Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.30018

315 (2023) 523–537
December

Contamination prevention in ASEAN aquaculture: a review of prospective challenges and mitigations

Wafi Diah[a,b], Cristalina Jalil Marsal[a], Wanidawati Tamat[b], Ahmed Jalal Khan Chowdhury[a,*]

[a]*Faculty of Agriculture, Sultan Sharif Ali Islamic University (UNISSA), Sinaut Campus TB 1741, Brunei Darussalam, email: ahmed.chowdhury@unissa.edu.bn (A.J.K. Chowdhury)*
[b]*Department of Fisheries, Ministry of Primary Resources and Tourism, Brunei Muara, BT 1728 Brunei Darussalam*

Received 20 August 2023; Accepted 22 October 2023

ABSTRACT

Over the past few decades, aquaculture activities have been expanding globally, including in the ASEAN region, to meet the growing demand for food. The demand for animal protein from the expanding human population is driving up trade in aquatic animal species and aquaculture. It is generally recognized that trading in live animals from aquaculture aids in the transboundary spread of infectious diseases, and the consequences can be severe if a pathogen extends its host range to new species towards new regions. Moving live aquatic animals is often thought to carry a higher risk of transmitting pathogens than moving processed or dead goods. However, the significant difficulties and problems have had an impact on this increase in productivity and faces massive challenges. The development of freshwater, marine and coastal areas through the stocking of aquatic animals raised in hatcheries, the increased globalization of trade and markets of post larvae, fry, fingerling, and brood-stock. The unanticipated interactions between cultured and wild populations of aquatic animals in the open and controlled conditions, poor or ineffective biosecurity measures and slow awareness on emerging detrimental infectious diseases due to the consequences of parasitic, bacterial, viral, and fungal infections. Furthermore, the misunderstanding and misuse of specific pathogen free (SPF) stocks, climate change and other human-mediated movements of aquaculture commodities. Due to fish mortality and sluggish growth caused by diseases, as well as the cost of disease control and mitigation, diseases have been one of the main reasons of economic losses encountered by aquaculture farmers and nation as well. In these contexts, this research-based review paper has discussed the prevailing challenges mitigation strategy used to combat all types of diseases, particularly parasitic infestations in ASEAN aquaculture exclusively some aspects of Brunei Darussalam. The authors provide pertinent examples of pathogen transfer leading to disease spread and consider the situation of emerging diseases, as well as the need for a holistic approach to deal with risk-based threats at their source for the sustainable development and effective commercialization of ASEAN aquaculture.

Keywords: ASEAN aquaculture; Biosecurity; Transboundary diseases; Disease prevention; Disease mitigation; Sustainable aquaculture and SDGs

1. Introduction

1.1. Importance of aquaculture

Aquaculture operations around the world have been increasing for the purpose of food production in the last few decades as demands for a good protein source in the world increase. It is also one of the fastest growing seafood production industries and it is almost catching up to capture fisheries in terms of production. In 2020, aquaculture contributed to almost 50% of the total production of seafood in the world as shown in Fig. 1 [1]. Even with the

* Corresponding author.

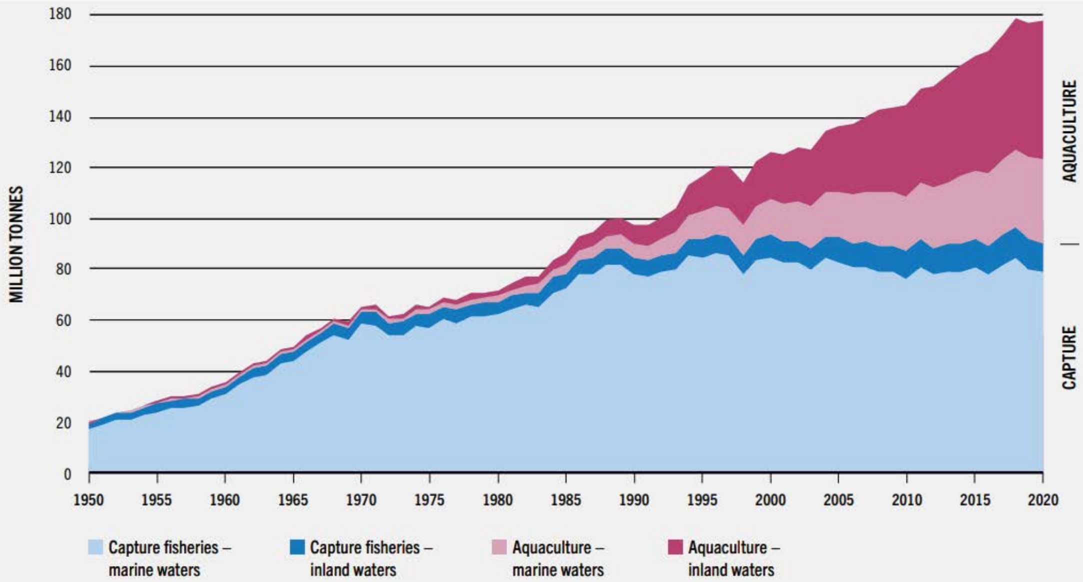


Fig. 1. Total world fisheries and aquaculture production from 1950 to 2020 [1]. Copyright 2022 by the Food and Agriculture Organisation of the United Nations (FAO).

spread of a global pandemic, aquaculture remains one of the fastest-growing seafood production industries as it still maintains its positive trend in 2020 [1]. Seafood production share in terms of quantity have been dominated by capture industries but it is not enough to cover the protein requirement of the world [2]. This is compounded by the active reduction of capturing fish for food.

In connection with this, SDG 14: Life Below Water of the United Nations Sustainable Development Goals clearly states one of the major problems to tackle is overfishing, where worldwide fish stocks have been overfished by more than 30% [3]. Moreover, to keep up with the demands for seafood that have been growing rapidly as the world population increases, aquaculture is seen as the most viable option to cover the difference left by capture fisheries production [4].

Interestingly, in developing countries with dense populations such as Egypt, Bangladesh, and Vietnam, aquaculture's importance is much more significant as it contributes to more than 50% of its total fisheries production [1]. As food demands increase in relation to the increasing world population, it highlights the importance of aquaculture even more in securing global food security as seafood is an important food source in numerous countries.

1.2. Global status of aquaculture

Global aquaculture production saw a yearly increase over the past decade, where the average annual production growth from 2011–2015 and 2016–2019 was at 5% and 3.7% respectively [2]. This steady growth was the result of the increase in aquaculture facilities adopting a more intensive production approach where commercial species are cultured in overcrowded, narrow, and enclosed spaces such as tanks, ponds, or cages. Global aquaculture production reached the highest value to date with 122.6 million tonnes of aquatic animals produced through aquaculture, which is equivalent to USD 264.8 billion in value [1].

From the total seafood production, the biggest producers were Asian countries with a share of 70%, with China being the most significant contributor [1]. Therefore, this suggests that aquaculture is a very important industry in the region. The most significant contributor to global aquaculture production is the production of seafood for human consumption and Fig. 2 shows its steady increase to 87.5 million tonnes in 2020 [1].

1.3. ASEAN aquaculture

Aquaculture is envisioned as the most probable solution to the decreasing fish stocks due to overfishing globally, and this thought is shared with most ASEAN countries. Indonesia had the biggest production of aquaculture products in 2019 (Table 1) with over 6 billion tonnes produced from brackish water, inland, and marine aquaculture while Brunei Darussalam had the smallest with a little over 972 tonnes but had a huge increase to around 3,500 tonnes in the year 2020, which is a 260% increase [5].

The three biggest aquaculture producers, in terms of value, within the ASEAN member states are still Indonesia being the largest and followed by Vietnam, and Thailand, and conversely, Brunei Darussalam had the least production value in the year 2021 as shown in Fig. 3. Indonesia has the biggest aquaculture production value with about USD 13.75 billion, followed by Vietnam and Thailand with USD 13.26 billion and USD 2.99 billion respectively [6]. In terms of the area of aquaculture farms, Vietnam has the largest area while Singapore has the smallest [7].

1.4 Aquaculture industry in Brunei Darussalam

Fisheries products have been one of the staples for Bruneian's protein source with a seafood consumption per capita of 47 kg in 2021 and a total production of 24,284.93 tonnes and almost 20% is from the aquaculture

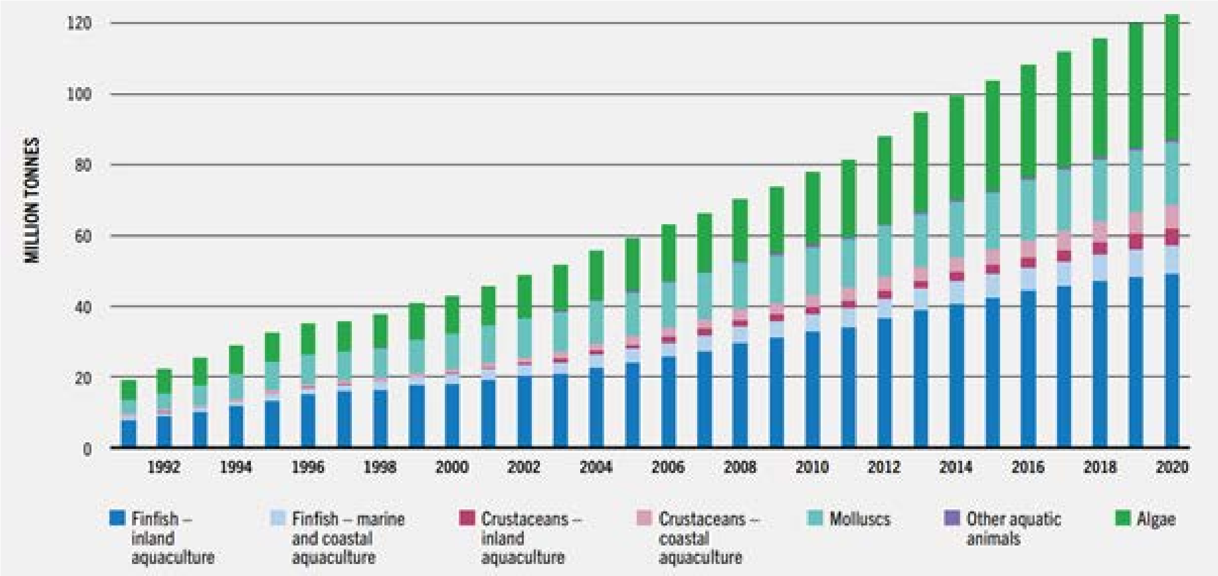


Fig. 2. World aquaculture production from 1992 to 2020 [1]. Copyright 2022 by the Food and Agriculture Organisation of the United Nations (FAO).

