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Biosecurity: Reducing the burden of disease

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Abstract

The challenges and problems of managing good biosecurity are wide-ranging and multifactorial with many compounding factors to pre-dispose farmed stocks to an increased risk of infection with consequential stock losses. Many challenges are anthropogenic in origin and may be the result of the physical location (site) and/or the poor design of the production facility (i.e., water re-use; lack of zoning based on biosecurity risk, etc.) as well as from inappropriate decisions and practices made once the site is in production (i.e., pushing the system for increased biomass production). There is a need for better regulation and health legislation across aquaculture—an industry that embraces the culture of >500 species. In the absence of regulatory frameworks and culture guidelines, it is difficult for farmers to apply certain measures such as maximum stocking densities and maximum allowed biomass, conduct disease surveillance and regular health checks, and report diseases to relevant authorities for advice. In this review, we have identified several issues which are continuing to challenge the design and implementation of efficient and effective biosecurity strategies and protocols at all levels, requiring attention over the coming decade. They are, not in any order of priority: (a) healthy seed, (b) emergency preparedness and response, (c) diagnostics, (d) microbial management at the production level, (e) disease and pathogen surveillance,

(f) trade in aquatic species, (g) policies and regulatory framework, (h) welfare, (i) research and technology development, (j) antimicrobial resistance, (k) non-conventional ways of pathogen transfer, and (l) Progressive Management Pathway.

KEYWORDS
diagnostics, microbial management, pathogen surveillance, policies and regulatory frameworks, progressive management pathway (PMP), seed quality, welfare

1 | INTRODUCTION

Aquatic products (i.e., fish, crustaceans, molluscs, and other aquatic animals, but excluding aquatic mammals, reptiles, seaweeds, and other aquatic plants) derived from aquaculture are an important, nutritious, and chosen food commodity with high consumer demand, requiring continuously increasing volumes of supplies. According to Food and Agriculture Organization (FAO) fisheries and aquaculture statistics, aquaculture accounted for 56.2 percent of combined global fisheries and aquaculture production in 2020 (122.58 million tonnes produced with a value of USD 281.5 billion; FAO FishStatJ, 2022). Aquaculture production accounted for 47.8 percent of fish for human consumption over the same year. With marine fish catches relatively static since the late 1980s, aquaculture has been responsible for the continuing impressive growth in the supply of fish for human consumption. If fish production and trade take place as "business as usual" (supply based on continued recent growth trends), there will be a significant demand–supply gap by 2030. Recent trends confirm that global aquaculture will continue to expand, diversify, and intensify over the coming decades, to bridge the demand–supply gap. What is important is that we bring our past experiences in tackling the hurdles and bottlenecks of sector growth, to ensure that this predicted expansion and intensification will result in sustainable aquaculture development and production.

One of the toughest hurdles that the aquaculture sector experienced in the past is reducing the socio-economic burden of disease and managing the health of cultured species. Disease is a major constraint to global aquaculture production. Conservative estimates suggest that 10 percent of all cultured aquatic animals are lost on a global scale, because of infectious diseases alone, amounting to over 10 billion USD in lost revenue annually (Shinn et al., 2015a). During the past two decades, we witnessed increasing incidents of emergence and re-emergence of pathogens and diseases. It has also become apparent that when a disease emerged or re-emerged, it spread across the region and beyond, regardless of water or land barriers. This concludes that the movement of pathogens and the spread of diseases are much related to the movement of fish, especially live animals destined for aquaculture or the ornamental fish industry. There are also other routes of pathogen transfer such as wild reservoirs, ballast water, biofouling, microplastics, and water currents. Considering the unaffordable socio-economic burdens that resulted in disease outbreaks and the complex nature of their spread, modern aquaculture disease control and health management strategies call for the application of a holistic approach, encompassing total biosecurity. In this regard, FAO recently stated that "a paradigm shift is needed in dealing with aquaculture biosecurity risks." By the time, the pathogen has been identified and its host range determined, it may have already become widespread globally (including to wild populations), through the movement of live animals of uncertain health status, most often for aquaculture development.

Biosecurity in aquaculture consists of practices that minimize the risk of pathogen transfer, establishment, and spread. These include practices for reducing the stress on fish, thus making them less susceptible to pathogens/disease. Over the past four decades, many disease outbreaks and mass mortality events in aquatic populations occurred, causing serious production losses and consequently food availability and job loss when farms are closed and markets affected, which have increased the awareness of the importance of biosecurity. Detailed analysis and assessment of the specific segments of the aquaculture value chain when pathogens may be introduced or disease may develop help us to develop precautionary measures.

According to FAO's novel approach—Progressive Management Pathway (PMP)—aquaculture biosecurity is defined as "cost-effective management of risks posed by pathogenic agents to aquaculture through a strategic approach at enterprise, national and international levels with shared public-private responsibilities." Main components of a holistic and progressive biosecurity management approach should include, among others: (a) animal management—obtaining healthy stocks and optimizing their health and immunity through good husbandry, (b) pathogen management—preventing, reducing, or eliminating pathogens, (c) people management—educating and managing relevant stakeholders, (d) appropriate research and more importantly (e) the conducive policy.

1.1 | Historical perspective

Globally, a trend in aquaculture is that a previously unreported pathogen that causes a new and unknown disease will emerge, spread rapidly, including across national borders, and cause major production losses approximately every three to five years. Similarly, the re-emergence of previously known diseases of reported pathogens takes place across borders. It is evident that the inadvertent transfer of pathogens through the uncontrolled or unregulated movement of fish is generally responsible for the spread of pathogens across borders. There are many such examples of transboundary outbreaks of fish disease over the past decades.

The last three decades have shown how government authorities, industry, and all stakeholders were and are still being challenged by serious diseases and mass mortality events (MMEs) of farmed and wild populations of aquatic organisms. Since 2009, for example, new pathogens and diseases, such as acute hepatopancreatic necrosis disease (AHPND), tilapia lake virus (TiLV), white feces syndrome (WFS), and more recently *Enterocytozoon hepatopenaei* (EHP), and the decapod iridescent virus 1 (DIV1) of cultured shrimp, prawn, and crayfish have emerged without warning. This is mostly related to the use of wild broodstock or broodstock exposed to wild animals (i.e., from cages) or fed with infected fresh/live feeds where the pathogen finds a new susceptible host (i.e., AHPND and EHP). Known diseases appeared into new geographical localities, for example, white spot disease (WSD) in the Kingdom of Saudi Arabia and Australia, koi herpesvirus (KHV) in Iraq, multinucleate spore X (MSX—*Haplosporidium nelsoni*) in Canada, epizootic ulcerative syndrome (EUS) in the Democratic Republic of Congo and Malawi, infectious myonecrosis virus (IMNV) in India and Malaysia, and infectious spleen kidney necrosis virus (ISKNV) in Ghana. Responses to aquatic disease outbreaks and MMEs varied, depending on the causative pathogen of concern and the industry affected. In most cases, losses were economically significant (Table 1), despite the lack of systematic economic evaluations.

1.2 | Global aquaculture conference 2000 and 2010

FAO has been promoting the importance of aquatic animal health management and aquatic biosecurity, especially in the aquaculture sector, over the past three decades. In February 2000, some 540 participants from 66 countries participated in the "Conference on Aquaculture in the Third Millennium" in Bangkok, Thailand. This Conference was organized by the Network of Aquaculture Centres in Asia-Pacific (NACA) and the FAO and hosted by the Government of Thailand. Against this background, the Conference participants discussed strategies for the development of aquaculture for the next two decades, in light of the future economic, social, and environmental issues and advances in aquaculture technologies. Based on these deliberations, the participants of the Conference adopted the Bangkok Declaration. This historical declaration explicitly called for efforts to improve aquatic animal health management. The declaration stated that:

TABLE 1 Examples of estimated losses because of diseases of aquatic organisms.

