, L., Furesi, R., Malorgio, G., Pulina, P., & Madau, F. A. (2023). Factors influencing consumption intention of insect-fed fish among Italian respondents. *Foods*, *12*(17), Article 3301. https://doi.org/10.3390/foods12173301

Munguti, J. M., Kirimi, J. G., Obiero, K. O., Ogello, E. O., Kyule, D. N., Liti, D. M., & Musalia, L. M. (2021). Aqua-feed wastes: Impact on natural systems and practical mitigations—A review. *Journal of Agricultural Science*, *13*(1), 111–124. https://doi.org/10.5539/jas.v13n1p111

Mustafa, S., Yusoff, N. H. N., Kua, B. C., Abdullah, A., & Ramly, R. (2021). Country report aquatic animal health in Malaysia. In *Proceedings of the International Workshop on the Promotion of Sustainable Aquaculture, Aquatic Animal Health, and Resource Enhancement in Southeast Asia* (p. 148). Aquaculture Department, Southeast Asian Fisheries Development Center. http://hdl.handle.net/10862/6267

Nam, S. E., Bae, D. Y., Ki, J. S., Ahn, C. Y., & Rhee, J. S. (2023). The importance of multi-omics approaches for the health assessment of freshwater ecosystems. *Molecular & Cellular Toxicology*, *19*(1), 3–11. https://doi.org/10.1007/s13273-022-00286-2

Nasir, N. M., Yunos, F. H. M., Jusoh, H. H. W., Mohammad, A., Lam, S. S., & Jusoh, A. (2019). Subtopic: Advances in water and wastewater treatment harvesting of *Chlorella* sp. microalgae using *Aspergillus niger* as bio-flocculant for aquaculture wastewater treatment. *Journal of Environmental Management*, *249*, Article 109373. https://doi.org/10.1016/j.jenvman.2019.109373

Nasr-Eldahan, S., Nabil-Adam, A., Shreadah, M. A., Maher, A. M., & El-Sayed Ali, T. (2021). A review article on nanotechnology in aquaculture sustainability as a novel tool in fish disease control. *Aquaculture International*, *29*(4), 1459–1480. https://doi.org/10.1007/s10499-021-00677-7

Natnan, M. E., Mayalvanan, Y., Jazamuddin, F. M., Aizat, W. M., Low, C. F., Goh, H. H., ... Baharum, S. N. (2021a). Omics strategies in current advancements of infectious fish disease management. *Biology*, *10*(11), Article 1086. https://doi.org/10.3390/biology10111086

Natnan, M. E., Low, C. F., Chong, C. M., Bunawan, H., & Baharum, S. N. (2021b). Integration of omics tools for understanding the fish immune response due to microbial challenge. *Frontiers in Marine Science*, *8*, Article 668771. https://doi.org/10.3389/fmars.2021.668771

Natrah, I., Muthukrishnan, S., Mohd-Padil, H., Mohamad, N., Alipiah, N. M., Shariff, M., ... Defoirdt, T. (2025). Antimicrobial resistance in Malaysian shrimp aquaculture and strategies to reduce its occurrence. *Reviews in Aquaculture*, *17*(3), Article e70020. https://doi.org/10.1111/raq.70020

Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., ... Troell, M. (2021). A 20-year retrospective review of global aquaculture. *Nature*, *591*(7851), 551–563. https://doi.org/10.1038/s41586-021-03308-6

Nephale, L. E., Moyo, N. A. G., & Rapatsa-Malatji, M. M. (2024). Partial replacement of fish meal with soldier termite in juvenile Mozambique tilapia: Effects on growth performance, blood serum chemistry and histomorphology. *Journal of Animal and Feed Sciences*, *33*(2), 243–252. https://doi.org/10.22358/jafs/175919/2024

Ng, A., Firouz, A. M. M., Khalidi, J. R., Muhtar, M. A., Tumin, S. A., Man, T. K., ... Gen, T. Z. (2018). *The state of households 2018: Different realities*. Khazanah Research Institute.