Table 1
Aquaculture production of Brunei Darussalam, Indonesia, Lao PDR, Malaysia, Myanmar, Singapore, and Thailand by quantity (t) and value (USD million) from 2018 to 2020 [5]

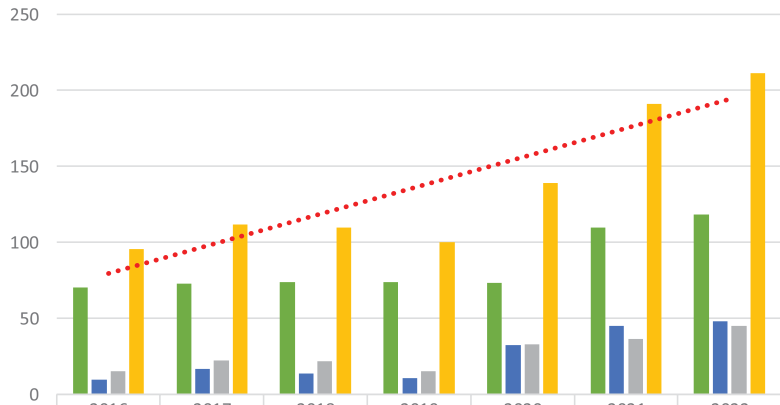
Country		Quantity (t)			Value (USD)		
		2018	2019	2020	2018	2019	2020
Brunei Darussalam	Brackish water	417.64	371.57	339.24	2.06	1.76	2.51
	Inland	724.30	590.90	3,045.78	4.89	4.13	19.56
	Marine	106.31	11.52	116.36	0.81	0.08	1.13
Indonesia	Brackish water	3,537,737.38	3,630,880.53	–	–	–	–
	Inland	9,268,216.17	879,033.21	–	–	–	–
	Marine	2,965,851.74	2,962,394.10	–	–	–	–
Lao PDR	Inland		67,000	122,000		33.58	33.97
Malaysia	Brackish water	290,195.00	307,181.00	302,807.25	565.28	615.64	582.70
	Inland	101,270.00	104,602.00	97,210.32	171.35	190.37	190.19
Myanmar	Total	1,130,350	1,121,350	–	–	–	–
Singapore	Brackish water	395.00	369.00	–	6.31	5.86	–
	Inland	854.00	1,014.00	–	6.11	7.86	–
	Marine	4,453.00	4,448.00	–	20.99	22.43	–
Thailand	Brackish water	495,022.00	536,466.00	514,600.00	2,242.68	2,361.01	2,235.09
	Inland	425,840.00	427,330.00	405,656.00	832.04	829.94	786.61

industry in the same year [8]. Aquaculture is the second biggest seafood producer in Brunei with a production quantity per population of almost 12 kg [6,9].

There are three sectors of the fisheries industry in Brunei Darussalam, which are capture fisheries, seafood processing, and aquaculture. Total fisheries production value showed an average increase of 14.2% per annum from 2016 to 2022 (Fig 4.) [10]. The highest contributor to the fisheries sector in Brunei is capture fisheries with a little over 60% in production quantity shares in 2021 [8] and there is not much change that can be seen with this in the year 2022 [10].

However, with the continuous implementations of measures for overfishing and declining fish stocks such as the moratorium on fishing operations in Zone 1 (0–3 nm) and the introduction of Marine Protected Areas (MPAs), it is expected that capture fisheries industries' growth will not increase exponentially and so, focus is also being put on the aquaculture sector [11]. Moreover, it is also anticipated that aquaculture production in Brunei Darussalam will intensify in the coming years as the country's fisheries production value is targeted to increase from BND 211.21 million in the year 2022 (Fig. 4) to BND 862.32 million in 2028, an excess of 300% rise [10].

Fig. 3. Total aquaculture production value (USD 1,000) of ASEAN member countries in 2021 [6].



	2016	2017	2018	2019	2020	2021	2022
Capture Fisheries	70.11	73.04	73.81	74.07	73.59	109.53	118.12
Aquaculture	9.89	16.7	13.77	10.64	32.35	44.9	48.12
Seafood Processing	15.33	22.17	21.94	15.44	33.11	36.51	44.97
Total	95.33	111.91	109.52	100.15	139.06	190.95	211.21

Fig. 4. Fisheries production value (in BND Million) of Brunei Darussalam from 2016 to 2022. (Green: Capture fisheries; Orange: Aquaculture; Blue: Seafood processing; Yellow: Total fisheries production value) [10].

Brunei's aquaculture industry's growth is relatively not developed yet compared to other countries [12]. The aquaculture industry in Brunei Darussalam is divided into five commodities namely marine fish, marine shrimp, freshwater fish, fish fry, shrimp fry, and crab [8]. All have the potential to be improved but focus must be put on maintaining the top producers and finding ways to improve rapidly the lowest contributors. The biggest contributor in 2021 is marine shrimp aquaculture (85%) and the second is marine fish with 6.79% or BND 3.05 million in value [8]. The main culture species in Brunei for marine fish aquaculture is grouper *Epinephelus* spp., Asian seabass or barramundi *Lates calcarifer*, pompano *Trachinotus blochii* and tilapia *Oreochromis* spp., which are cultured in both brackish water and freshwater [13,14].

Brunei's aquaculture industry has the capability to expand even more and is expected to do so as it has the right natural resources and environment [9]. The introduction of foreign direct investments (FDIs) from countries such as Taiwan, China, Singapore, and Oman have also given the grounds for Brunei's aquaculture industry to intensify in the coming years [15–20]. However, this intensification may also come with potential drawbacks in terms of environmental sustainability and detrimental welfare of the cultured animals.

The likelihood of serious disease issues fluctuates with several factors, much like in other agricultural industries. Activities related to aquaculture have increased and grown. Bacterial infections, fungal infections, parasite, or protozoan infections, along with physical ailments and wounds, are the four main categories of fish diseases. The primary barrier to the commercial cultivation of many aquatic species is illness, which has prevented the economic and social advancement of numerous countries [21].

In farmed fish, many illnesses are highly common, including epizootic ulcerative syndrome (EUS), skin erosion, gill damage, tail and fin rot, etc. Due to the high stocking density and erratic feed availability in the pond aquaculture system, disease outbreaks are particularly likely. Most of the pond fish growers lack a solid understanding of fish disease and health. Many fish diseases are caused by environmental damage, and they can be prevented through proper management [22–24].

1.5. Climate change and aquaculture

Climate change is a potential threat to the sustainability of aquaculture development. The impact of such can occur because of both gradual warming and associated physical changes as well as from frequency, intensity, and location of extreme events. It can take place in the context of other global socio-economic pressures on natural resources. Urgent adaptation measures are required in response to opportunities and threats to food and livelihood provision due to climatic variations. The present document briefly analyses the potential impacts of climate change on the aquaculture sector at the global and regional level. Overall, impacts on aquaculture are predicted to vary widely, depending on the current climatic zones of activity. Climate change impacts on aquaculture have both direct effects, for example, diseases through physical and physiological processes, and indirect effects, for example, through variations in fish meal supplies and trade issues. Regarding contributions to greenhouse gas (GHG) emissions, aquaculture has limited relevance and the primary mitigation route for the sector lies in the reduction of energy consumption, through fuel and raw material use. Options to increase resilience and adaptability include adequate policies and practices with an ecosystem and cross sectoral perspective at regional, national, watershed scales as well as improved management practices at the farm scale [25,26].

1.6. Sustainable aquaculture and SDGs

There is growing recognition that sustainable aquaculture can contribute in substantive ways to address global nutritional, economic, and environmental challenges. Aquaculture, as any human endeavor, has the potential to have either positive or negative impacts on the environment and on local communities. Over the past decades, various allegations have been made about aquaculture, with coastal and marine aquaculture bearing the brunt of the criticisms. Over time, however, an increasing body of research data has shown that many forms of aquaculture have been practiced in a sustainable manner, and additional progress continues to be made [1,27].