Period	Species group	Disease	Losses (USD)	Reference
1983	freshwater finfish	*Lernaea cyprinacea*	11.4 million	Djajadiredja et al. (1983)
1987–1994	shrimp	several pathogens	3019 million	Israngkura & Sae-Hae (2002)
1998–1999	salmon	infectious salmon anemia	39 million	Hastings et al. (1999)
1957-present	American oysters	*Haplosporidium nelsoni*	>133 million	Shinn et al. (2015b)
2002–2004	common carp and koi carp	koi herpesvirus	0.5 to 25 million	Bondad-Reantaso et al. (2007)
2002–2012	shrimp	infectious myonecrosis virus	1 billion	Lightner et al. (2012)
2010–2018	shrimp	acute hepatopancreatic necrosis disease (AHPND)	12 billion	Shinn et al. (2018)
2017	tilapia	several pathogens	450 million	BoF ARAAH (2018)
2017	shrimp	several pathogens	1.6 billion	BoF ARAAH (2018)
2017	oysters	several pathogens	540 million	BoF ARAAH (2018)
2017	seaweed	several pathogens	190 million	BoF ARAAH (2018)

Disease is currently an important constraint to aquaculture growth which has impacted both socio-economic development and rural livelihoods in some countries. Addressing aquatic animal health issues has, therefore, become an urgent requirement for the sustainable growth of aquaculture, especially through proactive programs. Harmonizing health protection approaches and measures and effective cooperation at national, regional, and inter-regional levels are needed to maximize the effectiveness of limited resources. This can be achieved through:

- developing, harmonizing, and enforcing appropriate and effective national, regional, and inter-regional policies and regulatory frameworks on the introduction and movement of live aquatic animals and products to reduce the risks of introduction, establishment, and spread of aquatic animal pathogens and resulting impacts on aquatic biodiversity.
- capacity building at both the institutional and farmer levels through education and extension.
- developing and implementing effective national disease reporting systems, databases, and other mechanisms for collecting and analyzing aquatic animal disease information.
- improving technology through research to develop, standardize, and validate accurate and sensitive diagnostic methods, safe therapeutants, effective disease control methodologies, and studies into emerging diseases and pathogens.
- promoting holistic systems approach to aquatic animal health management, emphasizing preventative measures, and maintaining a healthy culture environment; and
- developing alternate health management strategies such as the use of disease-resistant, domesticated strains of aquatic animals to reduce the impact of diseases.

Establishment of an effective international mechanism, such as an international task force that is outcome-oriented with focused strategies and milestones that are independent of vested interests, would be beneficial in reducing the losses because of diseases in aquaculture.

Ten years later, in 2010, FAO and NACA revisited the Bangkok Declaration and assessed the progress made in implementing its recommendation. The participants of the Global Conference on Aquaculture 2010 agreed that progress has been made in implementing the provisions of the Bangkok Declaration and Strategy; the Strategy continues to be relevant to the aquaculture development needs and aspirations of States; and there are elements of the Strategy that require further strengthening to enhance its effectiveness, achieve development goals and address persistent and emerging threats. They confirmed that these global accords, with the Bangkok Declaration and Strategy as the core instrument for aquaculture development, shall continue to guide the development and management of aquaculture beyond 2010 through the first quarter of this century.

1.3 | Achievements, issues, and challenges

Since the 2000 conference on aquaculture in the third millennium, there has been much progress in the understanding and control of diseases of certain cultured species. Examples of some major accomplishments include the development and widespread use of specific pathogen-free (SPF) stocks to supply farmers with clean seed stocks, sensitive and rapid molecular detection methods for pathogens, and innovative culture systems. The rate of these new innovations is increasing. Greater research efforts, however, are required to develop health management tools and strategies for low-value and affordable species, such as carps, tilapias, and catfishes, where the production is largely contributed by smallholders. Despite these advances, the translation of new knowledge into global practical applications has been slower and more patchier than desired, mainly because of inadequate dissemination and acceptance of new knowledge and technologies at the grass-roots level. In addition, farmers are often confused by non-aligned claims from academicians and commercial suppliers. Improving the situation will depend on the physical, economic, and human resources available in each country and on the level of priority that its government assigns to aquaculture. From the governance perspective, it is evident that many governments and national authorities have invested in improving and expanding national biosecurity governance capacities with mixed success.

In this review, the following issues which will continue to challenge the design and implementation of good aquatic biosecurity are discussed: (a) healthy seed, (b) emergency preparedness and response, (c) diagnostics, (d) microbial management at the production level, (e) disease and pathogen surveillance, (f) trade in aquatic species, (g) policies and regulatory frameworks, (h) welfare, (i) research and technology development, (j) antimicrobial resistance, (k) non-conventional ways of pathogen transfer, and (l) Progressive Management Pathways (PMP).

1.4 | Healthy seed

Years of experience have now convinced the aquaculture industry and community that the use of clean and healthy seed should be given high priority in biosecurity for preventing disease outbreaks and subsequent losses. We now understand that infection does not necessarily imply disease and often, because of the culture conditions, infected broodstock, in many species, does not show signs of disease. The fact that disease is not manifested in broodstock, does not imply they are not infected and that, therefore, offspring will not be infected. Quite the contrary, it can be assumed that any pathogen present in broodstock is likely to be transmitted to the offspring through different pathways. The use of infected broodstock, therefore, can perpetuate diseases in the production cycle.

Exclusion of pathogens is a strategy that has been practiced in agriculture for decades. The Specific Pathogen Free (SPF) strategy used in aquaculture was copied from the poultry industry developed in the 1950s when they realized that poultry research was dependent on the use of animals free of pathogens. The first aquaculture species that entered an SPF process was the whiteleg shrimp, *Penaeus vannamei*, in the late 1980s. These were initially developed for research purposes as the pathogen/disease variable is removed from experiments and has become fundamental for research purposes. SPF, also, has been the basis of the most successful breeding programs, and over the years, SPF shrimp jumped into industrial-scale commercial operations taking the lead within the aquaculture industry and allowing the exponential growth of *P. vannamei* in Asia. The SPF strategy is nowadays also applied in the salmon industry and is increasingly being embraced by other aquaculture species (i.e., Mediterranean species, barramundi, tilapia, and Chinese mandarin fish). It has been proven, beyond doubt, that developing, maintaining, and using domesticated SPF shrimp stocks reduces the risk of disease outbreaks in shrimp aquaculture and allows intensification increasing production and profit.

The most accurate definition till now is that SPF animal stocks must come from a population that has tested negative for specific pathogens for a period of at least two consecutive years, has been raised in highly biosecure facilities following stringent biosecurity management measures, and has been fed with biosecure feeds. To be able to maintain and claim SPF status, a suitable surveillance program for the specific pathogens, including both molecular and histopathological tools, must be in place. As mentioned above, SPF stocks are not necessarily free of all pathogens. Thus, a list of pathogens from which the animals are claimed to be free should always accompany them (Alday-Sanz et al., 2020).

SPF is a fundamental strategy for the sustainability of shrimp farming (including extensive and semi-extensive systems with low/no biosecurity), with increasing evidence showing that they have reduced the introduction of pathogens and disease expression in farms and provided a means for the safe introduction of *P. vannamei* around the world—the species of choice and the dominant species in shrimp farming. Optimizing the use of SPF stocks will secure sustainable and healthy production. However, accessibility of SPF seed to smallholder farmers is still a challenge in many countries, because of its availability and affordability. We believe, with the wider acceptability and use, demonstrating significant economic benefits, will improve the use of SPF seed in smallholder farming in the coming years.

The main economic burden of diseases in aquaculture happens in grow-out operations as it is the longest period of the culture, the lower the possibility of exclusion of pathogens, and where a significant part of the investment accumulates over time, with feed being the main cost. The use of infected fry reduces the chances of a successful crop and contributes to the increase of pathogens in the environment and the perpetuation of diseases in the area. Even if a high level of biosecurity cannot be maintained during the grow-out phase, using SPF fry will decrease the chances of infection and reduce the prevalence and impact of the disease. The horizontal transmission of pathogens is less efficient than those transmitted vertically. It needs to be understood that SPF only refers to the health status of the stocks, not to their degree of tolerance or resistance to a particular disease. Other approaches such as Specific Pathogen Tolerant (SPT) or Specific Pathogen Resistant (SPR) need to be considered in addition (Alday-Sanz, 2018). In the case of fish, tolerance can be achieved through vaccination while resistance has a genetic origin.

Developing and maintaining SPF stocks imply a significant technical and financial challenge that is often not affordable by individual companies and small producers. However, this is a small, centralized investment compared with the widespread cost of diseases in farms. The main steps of SPF development imply the acquisition of the diagnostic capacity for all known pathogens of the target species (at the molecular and histological level), the understanding of the pathogenesis of each of the targeted diseases, the collection and individual maintenance of the animals and the sequential testing at different stages of production. Introduced animals need to be kept individually, non-lethal testing performed and any positive animal discarded. After controlled mating and testing of the offspring, lethal sampling of the broodstock is performed. Any sign of pathogens, known or unknown, would imply the rejection of the offspring. Testing will continue at different stages of production until the cycle is completed.