Nogales-Mérida, S., Gobbi, P., Józefiak, D., Mazurkiewicz, J., Dudek, K., Rawski, M., Kierończyk, B., & Józefiak, A. (2019). Insect meals in fish nutrition. *Reviews in Aquaculture*, *11*(4), 1080–1103. https://doi.org/10.1111/raq.12281

Noordin, W. N. M., Misol Jr, G., & Johari, R. (2020). Aquaculture component of National Action Plan on antimicrobial resistance in Malaysia. *Asian Fisheries Science*, *33*, 90–96. https://doi.org/10.33997/j.afs.2020.33.S1.013

Obi, C., Dompreh, E. B., Manyise, T., Tan, S. H., Woo, S. P., & Rossignoli, C. M. (2025). Overview of the fishery and aquaculture sectors in Malaysia. *Frontiers in Sustainable Food Systems*, *9*, Article 1545263. https://doi.org/10.3389/fsufs.2025.1545263

O'Donncha, F., & Grant, J. (2019). Precision aquaculture. *IEEE Internet of Things Magazine*, *2*(4), 26–30. https://doi.org/10.1109/IOTM.0001.1900033

Okomoda, V. T., Oladimeji, S. A., Solomon, S. G., Olufeagba, S. O., Ogah, S. I., & Ikhwanuddin, M. (2023). Aquaponics production system: A review of historical perspective, opportunities, and challenges of its adoption. *Food Science & Nutrition*, *11*(3), 1157–1165. https://doi.org/10.1002/fsn3.3154

Omar, T. F. T., Aris, A. Z., Yusoff, F. M., & Mustafa, S. (2019). Occurrence and level of emerging organic contaminant in fish and mollusk from Klang River estuary, Malaysia and assessment on human health risk. *Environmental Pollution*, *248*, 763–773. https://doi.org/10.1016/j.envpol.2019.02.060

Overton, K., Dempster, T., Swearer, S. E., Morris, R. L., & Barrett, L. T. (2024). Achieving conservation and restoration outcomes through ecologically beneficial aquaculture. *Conservation Biology*, *38*(1), Article e14065. https://doi.org/10.1111/cobi.14065

Paolacci, S., Stejskal, V., Toner, D., & Jansen, M. A. (2022). Wastewater valorisation in an integrated multitrophic aquaculture system; assessing nutrient removal and biomass production by duckweed species. *Environmental Pollution*, *302*, Article 119059. https://doi.org/10.1016/j.envpol.2022.119059

Peh, K. L., Shapawi, R., & Lim, L. S. (2021). Black cricket (*Gryllus bimaculatus*) meal as a protein source in the practical diets for juvenile whiteleg shrimp (*Litopenaeus vannamei*). *Iranian Journal of Fisheries Sciences*, *20*(3), 731–740. https://doi.org/10.22092/ijfs.2021.124045

Perera, G. C., & Bhujel, R. C. (2022). Replacement of fishmeal by house cricket (*Acheta domesticus*) and field cricket (*Gryllus bimaculatus*) meals: Effect for growth, pigmentation, and breeding performances of guppy (*Poecilia reticulata*). *Aquaculture Reports*, *25*, Article 101260. https://doi.org/10.1016/j.aqrep.2022.101260

Perera, G. S. C., Athukorala, D. A., Ashinsani, M. N., & Sandeepani, D. G. (2025). Substituting the fishmeal with solid-state-fermented Black soldier fly (*Hermetia illucens*) larvae meal in GIFT tilapia (*Oreochromis niloticus*) fry diet: Effects for growth performance, carcass composition and liver histology. *Annals of Animal Science*, *25*(3), 1129–1139. https://doi.org/10.2478/aoas-2025-0031

Perillo, G. M., Botero, C. M., Milanes, C. B., Elliff, C. I., Cervantes, O., Zielinski, S., ... Glavovic, B. C. (2021). Integrated coastal zone management in the context of COVID-19. *Ocean & Coastal Management*, *210*, Article 105687. https://doi.org/10.1016/j.ocecoaman.2021.105687

Petrosillo, I., Scardia, A. M. S., Ungaro, N., Specchiulli, A., Fanelli, G., Centoducati, G., ... Mossa, M. (2023). Towards sustainable marine spatial planning of aquaculture. *Ecological Indicators*, *154*, Article 110542. https://doi.org/10.1016/j.ecolind.2023.110542