However, sustainability is considerably broader than only environmental sustainability. Communities, ecosystems, economies, and their resistance to a variety of external shocks are at the junction of the sustainability of food and agriculture systems. While all 17 of the Sustainable Development Goals of the Food and Agriculture Organization of the United Nations are somewhat relevant to aquaculture, those linked to food security, economic growth, and employment are particularly relevant. Specifically, the following SDGs are mentioned: #2 End hunger, achieve food security, improve nutrition, and support sustainable agriculture; #8 Decent work and economic growth; #11 Sustainable cities and communities; #12 Responsible consumption and production; and #14 Conserve and sustainably use the oceans, seas, and marine resources for sustainable development. Thus, development of indicators of sustainability and resource-use efficiency address not just environmental interactions but include those related to economic and social sustainability [28–30].

As global populations continue to increase, the pressure on communities and the environment will increase. With increased population pressure, the ability of communities to rebound and recover from external shocks and the need for sustainable food production systems will become ever more important. Communities with greater economic resources and more cohesive social networks are likely to be those that will be more resilient to continued changes as well as to external shocks. Aquaculture, when managed in environmentally and socially responsible ways, can be an important contributor to increased resilience of communities. Greater attention is needed on aquaculture regulatory processes to ensure that regulatory rulemaking, implementation, and enforcement measures address environmental and social issues adequately but avoid unintended negative consequences to the environment, local economies, and social networks [31,32].

1.7. Challenges in aquaculture globally: health as a constraint to aquaculture

Aquaculture health management is a term to describe practises designed to prevent fish diseases and promote good well-being in fishes. The success of health management starts with prevention preferably than treatment. Prevention of fish disease can be achieved by good water quality management, optimum fish number, nutrition, cleanliness practises, and usage of vaccines and other immunostimulants. Opportunistic diseases caused by bacteria, fungi and parasites that constantly surrounded fish in the same water containment. Poor water quality, poor nutrition and lower immunity in fish usually relate to the stressful condition that permits opportunistic pathogens to take advantage of the adverse condition and caused diseases [33].

The current trend in aquaculture development is towards increased intensification and commercialization of aquatic production. Like other farming sectors, the likelihood of major disease problems occurring increases as aquaculture activities intensify and expand. Thus, the aquaculture industry has been overwhelmed with its share of diseases and problems caused by viruses, bacteria, fungi, parasites, and other undiagnosed and emerging pathogens. Disease is now a primary constraint to the culture of many aquatic species, impeding both economic and social development in many countries [34].

This situation can be attributed to a variety of multifaceted and highly interconnected factors such as the increased globalization of trade in live aquatic animals and their products; the intensification of aquaculture through the translocation of brood stock, post larvae, fry and fingerlings; the development and expansion of the ornamental fish trade; the enhancement of marine and coastal areas through stocking aquatic animals raised in hatcheries; the misunderstanding and misuse of specific pathogen free (SPF) stocks (e.g., shrimps); unanticipated negative interactions between cultured and wild fish populations; poor or lack of effective biosecurity measures; slow awareness on emerging diseases; climate change; all other human mediated movements of aquaculture commodities. However, once a pathogen or disease agent is introduced and becomes established into the natural environment, there is little or no possibility for either treatment or eradication. While consequences of "trickle" infections from wild to cultured populations have predictable consequences due to accessible hosts under cultured conditions, the consequences of culture-borne transmission to wild stocks are harder to predict. Examples of infection of cultured stocks via wild stock reservoirs for shrimp diseases and for marine finfish disease [35].

1.8. Impact of transboundary diseases in aquaculture

Transboundary aquatic animal pathogens/diseases (TAAPs/TAADs), which are comparable to transboundary animal diseases (TADs) in the livestock industry, are a problem in the aquaculture industry. TAADs are highly contagious or transmittable illnesses that have the potential to spread very quickly across international borders and have major socio-economic and possibly health effects [36]. The emergence and spread of transboundary aquatic animal diseases are mainly a result of two important practices in aquaculture: intensification of culture systems; and international trade (movement) of live aquatic animals and aquatic animal products. The economic impact of these diseases is huge, around US$6 billion annually on direct production losses. Over the years, several transboundary aquatic animal diseases have affected the aquaculture industry in the region. These emerging diseases might spread in the region anytime, as we continue to trade live aquatic animals, as we continue to intensify culture systems, and as we continue to introduce new species for culture [37].

It should be noted that once a disease is introduced into a country or area, it is often very hard to eradicate. However, it can be managed to prevent or at least minimize the impacts of the disease to the cultured stocks and to the industry. As we have shared water bodies and epidemiological link through trade (especially movement of live aquatic animals), a collaborative approach is necessary in dealing with such disease emergencies for effective aquatic animal health management, for improved disease monitoring, surveillance, and reporting, and for effective disease preparedness and response system [38].

Following are the requirements for an urgent notification for the diseases of aquatic animals listed: When a disease first appears or reappears in a region of a country that was previously thought to be devoid of those diseases. Through direct production losses, increased operating costs, and indirect trade restrictions and repercussions on biodiversity, infectious diseases are limiting the growth and sustainability of the aquaculture business. Significant losses resulting from aquatic animal diseases have been caused by inadequate or improperly executed biosecurity controls in several nations across the world. The effects of aquatic animal diseases on wild populations and biodiversity are quantified in terms of the following: impact on aquatic community structure through changes in predator and prey populations; changes in host abundance (e.g., through altered genetic demands, altered host behaviour, increased mortality, decreased fecundity, and increased susceptibility to predation); reduction of intra-specific genetic variation; local extirpation of susceptible components of aquatic communities [39].

However, many nations are already offering some estimates of illness impacts due to the frequency of incidence, the scope of the spread, and the effects. Asian Development Bank (ADB) and Network Aquaculture Centres in Asia-Pacific (NACA) reported that the diseases causing losses in freshwater finfish pond culture and marine cage culture at the regional level included penaeid shrimp diseases, epizootic ulcerative syndrome of fresh and brackish water fishes, and a variety of other diseases. The expenses of investing in programs for disease research and control and health management have also been used to describe economic implications [40].

Due to their constant exposure to a stressful environment with changing environmental conditions, cultured fish have been negatively impacted in terms of their health and they are more vulnerable to numerous diseases. The production of grouper in aquaculture is one example of how transboundary movements of cultured fish have exacerbated this issue and may have done significant harm to the aquaculture industry [41].

The resources required to run aquaculture operations have placed constant pressure on industry players to procure it and sometimes operators have to look for supplies abroad. The growth and health status of cultured aquatic animals has suffered due to the occurrence of diseases, which include parasites [42].

Disease occurrence could be so severe that it would cause significant losses and problems to animal welfare, which in turn would cause a hindrance to aquaculture production growth worldwide. Diseases of cultured fish have caused losses of an excess of USD 6 billion annually [2]. Another example of this issue is when a company in Singapore had to stop its whole marine farming operations due to the persistent occurrence of scale drop disease virus (SDDV) in its Asian seabass culture farms in 2023, putting a dent in the country's aim of nutritional self-sufficiency of 30% by 2023 [43].

Locally, it might be comparable because the aquaculture sector was expected to contribute the most to Brunei Darussalam's fisheries industry [14]. But in 2021, the country's aquaculture sector only made up 24% of the value of all fisheries production [8]. Therefore, the existence of such problems may have prevented the aquaculture sector from surpassing capture fisheries as intended.

Due to the increase in intensive production, cultured fish health has been affected as they are continuously in a stressful environment with environmental fluctuations and that makes them more susceptible to various pathogens, including parasites [40]. This may also be a problem with the rapid growth of Brunei's aquaculture industry. With the influx of foreign direct investments (FDIs), also comes expertise, capital boost, and raw materials from overseas, such as fish or shrimp fry, broodstock, and new culture species along with its pathogens as shown by [41]. This can lead to devastating effects if introduced to species already cultured locally and wild fish stocks in the country. This movement of aquatic animals for seafood production, such as the international trade of fingerlings, may have been the cause of several emerging diseases in the aquaculture industry internationally, especially without a proper system for animal health management [44]. This also seems true with parasitic infestations on cultured fish from one country to another in the region [41]. The issue of sustainability will also be relevant as the region is likely to expand its aquaculture sector in the near future. Sustainability in this context refers to the wellbeing of fish, the environment, and the economy.

1.9. Biosecurity in aquaculture

There will be an increase in demand for aquatic animal biosecurity. The driving forces behind this will be a variety of objectives, such as resource protection (for aquaculture, wild fisheries, and the general environment), food security, trade, consumer preference for high-quality and safe products, production profitability, investment and development issues, and new threats of emerging health problems, such as new diseases/pathogens and new hosts for well-studied pathogens [45]. In order to ensure adequate protection, biosecurity programs have a solid scientific foundation and use risk assessment to assess the most significant disease hazards, their potential entry points, their likelihood of becoming established, their potential for spread, and risk management strategies [22].

The procedure makes use of reliable epidemiological principles, methods, and information. The goal of epidemiology, which examines the prevalence, causes, and distribution of disease, is to find solutions for animal health issues. The information needed for risk analyses is produced by epidemiological research; biosecurity measures call for correct information for an accurate assessment, which results in the right risk management decisions. Thus, risk analysis, epidemiology, and biosecurity are all closely related and all work toward making the best use possible of scientific information for disease management, control, and prevention [39].

1.10. Impact of diseases on fin fish aquaculture

One factor that is plaguing several aquaculture industries globally, which needs overcoming, is disease occurrence. Disease can be defined as "abnormalities of structure or function displayed by living organisms through a specific or non-specific sign" [40].