The use of SPF stocks as part of a biosecurity strategy has proven to be profitable and the way forward to reduce the economic burden of disease. Now, the challenge presented to the industry for the next decade is how to make SPF stocks available to a wider range of farmers, particularly small producers, with different types of culture systems and, in the development of SPF stocks for other species used in aquaculture.

1.5 | Emergency preparedness and response

Emergency preparedness has, traditionally, been developed based on experience from unprepared, or incompletely planned, responses to aquatic organism disease emergencies. This is not, however, a model that is economically sustainable and that also undermines confidence in aquaculture development. Learning from these experiences is important. Pre-emergency and contingency investment in insurance, especially for high-value species, has become a welcome trend.

In an emergency, all hands work together, but also learn each other's weaknesses and strengths. If the post-mortem does not build on that learning process, it is destined to be repeated for the next disease outbreak. Disease management success defaulted to pre-disease emergency "*status quo*," rather than investment in preparedness to ensure the next outbreak response would be more effective. Transparent reporting is of utmost importance. However, there is no longer a plausible excuse, with so many international examples as well as guidelines, audit systems, and shared experiences, to avoid investment in prevention strategies and infrastructure, which can offset the much greater cost of repeated response/emergency approaches.

Challenges encompassing technical, resource management, public relations, communication, information management, and endurance will always be there, and these need to be curbed. Dealing with such emergencies requires the following: (a) speed of response, decision making, and action; (b) systems of information management and communication; and (c) good science. The overall objective must be to minimize the risk of disease entering a country; maintaining alertness or vigilance will be essential to achieve this.

Following investments are essential to reduce losses from aquatic animal disease:

- Prevention strategies and back to basics: good aquaculture and best biosecurity practices at the farm level.
- Contingency plans to guide operational and technical response actions to emergency events including emergency preparedness response system audits.
- Education of risks at all levels including at the farm level—to support timely assessment of the threat from new or expanding species.
- Surveillance programs and diagnostic service provision at the local level to detect and identify the emergence and spread of diseases.
- Proactive and transparent reporting of serious disease outbreaks for early warning notifications.
- Enhancing the skills and knowledge of local front liners including dry-run or table-top exercises.
- Emergency preparedness is a core function of government services; thus, the need for legislation and commitment, and co-management of outbreaks and MMEs as a shared responsibility of both state and non-state actors; and
- Advance financial planning toward the allocation of emergency funds.

1.6 | Diagnostics

Advance molecular biological research efforts have allowed a better understanding of pathogen biology, pathogenicity, and behavior, which has resulted in better and more rapid diagnostic procedures and tests. However, molecular techniques have limitations in terms of disease diagnosis capacity and assessment of the viability of the pathogens for risk assessments (i.e., in aquatic products or aquaculture feeds). Molecular techniques have largely displaced tissue-based techniques (histology or wet mounts) that generate much more information and allow for a suitable interpretation of the health status and disease process. The shift toward molecular techniques and the near abandonment of the tissue-based technique has resulted in the loss of diagnostic accuracy and proper response. Further, making these techniques readily available and affordable to smallholder producers is a challenge. There is a need to rebuild capacity on these techniques at the government, academic, and industry levels. Until we have molecular techniques accessible and affordable to smallholders and remote producers, we should continue to use basic tissue-based techniques and build diagnostic capacity with properly trained fish health professionals which should be considered a priority.

Most molecular tests and tools are typically focused on commercially important, high-value species. The development of affordable, easy, and rapid diagnostic tests for mass-produced freshwater species is equally important. In the field of diagnostics, what is currently lacking and not given priority for development are accurate and affordable farm-level diagnostic tools for diseases and pathogens of mass-produced freshwater species such as carp and tilapia.

Although these species rank high in global production, silent mortalities because of undetected and unrecognized diseases are causing considerable production losses.

Molecular diagnostic technologies based on sequencing with the capacity to detect nucleic acids (DNA, RNA) of taxonomically diverse agents (from RNA viruses to metazoan parasites) are now in regular use. Conceptually, these approaches may propel not only our ability to detect more diverse pathogenic agents present in animals and the environment (eDNA), but also will challenge the single-agent/single-disease paradigm and lead to a wider acceptance that "pathobiomes and pathomicrobiomes" (mixtures of agents present in specific disease states) may underpin observations of clinical disease in both wild and farmed aquatic animal populations. Sequencing technologies also provide the capacity to profile symbionts in hosts where clinical disease is not observed. Linking host biome profiles of healthy populations and those suffering high levels of disease to broader environmental (e.g., climate, season, farming system) and host (e.g., genetics, feed type) metrics will provide a potentially powerful approach for defining those on-farm conditions which best support successful outcomes.

Proper disease diagnosis needs to consider the cultural conditions and management practices prior to the disease outbreak. Sending samples to diagnostic laboratories that do not grasp this type of information leads to wrong diagnosis and a misleading emphasis on bacteria as primary pathogens, with the subsequent misuse of antimicrobials. Farm-level health management can be improved by enhancing the capability of individual farmers to carry out health checks on their farms in "real-time" (i.e., within a time frame that allows effective decision making on therapeutic or preventative actions). Point of care diagnostics (POCDs), or in simple terms "pond-side diagnostics" are tests that are designed to be used on-site to provide rapid results without the need for dedicated laboratory facilities. They can facilitate decision making on the health status of animals without the delays associated with conventional laboratory testing. POCDs can be used in the investigation of disease outbreaks; in passive and active health surveillance for pathogen screening; as an early warning system to prevent disease outbreaks; in sanitary control points during production and, in certification for animal movements.

The rapid pond-side diagnosis of the disease can be supported through the development of RPA (Recombinase Polymerase Amplification) based testing strips and lateral flow cassettes to detect the presence of specific pathogens, based on host-specific DNA, RNA, or proteins, in a sample (Shahin et al., 2018; Shyam et al., 2022; Wang et al., 2018). Both are quick, easy to use, low in cost, and do not require specialized laboratory equipment or expertise. Farmers can perform the tests on-site, without the need for expensive and time-consuming sample transport to a central laboratory. RPA-based testing strips are based on the amplification of specific DNA or RNA sequences in a sample, which can then be detected using a colorimetric reaction. Lateral flow cassettes, however, use immunochromatography and depend on the binding of specific antibodies to the target substance, which produces a visible signal, typically a color change. One of the main advantages of RPA-based testing strips over lateral flow cassettes is their higher sensitivity and specificity; they can also be adapted to detect different strains or variants of a disease-causing organism, allowing for more targeted and effective treatment strategies. Limitations to the use of RPA-based testing strips include the need for careful sample preparation and storage, they may require equipment to perform the test, they can be more costly than lateral flow cassettes, and there is a potential for false positives or false negatives if the strips are not used correctly.

Accessibility to smartphones has already revolutionized many industries; by providing affordable access to mobile technology, farmers in remote and underserved areas can use smartphones to access expert systems and associated databases by helping them with the real-time and accurate diagnosis of diseases. These systems can be accessed through a smartphone app, allowing farmers to access information quickly and easily about various diseases, their symptoms, and the appropriate treatment options. Image analysis and expert systems have the potential to revolutionize the rapid pond-side diagnosis of aquatic diseases. By using computer vision algorithms, image analysis can quickly and accurately detect visual symptoms of diseases in aquatic organisms, such as changes in color, texture, and morphology (Mia et al., 2022). Expert systems can then use this information to provide a diagnosis based on established criteria and rules, thereby greatly improving the speed and accuracy of diagnosis, and allowing for prompt management decisions. Image analysis-based systems can be trained to recognize subtle symptoms that may be missed by human observation, increasing the sensitivity of disease detection. Moreover, these systems can be designed to provide customized recommendations based on the specific conditions and characteristics of the farmer's ponds or aquaculture systems. This can help farmers optimize their disease management strategies and improve the overall health and productivity of their farm stock. Investment in expert systems and associated databases can also help democratize access to knowledge and expertise in the field of aquaculture, allowing even small-scale farmers to benefit from the latest advances in health management. By making these technologies accessible and affordable, it will be possible to help promote sustainable and responsible aquaculture practices that benefit both farmers and the environment. There are, however, potential challenges and limitations to the use of image analysis and expert systems as pond-side diagnostic tools. These include the need for high-quality images, appropriate lighting, and accurate interpretation of results. The accuracy of the diagnosis will depend on the quality and comprehensiveness of the data used to train the system.