Pradeepkiran, J. A. (2019). Aquaculture role in global food security with nutritional value: A review. *Translational Animal Science*, *3*(2), 903–910. https://doi.org/10.1093/tas/txz012

Qi, Z., Shi, R., Yu, Z., Han, T., Li, C., Xu, S., ... Huang, H. (2019). Nutrient release from fish cage aquaculture and mitigation strategies in Daya Bay, southern China. *Marine Pollution Bulletin*, *146*, 399–407. https://doi.org/10.1016/j.marpolbul.2019.06.079

Quimpo, T. J. R., Ligson, C. A., Manogan, D. P., Requilme, J. N. C., Albelda, R. L., Conaco, C., & Cabaitan, P. C. (2020). Fish farm effluents alter reef benthic assemblages and reduce coral settlement. *Marine Pollution Bulletin*, *153*, Article 111025. https://doi.org/10.1016/j.marpolbul.2020.111025

Radhi, A. M., Rohasliney, H., & Zarul, H. (2017). Fish composition and diversity in Perak, Galas and Kelantan rivers (Malaysia) after the major flood of 2014. *Transylvanian Review of Systematical and Ecological Research*, *19*(3), 41–56. https://doi.org/10.1515/trser-2017-0020

Raghuvaran, N., Varghese, T., Jana, P., RJ, A. B., Sudarshan, S., Alrashdi, Y. B. A., Ibrahim, A. E., & El Deeb, S. (2024). Current status and global research trend patterns of insect meal in aquaculture from scientometric perspective: (2013–2022). *Aquaculture Nutrition*, *2024*, Article 5466604. https://doi.org/10.1155/2024/5466604

Raman, R. P. (2017). Applicability, feasibility and efficacy of phytotherapy in aquatic animal health management. *American Journal of Plant Sciences*, *8*(2), 257–273. http://dx.doi.org/10.4236/ajps.2017.82019

Rashvinjeet, S. B. (2024, January 8). *IN FOCUS: Falling fish catch in Malaysia spells trouble for industry, region; highlights need for sustainable practices*. Channel News Asia (CNA). https://www.channelnewsasia.com/asia/malaysia-fishing-industry-fishermen-food-climate-change-sustainability-4056331

Rasmussen, J. A., Villumsen, K. R., Ernst, M., Hansen, M., Forberg, T., Gopalakrishnan, S., ... Limborg, M. T. (2022). A multi-omics approach unravels metagenomic and metabolic alterations of a probiotic and synbiotic additive in rainbow trout (*Oncorhynchus mykiss*). *Microbiome*, *10*(1), Article 21. https://doi.org/10.1186/s40168-021-01221-8

Rastegari, H., Nadi, F., Lam, S. S., Ikhwanuddin, M., Kasan, N. A., Rahmat, R. F., & Mahari, W. A. W. (2023). Internet of Things in aquaculture: A review of the challenges and potential solutions based on current and future trends. *Smart Agricultural Technology*, *4*, Article 100187. https://doi.org/10.1016/j.atech.2023.100187

Rather, M. A., Agarwal, D., Kumar, S., & Sundaray, J. K. (2022). Nanobiotechnology: Prospects and applications in aquaculture. In *Advances in fisheries biotechnology* (pp. 197–210). Springer Nature Singapore.. https://doi.org/10.1007/978-981-16-3215-0_14

Rather, M. A., Ahmad, I., Shah, A., Hajam, Y. A., Amin, A., Khursheed, S., ... Rasool, S. (2024). Exploring opportunities of Artificial Intelligence in aquaculture to meet increasing food demand. *Food Chemistry: X*, *21*, Article 101309. https://doi.org/10.1016/j.fochx.2024.101309

Razak, R. A., Shariff, M., Yusoff, F. M., & Ismail, I. S. (2019). Bactericidal efficacy of selected medicinal plant crude extracts and their fractions against common fish pathogens. *Sains Malaysiana*, *48*(8), 1601–1608. http://dx.doi.org/10.17576/jsm-2019-4808-05