Diseases in aquaculture occur when there are interactions of three different factors: Host, which is the cultured fish; Pathogens, agents that cause the disease; and Environment, the culture site [46]. These interactions are illustrated clearly using Snieszko's (1974) diagram (Fig. 5). To summarise, a host can be susceptible or resistant to a disease and environment are the physico-chemical parameters and stability of the surrounding water.

Diseases can also be categorized into infectious and non-infectious diseases, and viral, bacterial, parasite and fungal diseases all fall into the former [47]. For pathogens, there are three types of disease-causing agents that can affect aquaculture production, these include biological, chemical, and environmental pathogens [40]. This paper will only discuss biological agents that cause infectious diseases in cultured fish, specifically parasites that can cause secondary viral, bacterial, and fungal infections.

1.11. Parasitic diseases in aquaculture

Parasites are diverse in species and many varieties of parasites can affect a wide array of host fishes [42]. The practice of a high number of stocked fish compounded with the small space in which fish are cultured has contributed to the proliferation of parasites in aquaculture. Moreover, the environmental conditions needed for aquaculture practices are also where disease agents such as parasites thrive [48].

Parasites can be categorized into two, endoparasites and ectoparasites [48]. Endoparasites are predominantly found inside the host, specifically the internal organs. The other type is ectoparasites, which affect the host externally. For fish, this includes the skin, eyes, fins, and gills. Fig. 6 shows an example of the ectoparasite, marine leech infesting cultured hybrid groupers.

1.12. Fish parasites and consequences

Fish parasites and their effects have been of concern to aquaculture production in the world for quite a while now, which is why parasitology has been on the rise over the last hundred years [49]. [50] highlighted that the costs of parasitic infestations can be divided into two categories, namely predictable and unpredictable. Predictable costs are costs related to methods of prevention, mitigation, and treatment of parasitic infestations, and this can already put a strain to the economical aspect of aquaculture operations.

Fish parasites can affect hosts in a number of ways including influencing the host morphologically and

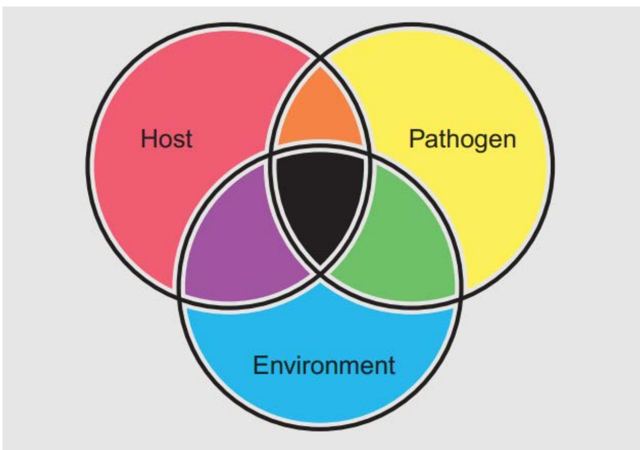


Fig. 5. Sniezko's (1974) diagram illustrates the complex interaction between host, pathogen, and environment for diseases in organisms to occur. The black triangular area shows disease occurrence when all three overlaps. [46].

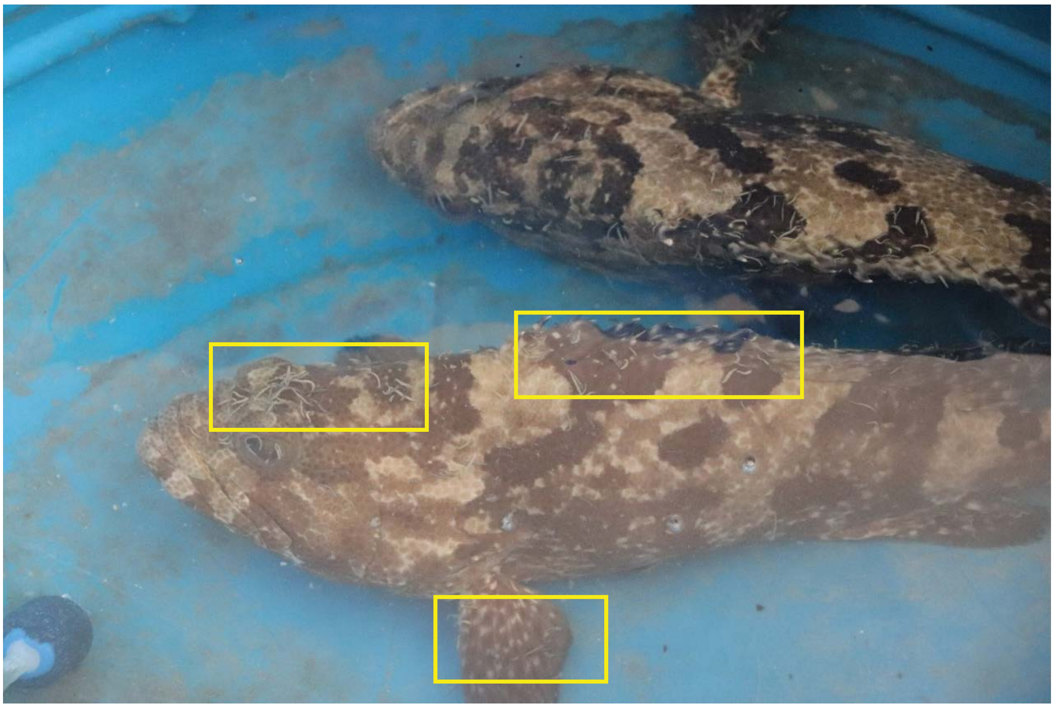


Fig. 6. Ectoparasites, marine leeches, attached to the head, fins, body, and eyes of cultured hybrid groupers (Yellow box).

physiologically, while also affecting their reproduction and behaviour [49]. The risk of parasite infection from wild fish stocks to aquaculture and vice versa is one of the troubling problems with the aquaculture systems where fish are contained in a closed space [49]. Parasitic infestations can also incur indirect losses to aquaculture operators. The cost of treatments, prevention, and even reduced fish growth due to loss of fish appetite because of treatments or the parasites can also be substantial and put a burden on farmers [51].

Another problem with parasitic infestations as primary infections to fish is that they can bring about an opening for opportunistic pathogens to infect the host and cause secondary infections. Secondary infections may be a more significant issue for aquaculture and have caused devastating losses, which will be discussed further in this paper.

1.13. Parasitic infestations

Parasitic infestations occur when hosts, in this case, fish become infested with organisms that live on or within them and bring harm to them [52]. Infestations in aquaculture have been known to cause economic loss and considerable damage to production, including both fish and shrimp, worldwide [53].

In the northern hemisphere and western part of the world, sea lice, particularly *Lepeophtheirus salmonis*, is a caligid copepod parasite that is affecting the highly-valued salmonid productions in Chile, Norway, and Scotland, where it has caused an estimated loss and cost of US$ 480 million annually, US$ 206 million annually, US$52.9 million respectively [50]. In addition to this, the paper also states that a huge amount of investment was also put into parasite controls to reduce and prevent the infestations of sea lice.

Regionally, Asian seabass or barramundi (*Lates calcarifer*) is cultured in the majority of farms and the most devastatingly costly parasite is monogeneans. One case of *Neobenedenia melleni* infestation caused an estimated loss of US$ 277,000 in Australian barramundi culture back in the year 2000 [50]. Parasitic marine leeches are also known to affect several countries in the Asian region, including Malaysia [54,55], Indonesia [56], the Philippines [57], Japan [58], Brunei Darussalam [59]. A heavy infestation of marine leeches on fish may also cause mortality in marketable-size fish due to heavy blood loss [57].

1.14. Secondary infections

Secondary infection is one of the main concerns of parasitic infections as they can be a vector for several diseases The infection of parasites can be described as the primary infection and this can lead to an even bigger problem, the attachment sites can cause an opening for secondary infections by viruses, bacteria, or even fungi [51,40]. Parasitic infestations have been suggested to be the pre-disposing factor for several diseases such as vibriosis and transmission of pathogenic viruses and flagellated hemoprotistans [60,61]. Viral and bacterial infections are a cause of great concern to many aquaculture operators globally as they can have devastating effects and cause huge mortalities and losses to fish stocks.

1.15. Viral diseases

Viruses are microscopic and infectious disease-causing agent that requires a living host to proliferate [47]. Viral diseases are diverse and each species can infect a plethora of fish species. Examples of viral diseases of importance and listed under the World Organisation for Animal Health (WOAH) notifiable diseases for finfish include, but are not limited to, Red Sea Bream Iridovirus, Viral Haemorrhagic Septicaemia, and Tilapia Lake virus [62]. Viral infections are very threatening and can cause devastating economic impacts to the aquaculture industry as they can cause mortalities of up to 100% on the farm and there are no prophylactics and treatments to treat most viral diseases.

Table 2 shows the viral disease occurrence in ASEAN countries but only viruses affecting finfish culture in the past decade. Some countries such as Brunei Darussalam, Cambodia, and Lao PDR did not report any viral disease cases in their fish culture in the last 10 y. However, this may not mean that these viruses are absent but it may be from a lack of reporting of mortality events by the farmers themselves.

1.16. Bacterial diseases

Bacteria are ubiquitous as they can be found worldwide and even in harsh environments. Bacterial diseases can be harmless but when cultured fishes are under stressful environments, they can cause heavy mortality and huge losses to the fisheries industry [47]. Disease-causing bacteria are usually found in aquatic environments and parasitic infestations can cause bacteria to become opportunistic pathogens and cause secondary infections.