There is a balance to be sought between response time, accuracy, and cost. Performance or errors of low-cost devices may be because of manufacturing quality, for example, leakage of chemicals between plastic compartments in some lateral flow systems. By contrast, the higher costs associated with the building of more sophisticated diagnostic instrumentation may be offset by more reliable diagnoses. For all these objectives, there is a paramount need for continual communication, training, and education in the interpretation of diagnostic results based on the technique used. In the absence of pond-side diagnostics and health management support, there may be losses because of treatment failures (incorrect diagnosis, wrong medicine, and/or dose). Likewise, disease episodes follow when there is a failure to recognize a problem or, more commonly, when there are lapses in biosecurity (i.e., excessive biomass, human nature to take shortcuts; lack of disinfection, or health screening). In many cases, problems arise from failure in equipment (i.e., oxygenation, power, water exchange), lack of awareness and failures in communication between managers and operators; lack of training in the quality and detail of the information that is shared; when assumptions are made in technical abilities without quality control (i.e., checking proficiency in the use and interpretation of analytical equipment); and, in the lack of knowledge transfer within teams (i.e., knowledge is lost when there is a high turnover of staff).

The Snieszko epidemiological triad that shows the interaction between a pathogen and susceptible environment that allows transmission of the pathogen and development of disease in a population and the three levels of diagnostics (Level I, II, and III) long promoted by FAO remain valid and essential as a continuum of observations from the field to the laboratory and the overall environmental conditions to reach an accurate diagnosis of disease.

Advanced molecular biological research efforts have allowed for a clearer understanding of pathogen biology, pathogenicity, and behavior which has resulted in improvements in the speed and diagnostic capabilities. In evaluating the biosecurity risks of aquafeeds, however, it should be stressed that current existing molecular diagnostic techniques do not allow for a comprehensive assessment, in neither characterizing the potential source of the pathogen, nor its viability status, and so are inadequate for the purpose. On the other hand, culture/in-feed trials as a gold standard may be able to challenge the question of pathogen viability, but this approach is too slow and most likely an impediment to commercial production.

Biosecurity risk evaluation of aquafeeds by means of PCR remains a widespread practice in the aquaculture industry. PCR could produce positive results even if there are no viable infective agents in the feed samples tested (Munkongwongsiri et al., 2021). Therefore, using PCR for testing feeds for infective agents is not considered accurate. Positive PCR results, even if not infectious, can lead to reputational damage, loss of client confidence, product recalls, restricted choice of feed ingredients, and trade barriers (Werbrouck et al., 2021). Feeds tested as PCR positive, even without viable infectious agents, could lead to PCR-positive results in animals fed with such feeds. This may mislead the assessment of the health status of the populations tested Leading to wrong diagnosis, rejection of larvae, or even loss of SPF status and depopulation of facilities. There is, therefore, an urgent need for reviewing current approaches with the development of appropriate and practical diagnostic techniques that would differentiate between viable pathogens (infectious) and nucleic acids (non-infectious) presence. In the interim, feed manufacturers may reduce this problem by screening the raw material used and producers may benefit from considering the manufacturing conditions of the ingredients and aquafeeds when evaluating the biosecurity status of aquafeed. Manufacturing facilities should be able to provide reliable production data to demonstrate that minimum pathogen inactivation levels have been achieved. For example, OIE (2019) provides guidelines on how to inactivate pathogens like WSSV during the production process.

In WOAH's Aquatic Animal Health Code, chapter 4.8 "Control of Pathogenic Agents in Aquatic Animal Feed" (OIE, 2015), WOAH confirms that extensive processing such as heat treatment, acidification, extrusion, and extraction results in a negligible risk for pathogen survival in aquafeed ingredients. There are, however, no details regarding the specific processing conditions that are needed to ensure the destruction or irreversible inactivation of individual pathogens. The disease-specific chapters of WOAH's Manual of Diagnostic Tests for Aquatic Animals (2023) contain some information on the conditions that result in the inactivation of pathogens, but this is limited and/or not available for all WOAH-listed aquatic pathogens. Thus, the primary goal should be to provide scientifically indisputable evidence on the conditions (temperature, pressure, moisture, irradiation, etc) that render each WOAH-listed pathogen inactive. In addition, this is to be confirmed by the testing of ingredients and aquafeeds that have been deliberately spiked with the pathogen and then produced under those conditions that should irreversibly render the pathogen inactive. Such testing, in the form of disease challenge trials including the necessary controls, must demonstrate that there is no subsequent manifestation of disease, thereby demonstrating the effectiveness of the process conditions to guarantee biosecure ingredients or aquafeeds.

The use of eDNA and eRNA can be used to determine the occurrence and transmission of pathogens in the aquatic environment and in environmental samples; however, the use of propidium monoazide-assisted qPCR and qPCR-based eRNA approaches could help in discriminating between viable and non-viable cells and in investigating non-cultivable pathogens (Kaushik & Balasubramanian, 2013; Lednicky et al., 2020; Merou et al., 2020); more research is needed to define protocols for each pathogen.

1.7 | Microbial management at the production level

The implementation of biosecurity measures becomes more and more accepted as an essential part of aquaculture farm management. Such measures range from pathogen exclusion to pathogen management within the facility. An exclusion strategy targets the prevention of entrance and spread of primary pathogenic microorganisms throughout the facility and thereby targets carriers that bring these pathogens in and spread them over production cycles. Having efficient protocols and procedures in place—with disinfection as a primary tool to kill/inactivate microbial pathogens—is an essential part of biosecurity. However, it is not enough to minimize the risk for infectious disease to occur as opportunistic or secondary pathogens may rise during the culture period. It should also be noted that in many instances antimicrobial agents are used without proper diagnosis, even for the primary pathogen or pathogens which could be a virus, parasite, or fungus. This practice must be stopped.

It is still too little realized that microorganisms inevitably grow alongside the animals in aquaculture systems, independent of whether efficient biosecurity measures are in place to keep out specific pathogens. In fact, the major number of microorganisms in the culture systems results from growth during production. The stability and composition of these in situ microbial populations have a determining role in product success. For this reason, the management of the microorganisms that grow in the system is as important as the biosecurity measures in place to keep pathogens out.

The perception of microbial management in aquaculture nowadays still exists almost exclusively out of "using disinfection to kill bad bacteria" and "using probiotics to add good bacteria." According to the definition, probiotics are live microorganisms that when administered in adequate amounts, confer a health benefit to the host. One of the main reasons why farmers use them is because these "good microbes" contribute to achieving control over the "bad microbes." The practice of adding probiotics to the feed and the culture water is now well-established in the field, and most often the only microbial management approach during production except for recirculation systems where ozone and UV are often incorporated. Despite the recorded benefits conferred to farmers, probiotics are currently still applied in a simplistic way. The practice does not fully take the ecological reality of all microbial populations growing in aquaculture systems into consideration, and for that reason cannot be expected to work to its full potential. It is to be concluded that the potential benefit of microbial management is only marginally exploited.

Traditionally, a key objective of farming activities is to keep water and feeding conditions optimal for cultured animals. A similar way of thinking is to be applied to the microorganisms that reside in the same system, that is, make the conditions optimal for benign microorganisms. In other words, microbial management in aquaculture systems should target the establishment of water and feeding conditions (or regimes) that select specific benign populations of microorganisms. The water and feeding conditions referred to are for example nutrient levels (C, N, P, etc.), water exchange rate, temperature, etc. This is conceptualized by the *r/K* selection strategy that has been proven effective for fish and shellfish larviculture and recently also for shrimp grow-out systems. By installing *r/K* selection regimes in the culture system, the competition-specialized bacteria (called *K* strategists) are promoted at the cost of fast-growing—often opportunistic—bacteria (called *r* strategists). The result is a more diverse, stable, and improved microbial community in the water dominated by neutral and beneficial microbes, which lead to beneficial fish/microbe interactions and more stable production.

It remains however unclear up to date how specific microbial selection regimes impact culture performance. From anecdotal data and empirical observations, however, it can be concluded that some types of systems appear to be less affected by unpredictable diseases, as illustrated by the following two examples. Shrimp and especially marine fish cultured in recirculation systems where the biofilter plays a crucial role in increasing the microbe-to-substrate ratios (i.e., more competition among microbes) seems to be less prone to unpredictable losses. Alternatively, integrated farming practices such as zero water exchange intensive shrimp farming whereby the effluent of the shrimp ponds is recirculated through tilapia and seaweed ponds before returning to the shrimp ponds seem to have a similar effect. It remains to be shown to what degree these system configurations indirectly are a microbial management practice that results in improved performance.