Ridzuan, M. S. M., Abdullah, A., Ramly, R., Mansor, N. N., Ramli, N., & Firdaus-Nawi, M. (2022). Current status and advances of fish vaccines in Malaysia. *Veterinary World*, *15*(2), 465–482. https://doi.org/10.14202/vetworld.2022.465-482

Rosilan, N. F., Waiho, K., Fazhan, H., Sung, Y. Y., Nor, S. A. M., Muhammad, N. A. N., ... Afiqah-Aleng, N. (2023). Protein-protein interaction network analysis on the whiteleg shrimp *Penaeus vannamei* and *Vibrio parahaemolyticus* host-pathogen relationship reveals possible proteins and pathways involved during infection. *Aquaculture Reports*, *30*, Article 101583. https://doi.org/10.1016/j.aqrep.2023.101583

Rosita, H. (2017). *Climate change and the aquaculture sector of Sarawak* (Doctoral dissertation, University of Malaya). Universiti Malaya Students Repository. https://studentsrepo.um.edu.my/8316/

Rusco, G., Roncarati, A., Di Iorio, M., Cariglia, M., Longo, C., & Iaffaldano, N. (2024). Can IMTA system improve the productivity and quality traits of aquatic organisms produced at different trophic levels? The benefits of IMTA—Not only for the ecosystem. *Biology*, *13*(11), Article 946. https://doi.org/10.3390/biology13110946

Sabjan, A., Lee, L. K., See, K. F., & Wee, S. T. (2022). Comparison of three water indices for tropical aquaculture ponds extraction using google earth engine. *Sains Malaysiana*, *51*(2), 369–378. http://dx.doi.org/10.17576/jsm-2022-5102-04

Sakinah, D. N., Aidilla, M., Zahidah, Z., Jung, I. H., & Hanum, A. N. A. (2024). Mathematical programming for an optimised fish feed formulation: Towards sustainable red hybrid tilapia farming. *Journal of Sustainable Science and Management*, *19*(4), 57–72. http://doi.org/10.46754/jssm.2024.04.006

Samah, R., & Kamaruddin, R. (2015). The influence of socio-demographic factors in adopting good aquaculture practices: Case of aquaculture farmers in Malaysia. *Journal of Sustainable Development*, *8*(9), 97–105. https://doi.org/10.5539/jsd.v8n9p97

Sany, S. B. T., Tajfard, M., Rezayi, M., Rahman, M. A., & Hashim, R. (2019). The west coast of Peninsular Malaysia. In *World seas: An environmental evaluation* (pp. 437–458). Academic Press. https://doi.org/10.1016/B978-0-08-100853-9.00050-6

Sarkar, B., Mahanty, A., Gupta, S. K., Choudhury, A. R., Daware, A., & Bhattacharjee, S. (2022). Nanotechnology: A next-generation tool for sustainable aquaculture. *Aquaculture*, *546*, Article 737330. https://doi.org/10.1016/j.aquaculture.2021.737330

Sasikaladevi, R., Kiruthika Eswari, V., & Nambi, I. M. (2020). Antibiotic resistance and sanitation in India: Current situation and future perspectives. *Antibiotic Resistance in the Environment: A Worldwide Overview*, 217–244. https://doi.org/10.1007/698_2020_608

SEAFDEC. (2022). *Fisheries country profile: Malaysia*. http://www.seafdec.org/fisheries-country-profile-malaysia/

Shaffril, H. A. M., Samah, A. A., & D'Silva, J. L. (2017). Adapting towards climate change impacts: Strategies for small-scale fishermen in Malaysia. *Marine Policy*, *81*, 196–201. https://doi.org/10.1016/j.marpol.2017.03.032

Shah, B. R., & Mraz, J. (2020). Advances in nanotechnology for sustainable aquaculture and fisheries. *Reviews in Aquaculture*, *12*(2), 925–942. https://doi.org/10.1111/raq.12356

Shaalan, M., Saleh, M., El-Mahdy, M., & El-Matbouli, M. (2016). Recent progress in applications of nanoparticles in fish medicine: A review. *Nanomedicine: Nanotechnology, Biology and Medicine*, *12*(3), 701–710. https://doi.org/10.1016/j.nano.2015.11.005