An example of secondary bacterial infection is vibriosis due to *Vibrio alginolyticus* infection caused by parasite infestations as the pre-disposing factor [61]. Vibriosis can be caused by this vibrio sp. and symptoms include haemorrhages in the body and internal organs [70]. Some Vibrio species can even affect human diseases such as gastroenteritis from *Vibrio parahaemolyticus* and *Vibrio cholera*, and wound infection from *Vibrio metschnikovii* [71]. It has caused considerable damage to the socio-economy of aquaculture operations example *Vibrio fluvialis* has caused more than USD 120 million annually in China [72].

One particular devastating disease caused by the virulent strain of the vibrio species *Vibrio parahaemolyticus* is Acute Hepatopancreatic Necrosis Disease (AHPND) in penaeid shrimp or its earlier name, early mortality syndrome (EMS). AHPND can cause considerable damage as it can cause up to 100% mortality within 30–35 d of stocking and has affected several countries in ASEAN such as Vietnam, Malaysia, and the Philippines [73].

1.17. Disease control and prevention: parasitic diseases

Numerous control strategies were developed in response to the worrisome problems caused by the presence of parasites in aquaculture to reduce parasitic infestations and get rid of secondary illnesses. Several recommendations call for the use of chemical techniques, such as formalin, hydrogen peroxide, and more commonly, fresh water [74]. Some studies have also come up with natural solutions such as using *Dillenia suffruticosa*, a medicinal plant containing phytochemical compounds revealed to have an effective antiparasitic activity against marine leeches [75].

Several control and prevention methods are suggested to help mitigate and prevent parasitic infestations in this review paper and these can be utilized by those affected in ASEAN countries. [49] state that different types of parasites bring about different impacts on aquaculture and require different methods to control it. The three main control methods for parasites that will be discussed in this study are biological, chemical, and mechanical controls.

1.18. Chemical control

The utilization of chemicals or chemotherapeutics in reducing diseases caused by parasites is still frequently used in aquaculture systems worldwide such as using antibiotics,

Table 2
Viral disease occurrences in aquaculture facilities culturing finfish in ASEAN countries in the past 10 y

Country	Viral disease cases in aquaculture facilities	Year	Source
Brunei Darussalam	None reported	–	[63]
Cambodia	None reported	–	[64]
Indonesia	Iridovirus infection	2018	[65]
Lao PDR	N/A	–	–
Malaysia	Koi herpesvirus	2022	[66]
	Viral encephalopathy and retinopathy	2022	
Myanmar	None reported	–	[67]
Philippines	Tilapia lake virus	2020	[63]
Singapore	Scale drop disease virus	2023	
	Viral encephalopathy and retinopathy	2020	[43]
	Red Sea Bream Iridovirus	2019	[63]
	Koi herpesvirus	2019	
	Grouper iridoviral disease	2014	
Thailand	Viral encephalopathy and retinopathy	2017	[63]
	Tilapia lake virus		[68]
Vietnam	Tilapia lake virus	2017	[69]

organophosphates, ivermectin, and other chemical prophylactics [76]. There are also many suggestions involving chemical methods such as using formalin, hydrogen peroxide and more conventionally, fresh water [74]. The efficacy of these chemicals cannot be denied as many studies have proven. The use of salt and freshwater on fish has been proven to significantly reduce parasitic infection but it still depends on the tolerance of the species [77]. The effectiveness of emamectin benzoate, a pharmaceutical drug, in reducing sea lice infections in hybrid groupers in Hong Kong was also proven by [78]. The efficacy of numerous chemicals on parasitic marine leech infestation in hybrid groupers have also been compared by [74] whereby the quickest way to kill marine leeches, *Zeylanicobdella arugamensis*, is by bathing them in freshwater and ivermectin was also effective even in lower concentrations, 30 min was enough to kill leeches at 62.2 ppm. Other chemicals such as formalin, levamisole and $CuSO_4$ can also kill marine leeches but at higher concentrations or bathing them at longer in the chemicals.

However, several problems were mentioned when using chemical controls to reduce parasitic infections in fish. Chemical controls do come with several drawbacks such as leaving harmful residues in host tissues and it is labour intensive, to name a few [79]. One problem that arises even with the effectiveness of chemical controls is the reinfection of these parasites. One example is the re-occurrence of marine leech infestation following freshwater baths due to its ineffectiveness to kill its cocoons [80]. This will defeat the purpose of controlling parasites and will bring more harm as chemicals will be continuously used and released into the environment. Another major problem is the increase in resistance of these parasites to chemical prophylactics due to excessive use [76].

1.19. Biological control

To tackle the shortcomings of using chemical controls, biological controls have also been proposed and used to combat parasitic infections in aquaculture. One fascinating method is finding the natural predators of parasites and releasing them to essentially clean the fish. This was studied by [76], where cleaner shrimps, *Lysmata vittata* (Fig. 7), were shown to effectively reduce parasitic infestations of *Cryptocaryon irritans*, *Neobenedenia girellae,* and *Zeylanicobdella arugamensis* in cultured fish. Several other studies were also done on using cleaner fish to reduce parasitic infestations in farmed fish [77].

Probiotics are also one of the promising biocontrol that can be utilized in aquaculture farms. There are many definitions of probiotics but to summarise [37], it is the use of live micro-organisms, such as specific types of bacteria, which has beneficial effects on the health of its host when ingested, or it can be used to change the microbial communities in the culture water or sediments to eliminate pathogens within it, that is, bioremediation.

The use of biocontrol in aquaculture shows promise in reducing parasite infestations. However, a few limitations have also been highlighted with this type of biocontrol, such as cost, availability, and predation of the shrimps, if in terms of cleaner shrimps [76]. Therefore, other alternatives should also be looked into in providing a sustainable solution to the problem of fish parasites.

1.20. Mechanical control

Mechanical methods in controlling parasite infestations have been done in hopes of reducing the drawbacks of using both chemical and biological controls. However, there was not much research done on mechanical controls to reduce parasitic infestations but some studies have been done on water filters, shaking in hand net, and mechanical removal of parasites [49].

A novel control of marine leech infestation was introduced by [82] (Fig. 8). It is the only known mechanical method devised to reduce marine leech infestations by disrupting its life cycle by removing the cocoons attached to the

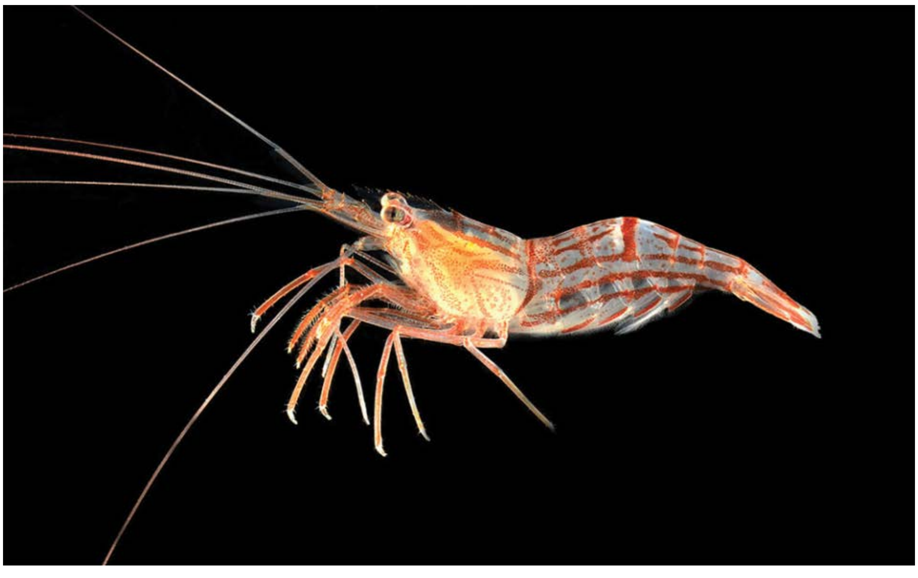


Fig. 7. *Lysmata vittata* or peppermint shrimp, a species of shrimp used as biological control to reduce parasitic infestations [81].

Fig. 8. Break and Protect 2 (BP2) marine leech trap device by Kua and Arbi [82] (Source: 3 Little Fish Malaysia).

device. [82] claimed the Break and Protect 2 (BP2) marine leech trap can effectively reduce leech prevalence from 70%–100% to 20%–28%. This novel method shows promise in becoming the solution to the marine leech problem faced regionally. However, data on its effectiveness in the aquaculture industry in Brunei Darussalam and regionally, specifically in open sea net cage culture is scarce.

1.21. Advantages of mechanical controls

One benefit that always emerged from the few research on the application of mechanical controls was that they offer a considerably more long-term alternative to parasitic controls. It can be less expensive in the long run since it can be used frequently rather than biological controls, which can become extinct, and it does not harm the environment because it does not utilize chemotherapeutics [82].

1.22. Disease prevention through biosecurity

Biosecurity measures in aquaculture farms or facilities aim to prevent the introduction of disease into the farm and the spread of disease out of it [83]. Prevention can be the best solution to disease, especially with pathogens that have no treatments such as viral infections. Strict biosecurity measures, for example, quarantine, can also reduce the risk of transboundary diseases. Preventive measures are also important as it can protect the cultured animals from viral and bacterial diseases [84].