One of the main impediments to the more broad and efficient use of microbial management in aquaculture is the lack of knowledge regarding how microbial communities develop and behave in aquaculture, and how this is affected by the different types of selection regimes or manipulations that are being done during culture. There are several research initiatives in this direction, but these are in general very small in scale and very different in set-up. Consequently, generalization and synthesis of the results are difficult. For this reason, we urgently need global concerted efforts in microbiome studies involving different culture systems and species, using the most advanced microbial analytical tools currently available, as well as a coherent theoretical framework for the analysis of data. Only then, we will be able to better understand the role of bacteria in aquaculture production systems and be able to transform this knowledge into efficient microbial monitoring and management tools. This will allow us to update Good Aquaculture Practices (GAP) with more targeted microbial management protocols, such as using probiotics, to better prevent disease outbreaks and to reduce the need for disease treatment and the use of antibiotics.

Microbial management is not important only in the actual culture period, but also in proper pond preparation and in wastewater management. At the national/government levels, it would be good to see tightening of regulations regarding waste and wastewater discharge practices, and sanitary practices in territories where it is needed. Under GAP, there is a wider responsibility to the community of producers in each region working in unison to lower the burden and potential threats from deleterious bacterial species. In the same vein, this is also about corporate responsibilities in minimizing the impacts on wild species and environments outside farms.

1.8 | Disease and pathogen surveillance

While some progress exists with regard to aquatic disease surveillance, many barriers remain to the development of surveillance systems that support effective national and farm biosecurity. Although awareness has been increased and efforts have been made, aquatic animal health services are inadequate in many geographies. Trained and qualified professionals for designing and conducting surveillance programs are lacking, and there may also be a weak system of regulation by the government's Competent Authorities (CA). Consequently, national surveillance systems are also often weak, and their principal outcomes are not achieved. Specifically, many countries are unable to meet OIE (now WOAH—World Organization for Animal Health) surveillance standards necessary to demonstrate and maintain a disease-free status, preventing them from taking full advantage of the system, established by the Sanitary and Phytosanitary (SPS) agreement of the World Trade Organization (WTO), to minimize the spread of disease via trade. Delayed detection of disease outbreaks because of weak surveillance results in higher response costs to control outbreaks, or, typically, disease establishment and rapid spread. Improving surveillance and biosecurity requires strengthened Government services and regulation.

The porous interface between many aquaculture production systems and natural or wild aquatic animal populations is a principal driver of disease emergence and spread in aquaculture. Further interactions arise from the use of wild aquatic animals as broodstock or from unprocessed aquatic animal products used as aquaculture feed. Disease surveillance illuminates the pathogen diversity within wild aquatic animal populations and the potential risks for pathogen transfer between wild and cultured stocks. These insights are especially important in regions where new aquaculture ventures are planned.

The relationship between investment in surveillance (e.g., for early detection of disease incursions) and the costs of intervention to mitigate disease needs to be integrated through economic modeling into aquatic animal health decision making. This needs to be done both at national and farm levels. Passive surveillance systems will make a step change when designed around the needs of the data providers (e.g., farmers). Barriers to data procurement will be overcome as web-based and mobile interfaces become standard and will greatly contribute toward farmer-centric systems. Improved understanding of the balance between privacy and access to potentially commercially sensitive production information is needed to support health surveillance and research into aquatic animal health. This will be achieved through innovative data governance approaches and closer collaborations between producers, government, and researchers, building on animal health governance models already being established in some countries.

Enhanced data collection, compilation, integration, and analysis, based on real-time mobile and automated data capture systems and farmer-centric approaches; will progressively address the challenge of access to surveillance data. This in turn will create new challenges for data analysis (and quality assurance), requiring epidemiological and statistical tools capable of prioritizing and linking different sources and vast volumes of data, and simultaneously dealing with a myriad of complex risk factors. In turn, the improved understanding of disease risk factors will allow risk-based surveillance to become more widely applied and better focused, improving the economic efficiency of surveillance.

There will be an increasing role in the economic analysis of disease surveillance, early detection, disease control, and eradication programs. Both government and industry decision-makers will demand improved objectives and reliable and accurate evidence for the return on investment for biosecurity, surveillance, and disease control programs.

1.9 | Disease reporting and trade

Reporting of aquatic animal diseases serves two main functions, one related to trade and the other related to controlling disease The World Trade Organization's SPS Agreement recognizes the importance of disease reporting as "…Part of a multilateral framework of rules … [applied to] … sanitary and phytosanitary measures in order to minimize their negative effects on trade." The WTO has appointed WOAH (formerly OIE) as the reference organization to develop standards and guidelines for animal health with the intention of ensuring that animal health is not used unfairly as a technical barrier to trade.

These dual objectives (disease control and trade) place a great strain on the disease reporting system as they can frequently be in conflict. Reports of new diseases, or occurrences of known diseases, in one country, can lead to trade barriers being erected by other countries to avoid the introduction of the pathogen(s) involved. Such barriers are not always erected fairly, for example, when the pathogen is already present in the importing country. Aside from being contrary to the SPS Agreement and WOAH standards, this provides a clear disincentive to countries or producers to report disease outbreaks.

An effective disease reporting system requires transparency. However, because reporting is largely through the relevant national Competent Authority, it can be subject to wider political considerations. In some countries, it is an offense to report diseases except through official channels or there may be "self-censorship" of reporting to avoid negative consequences.

The cost of establishing a national system of reporting and testing is significant and must be balanced against other development goals. Despite several initiatives over the past 20 years, many countries still lack the expertise, capacity, and infrastructure to operate effective disease reporting systems at the national level for terrestrial, much less aquatic, animals. This limits the effectiveness of international disease reporting and the potential trade consequences of reporting further reduce the incentive to prioritize investment in reporting, despite the potentially high cost of domestic disease losses alone.

The WOAH reporting system is largely restricted to WOAH-notifiable diseases and new or emerging diseases. Emerging diseases must be managed on inadequate data; however, methodologies exist to avoid always reverting to the precautionary principle whilst maintaining acceptable levels of risk. The WOAH list of notifiable diseases is the standard for international reporting. However, it suffers from some drawbacks as a means of controlling the international spread of disease, namely, emerging diseases could spread significantly before they are listed; and although the list is reviewed twice a year, de-listing of diseases that no longer have major significance can be slow. Although the requirements and the process to meet a pathogen/disease to be listed as notifiable by WOAH is robust, to achieve the true benefits, the listing process needs to be significantly accelerated.

Alternative reporting systems such as the FAO/NACA/OIE/WOAH Quarterly Aquatic Animal Disease Report also include information on diseases that are important in the region but not listed by the OIE. However, it suffers from many of the same weaknesses as the OIE reporting system, namely, dependence on the capacity, competence, and transparency of the individual countries.

As previously mentioned, one of the negative outcomes of disease reporting is the imposition of trade barriers by importing countries. Although there is some leeway in the event of a new or emerging disease, under the terms of the SPS Agreement, a science-based risk assessment is required to avoid unjustified barriers to trade. According to the WOAH Code, "The principal aim of import risk analysis is to provide importing countries with an objective and defensible method of assessing the disease risks" associated with an import.

International reporting systems and the implications for trade have been complicated by the inclusion of aquatic animal "commodities" and "products" within the WOAH Code. Testing commodities and products for pathogens, and actions taken as a result, appear to regard them as an equivalent risk to live animal movements. However, the likelihood of exposure should also be considered. For example, how probable is it that there will be uncooked waste, that the waste is infected, that it will reach susceptible species, that they will become infected or diseased, and that they will transmit it to others?

Risk of disease spread with aquatic animals and products can be ranked from highest to lowest (see Figure 1).

This is an important distinction as it is not consistent with SPS regulations to apply equal restrictions to products at both ends of the risk spectrum. Unfortunately, this is often the case.

Most reports of the proven transfer of pathogens are via live aquatic animals imported for aquaculture, the ornamental fish trade, and stock enhancement. There are also risks from the unintentional movement of live animals. For example, live animals from fouling and ballast water have largely been ignored, although they have resulted in the translocation of species and, presumably, their pathogens. Pathogens may also spread through discrete but interlinked populations that may span several countries and animals with long planktonic stages can be widely dispersed. Fishing boats may travel extensively across international borders but there is no scrutiny of fresh chilled or frozen fishery products.

FIGURE 1 Risk of disease spread with aquatic animals and products.

From the 1990s until 2004, when polymerase chain reaction (PCR) technology began to be widely used for testing of aquaculture products, enormous volumes of whole eviscerated fresh fish and fresh shrimp or shrimp tails (chilled or frozen) packaged for direct retail sale for human consumption were traded with no restrictions. The issues around PCR testing of products have been reviewed and during this time no epidemiologically-sound reports have been published demonstrating disease transmission by this route.