Shen, Y., & Yue, G. (2019). Current status of research on aquaculture genetics and genomics—Information from ISGA 2018. *Aquaculture and Fisheries*, *4*(2), 43–47. https://doi.org/10.1016/j.aaf.2018.11.001

Sin, M. S., & Yew, T. S. (2016). Assessing the exploitation status of marine fisheries resources for the west coast of peninsular Malaysia trawl fishery. *World Journal of Fish and Marine Sciences*, *8*(2), 98–107. https://doi.org/10.5829/idosi.wjfms.2016.8.2.102149

Siow, R., Nurridan, A. H., Hadil, R., & Richard, R. (2020). The establishment of fisheries refugia as a new approach to sustainable management of fisheries in Malaysian waters. *IOP Conference Series: Earth and Environmental Science*, *414*(1), Article 012023. https://doi.org/10.1088/1755-1315/414/1/012023

Siva, S. (2021, January 11). There aren't plenty fish in the sea anymore, Malaysians warned. *Malaysia Now*. https://www.malaysianow.com/news/2021/01/11/there-arent-plenty-fish-in-the-sea-anymore-malaysians-warned

Solaymani, S. (2018). Impacts of climate change on food security and agriculture sector in Malaysia. *Environment, Development and Sustainability*, *20*(4), 1575–1596. https://doi.org/10.1007/s10668-017-9954-4

Ssepuuya, G., Sebatta, C., Sikahwa, E., Fuuna, P., Sengendo, M., Mugisha, J., Fiaboe, K. K. M., & Nakimbugwe, D. (2019). Perception and awareness of insects as an alternative protein source among fish farmers and fish feed traders. *Journal of Insects as Food and Feed*, *5*(2), 107–116. https://doi.org/10.3920/JIFF2017.0056

Su, X., Sutarlie, L., & Loh, X. J. (2020). Sensors, biosensors, and analytical technologies for aquaculture water quality. *Research*, *2020*, Article 8272705. https://doi.org/10.34133/2020/8272705

Suzuki, A. (2021). *Rising importance of aquaculture in Asia: Current status, issues, and recommendations* (Asian Development Outlook Update Background Paper). Asian Development Bank.

Suzuki, A., & Hoang Nam, V. (2018). Better management practices and their outcomes in shrimp farming: Evidence from small-scale shrimp farmers in Southern Vietnam. *Aquaculture International*, *26*(2), 469–486. https://doi.org/10.1007/s10499-017-0228-9

Syukri, F., Hassan, N. H., & Ani, A. S. N. (2022). Performances of FS feed, *Artemia* nauplii and commercial. *Journal of Sustainable Science and Management*, *17*(2), 35–45. http://doi.org/10.46754/jssm.2022.02.004

Tan, S. Y., Sethupathi, S., Leong, K. H., & Ahmad, T. (2024). Challenges and opportunities in sustaining aquaculture industry in Malaysia. *Aquaculture International*, *32*(1), 489–519. https://doi.org/10.1007/s10499-023-01173-w

Tang, K. H. D. (2019). Climate change in Malaysia: Trends, contributors, impacts, mitigation and adaptations. *Science of the Total Environment*, *650*, 1858–1871. https://doi.org/10.1016/j.scitotenv.2018.09.316

Tengku Hashim, T. M. Z., Engku Ariff, E. A. R., & Suratman, M. N. (2021). Aquaculture in mangroves. *Mangroves: Ecology, Biodiversity and Management*, 419–438. https://doi.org/10.1007/978-981-16-2494-0_18

The Fish Site. (2023, November 28). *Veolia's insect meal and oil gain EU aquafeed approval*. https://thefishsite.com/articles/veolias-insect-meal-and-oil-gain-eu-aquafeed-approval

The Star. (2023, November 3). *Fish catch is fast declining*. https://www.thestar.com.my/news/nation/2023/11/03/fish-catch-is-fast-declining

The Straits Times. (2023, November 3). *Fish catches in Malaysia declining due to climate change*. https://www.straitstimes.com/asia/se-asia/fish-catches-in-malaysia-declining-due-to-climate-change

Thépot, V., Campbell, A. H., Rimmer, M. A., & Paul, N. A. (2021). Meta-analysis of the use of seaweeds and their extracts as immunostimulants for fish: A systematic review. *Reviews in Aquaculture*, *13*(2), 907–933. https://doi.org/10.1111/raq.12504