Several countries have also adopted a standard to impose biosecurity measures in aquaculture farms, such as the ASEAN Good Aquaculture Practice (ASEAN GAP) and in Brunei, the Brunei Good Aquaculture Practice (BGAqP) [14]. These manuals or standards should have the main characteristics and goals of biosecurity in aquaculture, which are managing cultured animals, disease agents, and people [83]. Table 3 highlights the important approaches to achieve these goals as gathered from [83,85,86].

1.23. Open sea cage aquaculture

For open sea cage aquaculture, specific biosecurity measures have to be employed and this may not be the same as measures for inland aquaculture or enclosed aquaculture. Sea cage culture using net cages is generally large and hard to handle, and it is also much easier to be contaminated as it is exposed to the natural environment [86]. These nets must regularly be washed to remove contaminants and also improve water flow through the nets. These nets may also be disinfected by immersing them in chemical disinfectants and drying but it can affect the quality of the nets in the long run.

1.24. Emergency response to disease epizootics

The Asia-Pacific region has been plagued with many disease emergencies during the last three decades. The most significant disease emergencies include that of EUS, shrimp viral diseases (WSD, YHD, IHHN, etc.), Akoya pearl oyster mortalities, and most recently, KHV and abalone mortalities. In a way, the region has learned to deal with the emergency using available limited resources, expertise, and facilities. Some of the important lessons and valuable insights learned from dealing with those epizootics include the need for: [39]

- increased awareness on emerging diseases in other parts of the globe and the possibility of their spread to the Asian region.

Table 3
Biosecurity goals and approaches in aquaculture

Biosecurity goals	Approaches and ways to achieve the goals
Management of animals	- Good husbandry: Improving fish welfare, feeding, reducing fish stress, handling, and water quality. - Good preventive procedures: pathogen surveillance, quarantines, vaccinations, immunostimulants, routine health checks, and waste management.
Management of disease agents	- Preventing pathogens: surveillance. - Reducing pathogens: compartmentalisation. - Eliminating pathogens: eradication, disinfection using chemicals, and removal of disinfectants.
Management of people	- Staff training: proper husbandry and handling techniques. - Movement control of visitors and staff: disinfection stations, hand washing, and vehicle disinfection.

- improved diagnostic capabilities at both the national and regional levels.
- pro-active reporting of serious disease outbreaks as a mechanism for early warning.
- contingency plans at both the national and regional levels.
- improved compliance and implementation of policies reached at the regional and international levels.
- emergency preparedness as a core function of government services.
- advanced financial planning such that adequate funds can be immediately provided to address serious emergency disease situations at both the national and regional levels.

2. Conclusion

This review article bestowed information about the potential aquaculture sector in the ASEAN region, including its importance and potential problems such disease outbreaks in Brunei Darussalam. In order to maintain aquaculture output and product commerce, health-related issues must be addressed through both proactive and reactive programs. To reduce the risks of disease invasions brought on by the movement of live aquatic animals and their products, the present approach in the Asia-Pacific area places an emphasis on responsible health management. The risk of serious disease incursions and newly emerging diseases will continue to pose a threat to the industry, and unless appropriate health management measures are maintained and effectively implemented, the public and private sectors will be forced to bear higher costs in the form of production losses and the efforts required to contain and eradicate diseases, money that would have been better spent preventing their entry into the system. It may be more crucial to concentrate on prevention, improved management techniques, and maintaining healthy fish than on the causes of fish illness through the applied procedures of biosecurity.

In ASEAN countries, there is widespread support to execute the Regional Technical Guidelines serve as a sound foundation for collaboration at the National, and International levels as well as important direction for regional and national initiatives to reduce these risks. Due to the necessity of live aquatic animal commerce for the growth of aquaculture at both the subsistence and commercial levels, the aquaculture industry will continue to expand. Each stakeholder's input is crucial to the health management process for the sustainable development of aquaculture, as health management is a shared duty. All industrial sectors should assess their present disease mitigation measures because there will likely be an increase in global worries about the emergence of new diseases in the future. In order to further develop alternative goods and tactics required to combat hazardous infections and safeguard fish health in aquaculture systems, international cooperation is vital.

There has been significant progress in this field of research over the past few years, and there is increased interest in finding alternatives to antimicrobial products. Even though there are numerous potential solutions that may vary depending on culture species and aquaculture methods, the ideal one is still unknown. However, methods that promote fish's general well-being and healthy immune system are probably the best course of action. The aquaculture sector will continue to intensify; trade in live aquatic animals will also persist because it is a necessity for aquaculture development at both the subsistence and commercial levels. Health management is a shared responsibility, and each stakeholder's contribution is essential to the health management process for the Sustainable Development of Aquaculture and Management in ASEAN countries.

As global populations continue to increase, the pressure on communities and the environment will increase. With increased population pressure, the ability of communities to rebound and recover from external shocks and the need for sustainable food production systems will become ever more important. Communities with greater economic resources and more cohesive social networks are likely to be those that will be more resilient to continued changes as well as to external shocks. Aquaculture, when managed in environmentally and socially responsible ways, can be an important contributor to increased resilience of communities. Greater attention is needed on aquaculture regulatory processes to ensure that regulatory rulemaking, implementation, and enforcement measures address environmental and social issues adequately but avoid unintended negative consequences to the environment, local economies, and social networks.

References

[1] FAO, The State of World Fisheries and Aquaculture 2022, Towards Blue Transformation, Food and Agriculture Organization, Rome, 2016.