The WOAH Code recognizes that live animals can be safely traded between countries with different disease statuses using zoning and compartmentalization. Essentially, these define specific areas or common biosecurity management that maintain freedom from specific diseases. This would allow trade between zones and compartments of equivalent health status, or else from higher to lower health status, despite differences at the national level. However, there appears to be little effort on the part of some countries to certify or declare zones as being free of disease (and of others to accept the legitimacy of zones) resulting in complete embargos against trade from the whole country regardless of the disease status of individual zones or compartments. In many of these cases, the country simply does not have the infrastructure in place to do so but in others, it is difficult to understand why a biosecure facility producing SPF animals and certified free by the Competent Authority for two years or more cannot be declared and accepted as a zone free of these diseases. Currently, barriers to the movement of relatively safe aquatic animal products on the pretense of biosecurity are a major inequity in international trade. Rational independent evaluation of risk analyses could provide the basis for a more equitable system.

The WOAH Aquatic Animal Health Strategy launched in May 2021 is aimed at improving aquatic animal health and welfare worldwide to contribute to sustainable economic growth, poverty alleviation, and food security to achieve the Sustainable Development Goals. This strategy can improve the implementation of international standards on aquatic animal health, especially disease reporting.

1.10 | Policies and regulatory frameworks

National strategic planning on aquatic health management and biosecurity is vital to reduce the vulnerability of the aquatic sector to new and emerging diseases and the often ad-hoc and reactive solutions to serious transboundary aquatic diseases and mass mortality events in aquatic populations. The FAO has long encouraged member countries to develop and formalize National Strategies for Aquatic Animal Health (NSAAH) and health management procedures. An NSAAH is a broad yet comprehensive strategy to build and enhance capacity for the management of national aquatic biosecurity and aquatic animal health. It contains the national action plans in the short-, medium-, and long-terms using a phased implementation based on national needs and priorities. The technical elements that may be considered in the strategic framework will vary depending on an individual country's situation, and thus may not include all the program elements (i.e., Policy, Legislation and Enforcement; Risk Analysis; National Aquatic Pathogen List; Health Certification, Border Inspection, and Quarantine; Disease Diagnostics; Farm-level Biosecurity and Health Management; Use of Veterinary Drugs and Avoidance of AMR; Surveillance, Monitoring and Reporting; Communication and Information Systems; Zoning and Compartmentalization; Emergency Preparedness and Contingency Planning; Research and Development; Institutional Structure (Including Infrastructure); Human Resources and Institutional Capacity; Regional and International Cooperation; Ecosystem Health). Alternatively, additional elements/components may be identified as having national and/or regional importance and thus need to be included.

As a result of the negative externalities associated with aquatic animal diseases, there is an obligation for authorities to implement national legislation related to biosecurity. This has initiated several international and national/regional biosecurity frameworks. Frameworks connected to agreements, declarations, guidelines, and policy plans. However, incomplete implementation of legislative and regulatory initiatives, inadequate knowledge, and infrastructure (e.g., diagnostic capacity and quarantine facilities)—lack of industry motivation and collaboration are factors that have reduced the effectiveness of biosecurity as a tool to control the spread and impact of infectious diseases. Interestingly, most international and regional biosecurity frameworks (57%) do not demand compliance, and all others (43%) do require compliance only when ratified by a nation state (Campbell et al., 2020).

Diseases in farmed aquatic animals are economic and environmental challenges to society and as such, aquatic animal health should be considered as a public good. Ideally, national legislation should therefore equally protect the interest of the various stakeholders and include general factors like:

- designation of Competent Authority(ies) with clear delineation of responsibilities;
- a national list of pathogens/diseases included in the specific legislation;
- farm certification based on biosecurity national standards (e.g., national or international certification schemes), which includes obligations to maintain a biosecurity plan and record keeping (e.g., medicine use and live animal import and movements);
- registration and authorization system for veterinary drugs, inspection, and surveillance;
- a national record on farm characteristics;
- protocols on import procedures and requirements;
- emergency disease awareness and response capability;
- programs on disease surveillance;
- availability of appropriate veterinary field and diagnostic services; and
- compulsory education and training.

In the absence of regulatory frameworks, farmers can decide to "push the system" to their convenience causing direct stress on the cultured species and greatly increasing the risk of disease outbreaks. One solution to the absence of regulatory measures can be through farmers cooperating to create, where possible, joint health plans and area management agreements. Thus, sustainable aquaculture with stable production at a national level cannot be achieved without enabling regulation. However, the regulations should be formulated through a consensus process via representatives of the government and all aquaculture industry stakeholders in a consortium-like process. This is the most likely way to achieve a high level of compliance.

However, it is important that the policing authority for adherence to regulations be clearly separated from the authority responsible for education and training. In addition to stocking density, other compulsory "product management practices" may include year class separation; synchronized production; "all in, all out"; fallowing/dry out periods; frequent mortality removal; health and pathogen screening pre-movement and, where appropriate and possible, systematic vaccination. The objective should be to move away from the current treatment-focused culture to one of long-term management of proper biosecurity planning and disease prevention, including disease surveillance and testing, vaccination, and in genetic selection for robustness or pathogen tolerance, etc. so that continual treatment is not necessary.

Legislation is of no value if it is not adequately enforced, followed up, and evaluated. Authorities, therefore, must facilitate effective procedures for the industry to comply. Both the authorities and the practitioners should be adequately trained and knowledgeable on the legislation and their enforcement and/or compliance requirements. Dedicated responsibilities need to be acknowledged and placed on both the authorities and individual enterprises, and through regional organizations and frameworks, linking the four vertically integrated levels (international, national, local, and farms) as well as horizontally between different enterprises and relevant national authorities. Identification of risks posed to various sectors and types of production will help the implementation of tailored and bio-economical efficient investments in biosecurity measures. This can only be achieved through close collaboration between industry and authorities, respecting and understanding each other's interests and responsibilities. Efficient disease prevention and control is a partnership approach that includes a common understanding and compliance with a basic framework and transparency about relevant health threats. Given the significance of transparency and compliance in safeguarding the industry, an agreement on incentives should be discussed between authorities and the industry and embedded in the legislation.

1.11 | Fish welfare

A generally accepted definition of the concept of “animal welfare” does not exist. However, the following three welfare dimensions are frequently cited: (i) Function-based: The animals can cope physiologically with their environment and are in good health (Arndt et al., 2022). (ii) Nature-based: the animals can lead natural lives, using their natural adaptations (Veissier & Forkmann, 2008). (iii) Feelings-based: animals should be free from prolonged or intense unpleasant emotional states such as pain, fear, and hunger and have access to rewarding experiences such as social companionship or comfort (Boissy et al., 2007). In aquaculture, the most accepted is the function-based welfare concept, as this can be parameterized via production-related indicators that are often routinely measured such as animal growth or water quality. However, the function-based concept reduces welfare to physical health and excludes mental health, although there is growing evidence that aquatic animals are sentient and possess awareness of positive and negative mental states. Animal suffering is also what leads to public concern for farmed animal welfare. A conclusive answer to this ongoing controversial discussion is complicated by the diversity of farmed aquatic species.

The linkage between biosecurity and welfare comes from the fact that welfare relates to the health and disease status of the animals on a farm. Good welfare enhances an animal's ability to resist disease, while poor welfare increases the susceptibility of the animals to infection and disease. Of course, it is overly simplistic to assume that disease is invariably linked with the welfare status of the animals, but the welfare status alters the risk of disease on a farm. The relation between welfare and biosecurity is bidirectional. If animals get diseased because of pathogenic infections, this means an impairment of their welfare. Thus, controlling the entry of pathogens and other hazards, and combating diseases by efficient biosecurity measures promotes the welfare of farmed aquatic animals. The design of an effective farm biosecurity program hinges on an understanding of the factors that drive disease events to reduce the risk of infections and their adverse outcomes. To date, the focus is given to factors such as good hygiene, disinfection procedures, or control of pathogen spread, but future biosecurity programs should integrate the management of aquatic animal health and welfare.

To implement welfare as an integrated part of biosecurity programs, practical parameters and approaches to safeguard animal welfare are needed. On the farm, gentle handling, suitable environments, minimizing handling, using a feeding regime appropriate to the species, and the breeding of robust animals benefit the welfare of the animals. During transport, it is essential to apply best handling practices and to ensure good water quality.