Thiang, E. L., Lee, C. W., Takada, H., Seki, K., Takei, A., Suzuki, S., ... Bong, C. W. (2021). Antibiotic residues from aquaculture farms and their ecological risks in Southeast Asia: A case study from Malaysia. *Ecosystem Health and Sustainability*, *7*(1), Article 1926337. https://doi.org/10.1080/20964129.2021.1926337

Tom, A. P., Jayakumar, J. S., Biju, M., Somarajan, J., & Ibrahim, M. A. (2021). Aquaculture wastewater treatment technologies and their sustainability: A review. *Energy Nexus*, 4, Article 1000022. https://doi.org/10.1016/j.nexus.2021.100022

United Nations. (2015). *United Nations Sustainable Development Goals*. United Nations Development Programme. https://www.undp.org/sustainable-development-goals

Van Huis, A. (2020). Insects as food and feed, a new emerging agricultural sector: A review. *Journal of Insects as Food and Feed*, *6*(1), 27–44. https://doi.org/10.3920/JIFF2019.0017

Vijayaram, S., Ringø, E., Zuorro, A., van Doan, H., & Sun, Y. (2023). Beneficial roles of nutrients as immunostimulants in aquaculture: A review. *Aquaculture and Fisheries*, *9*(5), 707–720. https://doi.org/10.1016/j.aaf.2023.02.001

Waiho, K., Fazhan, H., Ishak, S. D., Kasan, N. A., Liew, H. J., Norainy, M. H., & Ikhwanuddin, M. (2020). Potential impacts of COVID-19 on the aquaculture sector of Malaysia and its coping strategies. *Aquaculture*

Reports, *18*, Article 100450. https://doi.org/10.1016/j.aqrep.2020.100450

Waiho, K., Afiqah-Aleng, N., Iryani, M. T. M., & Fazhan, H. (2021). Protein–protein interaction network: An emerging tool for understanding fish disease in aquaculture. *Reviews in Aquaculture*, *13*(1), 156–177. https://doi.org/10.1111/raq.12468

Wang, L., Xu, X., Zhang, Z., Li, K., Yang, Y., Zheng, W., ... Chen, S. (2022). Transcriptome analysis and protein-protein interaction in resistant and susceptible families of Japanese flounder (*Paralichthys olivaceus*) to understand the mechanism against *Edwardsiella tarda*. *Fish & Shellfish Immunology*, *123*, 265–281. https://doi.org/10.1016/j.fsi.2022.02.055

Wang, X., Cuthbertson, A., Gualtieri, C., & Shao, D. (2020). A review on mariculture effluent: Characterization and management tools. *Water*, *12*(11), Article 2991. https://doi.org/10.3390/w12112991

Weitzman, J., & Filgueira, R. (2020). The evolution and application of carrying capacity in aquaculture: Towards a research agenda. *Reviews in Aquaculture*, *12*(3), 1297–1322. https://doi.org/10.1111/raq.12383

Witus, I. W., & Vun, L. W. (2016). Aquaculture in Malaysia: A short review on current policy and legislation. *Transactions on Science and Technology*, *3*(1-2), 150–154. http://www.transectscience.org/pdfs/vol3/no1_2/31-2_150_154.pdf

Wong, H. S., & Yong, C. C. (2020). Fisheries regulation: A review of the literature on input controls, the ecosystem, and enforcement in the Straits of Malacca of Malaysia. *Fisheries Research*, *230*, Article 105682. https://doi.org/10.1016/j.fishres.2020.105682

Yang, H., Tang, B., Zhou, H., Zhong, P., & Zhao, L. (2025). Research on the construction of an Integrated Multi-Trophic Aquaculture (IMTA) model in seawater ponds and its impact on the aquatic environment. *Water*, *17*(6), Article 887. https://doi.org/10.3390/w17060887

Yavuzcan Yildiz, H., Robaina, L., Pirhonen, J., Mente, E., Domínguez, D., & Parisi, G. (2017). Fish welfare in aquaponic systems: Its relation to water quality with an emphasis on feed and faeces—A review. *Water*, *9*(1), Article 13. https://doi.org/10.3390/w9010013