[2] FAO, FAO Yearbook: Fishery and Aquaculture Statistics 2019/ FAO annuaire, Statistiques des pêches et de l'aquaculture 2019/FAO anuario, Estadísticas de pesca y acuicultura 2019, Food and Agriculture Organization, Rome/Roma, 2021.
[3] Transforming Our World: The 2030 Agenda for Sustainable Development, Department of Economic and Social Affairs Sustainable Development, United Nations, 2015. Available at: https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981
[4] D. Peng, Y. Mu, Y. Zhu, J. Chu, U. Rashid Sumaila, Insights from Chinese mariculture development to support global blue growth, Rev. Fish. Sci. Aquacult., 31 (2023) 453–457.
[5] W. Tamat, W. Diah, C.J. Marsal, A.J.K. Chowdhury, A.S. Anwari, A. Johari, Covid-19 Impacts on ASEAN Aquatic Environment: Towards Mitigation Actions for Impending Resilience on Aquaculture and Fisheries in Brunei Darussalam, Environmental Resilience in the Pandemic Years 2020-2021 - Covid-19 and Environmental Ecosystem, Springer Publishers, 2024.
[6] FAO, FishstatJ - FAO Global Fishery and Aquaculture Production Statistics, Food and Agriculture Organization, 2023. Available at: https://www.fao.org/fishery/en/statistics
[7] R.C. Borromeo Jr., J.M. Urbano, A.T. Rivera, Eco-friendly fish farming: responsibly-sustainable aquaculture among ASEAN countries, J. Sociae Polites, 23 (2022), doi: 10.33541/sp.v23i1.4114.
[8] Department of Fisheries, Brunei Darussalam, Brunei Darussalam Fisheries Statistic in Brief 2021, 2022. Available at: https://www.fisheries.gov.bn
[9] C.J. Marsal, M.H. Jamaludin, A.S. Anwari, A.J.K. Chowdhury, The potential of aquaculture development in Brunei Darussalam, Agric. Rep., 2 (2023) 12–21.
[10] Ministry of Primary Resources and Tourism, Brunei Darussalam, Pelan Strategik 2023–2028, Kementerian Sumber-Sumber Utama dan Pelancongan, 2023.
[11] Department of Fisheries, Brunei Darussalam, Status of Marine Resources in Brunei Darussalam, Available at: http://www.fisheries.gov.bn/SiteCollectionDocuments/FAQs/FAQ%20CFDD%20(matzai).pdf
[12] H.L.H.A. Hamid, Brunei Darussalam: Mangrove-Friendly Aquaculture, J.H. Primavera, L.M.B. Garcia, M.T. Castaños, M.B. Surtida, Eds., Mangrove-Friendly Aquaculture: Proceedings of the Workshop on Mangrove-Friendly Aquaculture Organized by the SEAFDEC Aquaculture Department, January 11–15, 1999, Iloilo City, Philippines, Tigbauan, Iloilo, Philippines: Southeast Asian Fisheries Development Center, Aquaculture Department, 2000, pp. 95–103. Available at: https://aquadocs.org/bitstream/handle/1834/9151/hamid2000-brunei-mangrove-friendly-aquaculture.pdf?sequence=1
[13] Southeast Asian Fisheries Development Centre (SEAFDEC), Fisheries Country Profile: Brunei Darussalam 2022.
[14] W. Tamat, D.S.N.P.H.A. Halim, E.F.B. Pakar, Current Status, Issues and Gaps of Aquatic Emergency Preparedness and Response Systems Practiced in Brunei Darussalam, E.A. Tendencia, L.D. de la Peña, J.M.V. de la Cruz, Eds., Aquatic Emergency Preparedness and Response Systems for Effective Management of Transboundary Disease Outbreaks in Southeast Asia: Proceedings of ASEAN Regional Technical Consultation, 20–22 August 2018, Centara Grand Central Ladprao, Bangkok, Thailand Tigbauan, Iloilo, Philippines: Aquaculture Department, Southeast Asian Fisheries Development Center, 2019, pp. 3–6. Available at: https://repository.seafdec.org.ph/handle/10862/3455
[15] Borneo Bulletin, Aquaculture in Borneo Bulletin Yearbook 2023, 2023. Available at: https://borneobulletinyearbook.com.bn/aquaculture/
[16] The Fish Site, Brunei Set for 10,000 tonne Salmon Farm, December 12, 2019. Available at: https://thefishsite.com/articles/brunei-set-for-10-000-tonne-salmon-farm
[17] The Scoop, Oman Eyes More Aquaculture Investment in Brunei, July 26, 2022. Available at: https://thescoop.co/2022/07/06/oman-eyes-more-aquaculture-investment-in-brunei/
[18] The Scoop, Brunei's Aquaculture Sector Gets $300 Million Boost, May 6, 2019. Available at: https://thescoop.co/2019/05/06/bruneis-aquaculture-sector-gets-300-million-boost/
[19] The Scoop, Brunei-Oman Joint Venture Acquires 50% Stake in Golden Corporation, November 28, 2019. Available at: https://thescoop.co/2019/11/28/brunei-oman-joint-venture-acquires-stake-in-golden-corporation/
[20] The Scoop, Singapore Company to Build Salmon Farm in Brunei, December 12, 2019. Available at: https://thescoop.co/2019/12/12/singapore-company-to-build-salmon-farm-in-brunei/
[21] World Aquaculture Society, The Many Challenges of Disease Management in Aquaculture, 2023. Available at: https://www.was.org/articles/The-many-challenges-of-disease-management-in-aquaculture.aspx
[22] A.I. Aadil, P.R. Anand, V. Sugumar, P. Vasantha-Srinivasan, G. Raja, Bacterial pathogenesis in various fish diseases: recent advances and specific challenges in vaccine development, Vaccines (Basel), 11 (2023) 470, doi: 10.3390/vaccines11020470.
[23] I. de Bruijn, Y. Liu, G.F. Wiegertjes, J.M. Raaijmakers, Exploring fish microbial communities to mitigate emerging diseases in aquaculture, FEMS Microbiol. Ecol., 94 (2018) 12, doi: 10.1093/femsec/fix161.
[24] M.-M. Juan José, C.-P. Luis Jesús, P.-H. Amauri, C.-Á. Candy, Chapter 19 - Summary of Economic Losses Due to Bacterial Pathogens in Aquaculture Industry, G.H. Dar, R.A. Bhat, H. Qadri, K.M. Al-Ghamdy, K.R. Hakeem, Eds., Bacterial Fish Diseases, Elsevier, 2022, pp. 399–417. Available at: https://www.researchgate.net/publication/359488452_Summary_of_economic_losses_due_to_bacterial_pathogens_in_aquaculture_industrry
[25] Food and Agriculture Organization, Climate Change and Aquaculture: Opportunities and Challenges for Adaptation and Mitigation COFI/AQ/V/2010/6, 2010, p. 9.
[26] K. Cochrane, C. De Young, D. Soto, T. Bahri, Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge, FAO Fisheries and Aquaculture Technical Paper No. 530, FAO, Rome, 2009, p. 212.
[27] R.L. Naylor, R.W. Hardy, A.H. Buschmann, S.R. Bush, L Cao, D.H. Klinger, D.C. Little, J. Lubchenco, S.E. Shumway, M. Troell, A 20-year retrospective review of global aquaculture, Nature, 591 (2021) 551–563.
[28] Food and Agriculture Organization (FAO), Building a Common Vision for Sustainable Food and Agriculture: Principles and Approaches, Food and Agriculture Organization, United Nations, Rome, Italy, 2014. Available at: www.fao.org/sustainability/background/en/
[29] J. Hambrey, The 2030 Agenda and the Sustainable Development Goals: The Challenge for Aquaculture Development and Management, FAO Fisheries and Aquaculture Circular No. 1141, Food and Agriculture Organization of the United Nations: Rome, Italy, 2017.
[30] P. Zajicek, J. Corbin, B. Sebastian, R. Robert, Refuting marine aquaculture myths, unfounded criticisms, and assumptions, Rev. Fish. Sci. Aquacult., 31 (2023) 1–28.
[31] R.E. Carole, V.S. Jonathan, Resilience of communities and sustainable aquaculture: governance and regulatory effects, Fishes, 7 (2022) 268, doi: 10.3390/fishes7050268.
[32] W.C. Valenti, J.M. Kimpara, B. de L. Preto, P. Moraes-Valenti, Indicators of sustainability to assess aquaculture systems, Ecol. Indic., 88 (2018) 402–413.
[33] R. Lulijwa, E.J. Rupia, A.C. Alfaro, Antibiotic use in aquaculture, policies and regulation, health and environmental risks: a review of the top 15 major producers, Rev. Aquacult., 12 (2020) 640–663.
[34] FAO, Report of the FAO/MARD Technical Workshop on Early Mortality Syndrome (EMS) or Acute Hepatopancreatic Necrosis (AHPND) of Cultured Shrimp (TCP/VIE/3304), Fisheries and Aquaculture Report No. 1053, Food and Agriculture Organization, 2013.
[35] T.W. Flegel, Historic emergence, impact and current status of shrimp pathogens in Asia, J. Invertebr. Pathol., 110 (2012) 166–173.
[36] NACA, NACA, OIE and FAO, Quarterly Aquatic Animal Disease Report (Asia and Pacific Region), 2018/1, January – March 2018, Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand and OIE-RRAP, Tokyo, Japan, 2018.