To assess the welfare status of the farmed animals, “operational welfare indicators (OWIs)” are useful practical tools (Flores-García et al., 2022; Noble et al., 2018; Segner et al., 2012). Usually, no single indicators are used, but a series of parameters are measured and integrated. Efforts are underway to develop automated systems taking advantage of digital technologies to continuously monitor the welfare status of the farmed animals. The welfare indicators are, at least partly, species-specific, and to date, OWIs are available only for some of the over 200 main cultured species. Development of OWIs has largely focused on high-value species such as salmon, but more practical and robust welfare indicators are needed also for species like shrimp, carp, or tilapia which constitute the bulk of the global aquatic food supply. It is clearly a task of future research to identify OWIs and implement welfare assessment and management for a higher percentage of cultured aquatic species.

1.12 | Research and technology

It is evident that most aquatic animal health research, especially on diagnostics and health management technologies, is focused on commercially important and internationally traded species. This skewed research focus undermines the role of mass-produced species such as carps and tilapias for global food security and nutrition. Therefore, it is critical to rectify this shortfall and address the research needs of the species which provide livelihoods to many smallholders and contribute to global nutrition and food security.

The overriding consideration in the development of national R&D frameworks is who the client is. Recognizing that clients will be varied—from governments to large-scale industries, to start-ups and small-scale producers—it is understood that national R&D frameworks need to be holistic and responsive. It is, therefore, appropriate to consider the various components that would make up a national framework; with universities and government research stations being the classic components, and private research centers, company farms, colleges, and schools providing additional input. Outlets for new knowledge also need to be considered—conferences, seminars, trade shows, and demonstration sites.

The political and industrial clients of all scales will require different outputs, depending not least on the level of development of the sector. In early-stage aquaculture sectors, we should expect that the principal clients may be government departments and small-scale producers who will need R&D systems that are largely government/donor funded and provide outputs that are generally public goods, such as basic production approaches, simple health management tools and formulae for basic feeds. Highly commercialized industries will have an increasing amount of privately funded research, although some of the outputs should still be public goods. As industries develop, government-funded research will likely shift from technical solutions to developing effective, evidence-based regulatory tools. In these latter stages of development, it is also important that government departments, which will have typically been the leaders in research, become more open to accessing the outputs of commercial research, even for use in regulatory systems.

Although many bacterial diseases are now effectively controlled using vaccines, viral diseases still present significant infectious disease challenges for the salmonid and marine finfish, and there are only a limited number of effective vaccines commercially available for these. Bacterial pathogens still present some major challenges for rainbow trout, carp, tilapia, and catfish as well as for cleaner fish, for example, for Ballan wrasse (*Labrus bergylta*) and lumpsucker (*Cyclopterus lumpus*), among others, which are currently being used for sea lice (*Lepeophtheirus salmonis* and *Caligus* spp.) control in Atlantic salmon (*Salmo salar*) production. Ectoparasites currently pose the most significant disease threat to the Atlantic salmon industry and there are no commercial vaccines available at present for these or fungal diseases. More research efforts are necessary to address these knowledge gaps.

Over the coming decade, we should make special emphasis on addressing the following aspects of biosecurity. It is deemed essential to create International Research Groups toward standardized methodologies and to create global datasets to enable more effective research outcomes; and increase efficiency, cost-effectiveness, and involvement of commercial sectors.

- Climate change impacts on disease
- Ecosystem-based management approaches
- Integrated pest/disease management approaches (e.g., sea lice)
- AMU and AMR management
- AMR assessment and reduction
- Anthropogenic impacts
- Marine environmental impacts including microplastics in mariculture
- Microbiome/pathomicrobiome studies
- Development and application of smart-biosecurity tools and techniques

- Modern technologies (digitalization, automation, smart biosecurity, etc.)
- Best management structures (zones)
- Species-specific welfare (toward the development of indicators)
- Genetic and epigenetic developments
- Epidemiological analysis of disease
- Vaccination development and delivery

1.13 | Antimicrobial resistance (AMR)

The emergence of antimicrobial agent resistance (AMR) in bacteria associated with aquaculture and the aquatic environment is of concern for three main reasons:

1. It has a clear, obvious, and negative impact on the therapy of bacterial diseases in animals raised in this industry;
2. It has a potential negative impact on the therapy of bacterial diseases in consumers of the products of the industry;
3. Also, as much of the AMR is encoded by transferable resistance genes, it will contribute to the total environmental resistance.

It should be noted that the uses of antimicrobial agents in human and terrestrial animal therapies also contribute to this resistance that is postulated to be the main global reservoir of resistance genes (Lindmeier, 2017).

The main driver of the emergence of AMR in bacteria associated with aquaculture and the aquaculture environment is the use of antimicrobial agents (AMU) in this industry. It is clear, therefore, that the only way that the emergence of resistance can be slowed down or halted is by reducing the number and volume of antimicrobials used in the industry. The central question that must be addressed is how to achieve this in an aquaculture industry while, at the same time, increasing the volume of its production.

With this aim in mind, it should be noted that the emergence of AMR strains is driven by all uses of antimicrobial agents in aquaculture. Some of these uses may be appropriate and well-designed and given the intensive nature of most aquaculture production systems, unavoidable. Others, however, represent the misuse or inappropriate use of these agents. Attempts at reducing AMU and, therefore, the emergence of AMR, should be initially focused on reducing the misuse or inappropriate use of these agents.

The industry uses antimicrobials to reduce economic losses resulting from bacterial diseases presumed to be caused by bacterial infections. However, these diseases are rarely caused by bacterial agents alone. Their etiology is nearly always multifactorial with environmental and husbandry factors frequently playing an important, and possibly dominant, role in the occurrence or severity of these diseases. Empirical evidence has shown, that, in many situations, identifying and correcting these environmental and husbandry factors before a bacterial infection occurs will significantly reduce disease incidence (Hanson, 2020; Henriksson et al., 2018; Pruden et al., 2013; Schulz et al., 2022; Silva et al., 2014). The implementation of these prophylactic preventative measures represents a rational and cost-effective approach to managing economic losses. Their adoption would significantly reduce bacterial diseases and antimicrobial use and therefore the emergence of AMR.

In attempting to limit the emergence of AMR it is suggested that national authorities should concentrate on developing educational programs and support services, and on the acquisition of good-quality data. The central message of education programs should be that the need to resort to antibiotic therapy should always be the consequence of a prior failure to implement good stock management to maintain environmental quality and microbial stability and to eventually adopt appropriate non-drug prophylactic procedures. Antimicrobial therapy should always be a last resort and not a first response. Sample educational messages might include:

"Prevention is better than treatment."

"Animals in a good environment have fewer infections than those in a poor environment."

"Bad husbandry triggers secondary (opportunistic) pathogens to become virulent and cause more infections than bacteria. Poor animal management practices, including overcrowding, maintenance in unsanitary conditions, fed improper feeds, treatment practices that result in the proliferation of antibiotic-resistant bacteria, etc can create conditions that favor the growth and spread of harmful microorganisms and that can also weaken the immunocompetency of stock."

"Antimicrobial therapy cannot reduce losses resulting from poor rearing environments or bad husbandry."

The support services developed for the aquaculture industry must be based on an understanding that the implementation of appropriate biosecurity measures starts at the planning stage of a production cycle. Support services must be designed to provide farmers with assistance and advice at all stages of a production cycle and not be confined to crisis intervention after a disease occurs. The provision of diagnostic services is an essential component of support services. However, disease diagnosis must not be reduced to pathogen identification. Reliance on pathogen identification alone, with insufficient attention being given to other contributing environmental and husbandry-related factors, will lead to an overemphasis on the bacterial component of the disease etiology and to an excessive and possibly inappropriate recommendation for antimicrobial use and appropriate microbial management (Bass et al., 2019; Mougin & Joyce, 2022; Stentiford et al., 2020). In the past, the value of the studies of AMR that have been performed has been seriously limited by the lack of international harmonized standard methods for performing susceptibility tests and the lack of agreed consensus criteria to interpret the meaning of the data generated (Smith, 2020). In recent years, however, significant advances in the awareness of AMR have been made in many countries, and few are even implementing surveillance programs for AMU and AMR in both aquatic and terrestrial farmed animals. The current situation is that standard methods now exist for susceptibility testing of most of the species frequently isolated from aquatic animals (Smith, 2019). National authorities should encourage and actively promote the adoption of these standard methods. There is still a lack of consensus on species-specific interpretive criteria for many species, but these are relatively easy to generate.

The need to continuously understand the threat of AMR and its avoidance should be pursued. Source attribution of AMR in aquaculture-associated bacteria is very complex and caution needs to be exercised in the interpretation of data. Mere detection of AMR in aquaculture systems does not imply misuse of antimicrobials in aquaculture. The direct link between the resistance profile and AMU needs to be clearly established as AMR may be naturally present in the aquatic environment or derived from AMU in other sectors or derived from AMU in aquaculture.