Ytteborg, E., Falconer, L., Krasnov, A., Johansen, L. H., Timmerhaus, G., Johansson, G. S., ... Lazado, C. C. (2023). Climate change with increasing seawater temperature will challenge the health of farmed Atlantic Cod (*Gadus morhua* L.). *Frontiers in Marine Science*, *10*, Article 1232580. https://doi.org/10.3389/fmars.2023.1232580

Yue, K., & Shen, Y. (2022). An overview of disruptive technologies for aquaculture. *Aquaculture and Fisheries*, *7*(2), 111–120. https://doi.org/10.1016/j.aaf.2021.04.009

Yunus, K., Zuraidah, M. A., & John, A. (2020). A review on the accumulation of heavy metals in coastal sediment of Peninsular Malaysia. *Ecofeminism and Climate Change*, *1*(1), 21–35. https://doi.org/10.1108/EFCC-03-2020-0003

Yusoff, A. (2015). Status of resource management and aquaculture in Malaysia. In M. R. R. Romana-Eguia, F. D. Parado-Estepa, N. D. Salayo, & M. J. H. Lebata-Ramos (Eds.), *Resource Enhancement and Sustainable Aquaculture Practices in Southeast Asia: Challenges in Responsible Production of Aquatic Species: Proceedings of the International Workshop on Resource Enhancement and Sustainable Aquaculture Practices in Southeast Asia 2014 (RESA)* (pp. 53–65). Aquaculture Dept., Southeast Asian Fisheries Development Center. http://hdl.handle.net/10862/2763

Zainorahim, N., Taufek, N. M., Ganesan, P. B., & Tan, G. Y. A. (2024). *Hermetia illucens* larvae meal as partial fishmeal replacement in Jade Perch diet cultured in biofloc: Growth performance, feed efficiency and consumer acceptance. *Sains Malaysiana*, *53*(3), 501–518. http://doi.org/10.17576/jsm-2024-5303-03

Zarantoniello, M., Randazzo, B., Truzzi, C., Giorgini, E., Marcellucci, C., Vargas-Abúndez, J. A., Zimbelli, A., Annibaldi, A., Parisi, G., Tulli, F., & Riolo, P. (2019). A six-months study on Black Soldier Fly (*Hermetia illucens*) based diets in zebrafish. *Scientific Reports*, *9*(1), Article 8598. https://doi.org/10.1038/s41598-019-45172-5

Zhang, H., Liu, Y., Gui, F., & Yang, X. (2023). A universal aquaculture environmental anomaly monitoring system. *Sustainability*, *15*(7), Article 5678. https://doi.org/10.3390/su15075678

Zhang, M. Q., Yang, J. L., Lai, X. X., Li, W., Zhan, M. J., Zhang, C. P., ... Shu, H. (2022). Effects of integrated multi-trophic aquaculture on microbial communities, antibiotic resistance genes, and cultured species: A case study of four mariculture systems. *Aquaculture*, *557*, Article 738322. https://doi.org/10.1016/j.aquaculture.2022.738322

Zhao, J., Pan, J., Zhang, Z., Chen, Z., Mai, K., & Zhang, Y. (2023). Fishmeal protein replacement by defatted and full-fat black soldier fly larvae meal in juvenile turbot diet: Effects on the growth performance and intestinal microbiota. *Aquaculture Nutrition*, *2023*(1), Article 8128141. https://doi.org/10.1155/2023/8128141

Zhou, C., Xu, D., Chen, L., Zhang, S., Sun, C., Yang, X., & Wang, Y. (2019). Evaluation of fish feeding intensity in aquaculture using a convolutional neural network and machine vision. *Aquaculture*, *507*, 457–465. https://doi.org/10.1016/j.aquaculture.2019.04.056

Zhou, J. S., Liu, S. S., Ji, H., & Yu, H. B. (2018). Effect of replacing dietary fish meal with black soldier fly larvae meal on growth and fatty acid composition of Jian carp (*Cyprinus carpio* var. Jian). *Aquaculture Nutrition*, *24*(1), 424–433. https://doi.org/10.1111/anu.12574