[37] G.D. Lio-Po, Probiotics in Aquaculture, G.D. Lio-Po, Y. Inui, Eds., Health Management in Aquaculture, 2nd ed., Southeast Asian Fisheries Development Centre, 2010.
[38] E.M. Leaño, Transboundary Aquatic Animal Diseases: History and Impacts in ASEAN Aquaculture, E.A. Tendencia, L.D. de la Peña, J.M.V. de la Cruz, Eds., Aquatic Emergency Preparedness and Response Systems for Effective Management of Transboundary Disease Outbreaks in Southeast Asia: Proceedings of ASEAN Regional Technical Consultation, 20–22 August 2018, Centara Grand Central Ladprao, Bangkok, Thailand, Tigbauan, Iloilo, Philippines: Aquaculture Department, Southeast Asian Fisheries Development Center, 2019, pp. 72–79.
[39] V. Kumar, R. Suvra, B. Debtanu, Importance of health management in aquaculture, Aquafind, (2021) 8.
[40] C.R. Lavilla-Pitogo, Disease Development, G.D. Lio-Po, Y. Inui, Eds., Health Management in Aquaculture, 2nd ed., Southeast Asian Fisheries Development Centre, 2010.
[41] S. Azmey, H. Taha, G. Mahasri, M. Amin, A. Habib, M.P. Tan, T. Arai, Population genetic structure of Marine Leech, *Pterobdella arugamensis* in Indo-West Pacific region, Genes, 13 (2022) 956, doi: 10.3390/genes13060956.
[42] B.S. Dezfuli, T. Scholz, Fish parasites (special issue), Parasitology, 149 (2022) 1811–1814.
[43] A. Qing, S. Begum, Barramundi Group Stops Farming Sea Bass in S'pore Due to Deadly Virus Outbreak, The Strait Times, 31 July 2023. Available at: https://www.straitstimes.com/singapore/barramundi-group-stops-farming-sea-bass-in-s-pore-due-to-deadly-virus-outbreak?close=true
[44] A. Muniesa, B. Basurco, C. Aguilera, D. Furones, C. Reverté, A. Sanjuan-Vilaplana, M.D. Jansen, E. Brun, S. Tavornpanich, Mapping the knowledge of the main diseases affecting sea bass and sea bream in Mediterranean, Transboundary Emerging Dis., 67 (2020) 1089–1100.
[45] C.J. Rodgers, C.V. Mohan, E.J. Peeler, The spread of pathogens through trade in aquatic animals and their products, Rev. Sci. Tech. Off. Int., 30 (2011) 241–256.
[46] C.R. Lavilla, Disease Development, G.D. Lio-Po, C.R. Lavilla, E.R. Cruz-Lacierda, Eds., Health Management in Aquaculture, Aquaculture Department, Southeast Asian Fisheries Development Center, Tigbauan, Iloilo, Philippines, 2001, pp. 1–8.
[47] O. Alfred, A. Shaahu, D.A. Orban, M. Egwenomhe, An overview on understanding the basic concept of fish diseases in aquaculture, Iconic Res. Eng. J., 4 (2020) 83–91.
[48] E.R. Cruz-Lacierda, Health Management in Aquaculture, 2nd ed., Southeast Asian Fisheries Development Centre, 2010.
[49] J.T. Timi, K. Buchmann, A century of parasitology in fisheries and aquaculture, J. Helminthol., 97 (2023) e4, doi: doi: 10.1017/S0022149X22000797.
[50] A.P. Shinn, J. Pratoomyot, J.E. Bron, G. Paladini, E.E. Brooker, A.J. Brooker, Economic costs of protistan and metazoan parasites to global mariculture, Parasitology, 142 (2015) 196–270.
[51] A. Mustafa, W. Rankaduwa, P. Campbell, Estimating the cost of sea lice to salmon aquaculture in eastern Canada, Can. Vet. J., 42 (2001) 54–56.
[52] Centre for Disease Control and Prevention (CDC). Available at: https://www.cdc.gov/parasites/about.html#:~:text=A%20parasite%20is%20an%20organism,Protozoa
[53] E.R. Cruz-Lacierda, Parasitic Diseases and Pests, Southeast Asian Fisheries Development Centre, 2001.
[54] B.C. Kua, What is the Risk of Leech Infestation in Cultured Marine Seabass, FRI Newsletter, 2008.
[55] R. Ravi, Z.S. Yahaya, *Zeylanicobdella arugamensis*, the marine leech from cultured crimson snapper (*Lutjanus erythropterus*), Jerejak Island, Penang, Malaysia, Asian Pac. J. Trop. Biomed., 7 (2017) 473–477.
[56] Murwantoko, S.L.C. Negoro, A. Isnansetyo, Zafran, Short communication: identification of marine leech and assessment of its prevalence and intensity on culture hybrid groupers (*Epinephelus* sp.), Biodiversitas, 19 (2018) 1798–1804.
[57] E.R. Cruz-Lacierda, J.D. Toledo, J.D. Tan-Fermin, E.M. Burreson, Marine leech (*Zeylanicobdella arugamensis*) infestation in cultured orange-spotted grouper, *Epinephelus coioides*, Aquaculture, 185 (2000) 191–196.
[58] K. Nagasawa, D. Uyeno, *Zeylanicobdella arugamensis* (Hirudinida, Piscicolidae), a leech infesting brackish-water fishes, new to Japan, Biogeography, 11 (2009) 125–130.
[59] S. Azmey, M. Taruna, H. Taha, T. Arai, Prevalence and infestation intensity of a piscicolid leech, *Zeylanicobdella arugamensis* on cultured hybrid grouper in Brunei Darussalam, Vet. Parasitol.: Reg. Stud. Rep., 20 (2020) 100398, doi: 10.1016/j.vprsr.2020.100398.
[60] A.P. Shinn, A. Avenant-Oldewage, M.G. Bondad-Reantaso, A.J. Cruz-Laufer, A. García-Vásquez, J.S. Hernández-Orts, R. Kuchta, M. Longshaw, M. Metselaar, A. Pariselle, G. Pérez-Ponce de León, P.K. Pradhan, M. Rubio-Godoy, N. Sood, M.P.M. Vanhove, M.R. Deveney, A global review of problematic and pathogenic parasites of farmed tilapia, Rev. Aquacult., Supplement: Tilapia health: quo vadis? Guest Editors: Devin Bartley, Michael Philips, Kevin Fitzsimmons, Richard Arthur, Melba G. Bondad-Reantaso. This supplement was supported by a grant from Food and Agriculture Organization of the United Nations, 15 (2023) 92–153.
[61] E. Suyanti, G. Mahasri, W.P. Lokapirnasarai, Marine Leech *Zeylanicobdella arugamensis* infestation as a predisposing factor for *Vibrio alginolyticus* infection on the Hybrid Grouper "Cantang" (*Epinephelus fuscoguttatus* × *Epinephelus lanceolatus*) from traditional ponds in the Kampung Kerapa Lamongan East Java Indonesia, IOP Conf. Ser.: Earth Environ. Sci., (2021) 718, doi: 10.1088/1755-1315/718/1/012035.
[62] World Organisation for Animal Health (WOAH), Diseases Listed by WOAH. Available at: https://www.woah.org/fileadmin/Home/eng/Health_standards/aahc/current/chapitre_diseases_listed.pdf
[63] World Organisation for Animal Health (WOAH), Quarterly Aquatic Animal Disease Report (Asia and Pacific Region), 2021. Available at: https://rr-asia.woah.org/wp-content/uploads/2021/05/qaad-2020-4q.pdf
[64] V. Hou, C.D. Khan, S. Thay, The Status of Aquatic Animal Health in Cambodia, F.A. Aya, L.D. de la Peña, N.D. Salayo, E.A. Tendencia, Eds., Proceedings of the International Workshop on the Promotion of Sustainable Aquaculture, Aquatic Animal Health, and Resource Enhancement in Southeast Asia Tigbauan, Iloilo, Philippines: Aquaculture Department, Southeast Asian Fisheries Development Center, 2021, pp. 131–137.
[65] Y. Evan, N.E. Putri, Status of Aquatic Animal Health in Indonesia, Country Paper, 2015.
[66] World Organisation for Animal Health (WOAH), Quarterly Aquatic Animal Disease Report, Malaysia, 2021.
[67] World Organisation for Animal Health (WOAH), Quarterly Aquatic Animal Disease Report, Myanmar, 2021.
[68] H.T. Dong, G.A. Ataguba, P. Khunrae, T. Rattanarojpong, S. Senapin, Evidence of TiLV infection in tilapia hatcheries from 2012 to 2017 reveals probable global spread of the disease, Aquaculture, 479 (2017) 579–583.
[69] T.H. Tran, V.T.H. Nguyen, H.C.N. Bui, Y.B.T. Tran, H.T.T. Tran, T.T.T. Le, H.T.T. Vu, T.P.H. Ngo, Tilapia Lake Virus (TiLV) from Vietnam is genetically distantly related to TiLV strains from other countries, J. Fish Dis., 45 (2022) 1389–1401.
[70] S.R.K. Sharma, G. Rathore, D.V. Verma, N. Sadhu, K.K. Philipose, *Vibrio alginolyticus* infection in Asian seabass (*Lates calcarifer*, Bloch) reared in open sea floating cages in India, Aquacult. Res., 44 (2013) 86–92.
[71] E.V. Alapide-Tendencia, L.D. de la Peña, Bacterial Diseases, G.D. Lio-Po, Y. Inui, Eds., Health Management in Aquaculture, 2nd ed., Aquaculture Department, Southeast Asian Fisheries Development Center, Tigbauan, Iloilo, Philippines, 2010, pp. 52–76.
[72] R. Novriadi, Vibriosis in aquaculture, OmniAkuatika, 12 (2016) 1–12.
[73] World Organisation for Animal Health (WOAH). Acute Hepatopancreatic Necrosis Disease. Available at: https://www.woah.org/fileadmin/Home/eng/Health_standards/aahm/current/chapitre_ahpnd.pdf

[74] Murwantoko, S.L.C. Negoro, A. Isnansetyo, Zafran, Life cycle of marine leech (*Zeylanicobdela arugamensis*) from cultured cantik hybrid grouper (*Ephinephelus* sp.) and their susceptibility against chemicals, Aquacult. Indonesiana, 18 (2017) 72–76.
[75] M.D. Shah, B.A.V. Maran, M. Iqbal, F.F. Ching, M.T. Mohamad Lal, R.B. Othman, R. Shapawi, Antiparasitic activity of the medicinal plant *Dillenia suffruticosa* against the marine leech *Zeylanicobdella arugamensis* (Hirudinea) and its phytochemical composition, Aquacult. Res., 51 (2019) 215–221.
[76] D.B. Vaughan, A.S. Grutter, K.S. Hutson, Cleaner shrimp are a sustainable option to treat parasitic disease in farmed fish, Sci. Rep., 8 (2018) 13959, doi: 10.1038/s41598-018-32293-6.
[77] K. Buchmann, Control of parasitic diseases in aquaculture, Parasitology, 149 (2022) 1985–1997.
[78] S. St.-Hilaire, T.H. Cheng, S.C.H. Chan, C.F. Leung, K.M. Chan, K.Z. Lim, W. Furtado, G.B. Gomes, Emamectin benzoate treatment of hybrid grouper infected with sea lice in Hong Kong, Front. Vet. Sci., 8 (2021) 646652, doi: 10.3389/fvets.2021.646652.
[79] E.R. Cruz-Lacierda, G.E. Erazo-Pagador, Physical, Environmental, and Chemical Methods of Disease Prevention and Control, G.D. Lio-Po, Y. Inui, Eds., Health Management in Aquaculture, 2nd ed., Aquaculture Department, Southeast Asian Fisheries Development Center, Pagador, Tigbauan, Iloilo, Philippines, 2010, pp. 213–228.
[80] B.C. Kua, M.N. Abd. Malek, H.C. Kok, Reoccurrence of Marine Leech *Zeylanicobdella argumensis*, a marine fish parasite following a freshwater bath, Biomed. J. Sci. Tech. Res., 22 (2019) 16881–16884.
[81] I. Loomis, Researchers in the Tropics Take a Hard Look at Peppermint Shrimp in Parasite Control in Aquaculture Takes Teamwork, Global Seafood Alliance, 2019. Available at: https://www.globalseafood.org/advocate/parasite-control-in-aquaculture-takes-teamwork/
[82] B.C. Kua, N.A. Arbi, R&D Innovations on Fish Health Management and Disease Control, Fisheries Research Institute, Department of Fisheries Malaysia, 2022.
[83] R.P.E. Yanong, C. Erlacher-Reid, Biosecurity in Aquaculture, Part 1: An Overview, Southern Regional Aquaculture Centre Publication, 2012. Available at: http://fisheries.tamu.edu/files/2013/09/SRAC-Publication-No.-4707-Biosecurity-in-Aquaculture-Part-1-An-Overview.pdf
[84] E.C. Amar, J.M.E. Almendras, Immunity and Biological Methods of Disease Prevention and Control, G.D. Lio-Po, Y. Inui, Eds., Health Management in Aquaculture, 2nd ed., Southeast Asian Fisheries Development Centre, 2010.
[85] K.K. Bera, S. Karmakar, P. Jana, S. Das, S. Purkait, S. Pal, R. Haque, Biosecurity in aquaculture: an overview, Aqua Int., (2018) 42–46.
[86] WOAH, Aquatic Animal Health Code, 22nd ed., World Organisation for Animal Health, 2019. Available at: https://rr-europe.woah.org/wp-content/uploads/2020/08/oie-aqua-code_2019_en.pdf