Since the adoption of the Global Action Plan (GAP) on Antimicrobial Resistance (AMR) during the 68th World Health Assembly in 2015, commitments to support the GAP were obtained from Members attending the OIE's 83rd General Assembly and the 39th FAO Conference in 2015. This support included the development of National Action Plans (NAPs) on AMR. The OIE Strategy on AMR and the Prudent Use of Antimicrobials (2016) and the FAO Action Plan on AMR (2021–2025) are useful instruments to guide countries in the development of the NAPs, especially the aquaculture component and integrated into the country NAP under the One Health platform. Aquaculture biosecurity and AMR may be complex and are driven by many interconnected factors. Single, isolated interventions have limited impact. Greater innovation, research, and investment are required in surveillance, maximum residue limits, new antimicrobials, vaccines for low-value species, and other alternatives to antimicrobials and diagnostic tools. Aquaculture-producing countries need to develop the aquaculture component and integrate it into country NAPs.

1.14 | Non-conventional ways of pathogen transfer

Conventional ways of pathogen transfer and the opportunities for mitigation have been given ample coverage over the years. Need for the application of risk analysis and epidemiology to identify common and often unexpected risk factors leading to disease transmission has been duly considered. However, aquatic environments are biologically connected through complex hydrodynamic regimes and associated ecological processes, thus these connections disregard human-made administrative borders and allow the natural dispersal of Harmful Aquatic Organisms and Pathogens (HAOP) (Ojaveer et al., 2018) between ecosystems. However, the massive development of anthropological activities in aquatic environments and particularly at sea disturbs ecosystems and increases the rates of transfers of HAOP beyond their natural habitats. HAOP may settle and reproduce beyond control to become pests in areas outside their original geographical distribution. The successful transfers are exacerbated by the changes in natural habitats (global warming, physical barrier/habitat destructions), facilitating and increasing species' direct transfer across natural boundaries.

Unlike pollution, as defined by the United Nations Convention on the Law of the Sea (UN General Assembly, 1982), HAOP often exhibits robust biological traits and can reproduce over time which makes their eradication almost impossible. This makes HAOP a challenging hazard to manage. Bio-invasions are seriously impacting aquatic ecosystems which are used by multiple industries, including aquaculture and fisheries. Therefore, science-based policies to protect marine ecosystems and the communities living on them must consider the specificity related to the risk of transfer and spread of HAOP.

Some concerns emerged about ballast water management's efficiency in ensuring the high level of biosecurity required to sustain aquaculture development and manage pandemic risk. Compliance with shipping regulations is driven by statutory documentation such as type approval of the equipment and regular surveys from administrations (or recognized organizations acting on their behalf). Unfortunately, annual surveys related to the Ballast Water Management (BWM) Convention do not require any verification that the water discharged from ships meets the limits set forth by the Convention (IMO, 2004). However, one country (the United States of America), not party to the BWM Convention but conversant with the issue, unilaterally decided to monitor the ballast water discharged from vessels operating in its waters through the Vessel General Permit (VGP 2013) and regular testing is recommended by most experts (United States Environmental Protection Agency, 2013).

While the shipping industry finances the costly installation of a Ballast Water Management System (BWMS), it seems inconsistent not to require initial and regular verification of the equipment's capacity to meet the standards. Without such analysis, it is impossible to evaluate whether biosecurity risks are successfully managed globally. From multiple testing carried out during the commissioning of new installations onboard vessels, it has been found that about 20% of ships failed to meet the discharge objective of the Convention. To address questions raised by unmatured technology and practices, the International Maritime Organization (IMO) has initiated the experience-building phase (SGS, 2020). During this period, the maritime administrations are urged to collect data from their fleet and submit information about ships' capacity to manage ballast water to evaluate the needs and initiate amendments to the BWM Convention.

Another complex shipping issue is HAOP transfer risk through biofouling associated with the submerged hull of vessels. The biofouling process begins after immersion of the ship/structure in water. Countries such as Australia and New Zealand demonstrated the impact of biofouling on the marine environment. They urged the IMO to respond to this global threat by promoting quality anti-fouling systems and regular underwater cleaning of ship hulls and niche areas. Consequently, the IMO developed the Guidelines for the Control and Management of Ships' Biofouling and the Guidance for Minimizing the Transfer of Invasive Aquatic Species as Biofouling (Hull Fouling) for Recreational Craft. As these legal instruments are non-binding, they have limited impact, and there is no global enforcement regime (IMO, 2011, 2012). However, the adoption of an IMO Convention on vessel biofouling may be possible in the future and would support a coordinated effort to manage this issue.

Managing the risks of the transfer of HAOP requires robust risk assessments able to integrate global changes. When taking ecosystem connectivity and dynamics into account, risk assessments can better estimate the natural dispersion of HAOP. Indeed, the natural spread of HAOP is driven by hydrodynamic connectivity (physical), the capacity of organisms to swim (nekton), and the biological traits and tolerances of species (capacity to survive and strive in a different ecosystem) (Bowley et al., 2020).

One of the methods to assess such risk is based on particle tracking modeling combined with ecological modeling (agent-based modeling). This approach may also allow estimating the extension of the indirect spread of pathogens from the presence of floating or immersed particles (e.g., marine litter, plastics) covered with biofouling. Indeed, such marine debris or elements may act as shuttles to increase the "natural" spread of pathogens through currents. This is even accentuated by the presence of sensitive zones created by ecological stresses, including those made by global warming. Such modeling approaches to dissemination have been proposed as part of the Guidelines G7 of the BWM Convention to support ship exemption when the risks of species transfer (from ships) between specific ports are considered limited compared to that driven by natural dispersion.

Considering the complexities of global economies and their reliance on stable ecosystems, governments' efforts to work toward zero hunger should not be negatively impacted by sub-optimal compliance monitoring and enforcement programs. Therefore, the regular assessment of the numerous industries discharging directly or indirectly into the aquatic ecosystems is necessary, as well as the continuous monitoring and development of control to address secondary natural dispersion of HOAP related to global changes.

1.15 | Progressive management pathway (PMP) approach

As mentioned before, approximately every three to five years, a previously unreported pathogen that causes new and unknown diseases will emerge and spread rapidly, crossing national and international borders (Bondad-Reantaso et al., 2018; FAO, 2020a). A long period usually elapses before the pathogen has been identified, host range determined, pathology understood, global awareness and effective disease containment and management measures established. This enables the spread and establishment of new areas and previously unexposed populations (wild and farmed). The socio-economic and environmental impacts of disease outbreaks in aquaculture can be substantial, including reduced food availability, temporary or permanent business closure, and loss of employment, including upstream and downstream value-chain industries. Production losses because of the mortalities and slow growth, decreased trade, and lost markets may be as a result of bans on exportation, public concerns over food safety, and the costs required to manage the disease (biosecurity measures, treatment, vaccines, compensation, eradication, etc.). Repeated outbreaks of new diseases (e.g., DIV1, EHP, etc.), with high economic losses, reflect an immature aquaculture industry (FAO, 2019, 2020a; Geetha et al., 2022; Qian et al., 2023; Shinn et al., 2018).

A good understanding of the factors and pathways leading to exotic and endemic diseases is necessary. They are grouped into four, namely:

- *trade in live animals and their products*: aquatic animals (and aquatic plants) are food commodities that are traded globally; in the absence of adequate national biosecurity, pathogens may be transferred alongside host movement.
- *knowledge of pathogens and their hosts*: knowledge about new pathogens (pathology and transmission routes), susceptible hosts (species, life stages affected, immunity, genetics), and diagnostics (specific, sensitive, and rapid) curtails the fast development of the sector and the large number of species reared under varied farming systems; slow collective awareness of new threats show complacency during periods of no outbreaks.
- *aquatic health management and disease control*: limited or absent institutional and technical capacities, including enforcement and implementation of international standards and guidelines for biosecurity best practices, coordination between the multiple institutions involved in aquaculture production and aquatic health management, and

capacity for response to emergencies, all impede the application of effective health management and biosecurity measures.

- *ecosystem changes*: aquatic ecosystems are dynamic, changing through direct human activity (e.g., dams, pollution, shipping, new species introductions) and indirect human impacts (climate change, weather extremes, algal blooms, etc.). Under such dynamic conditions, aquaculture is limited by the physiology of the animals, the emergence of opportunistic pathogens, and changing geographical ranges of wild stocks, microbes, and parasites (Subasinghe & Shinn, 2023).

Ineffective biosecurity is the main challenge impacting aquaculture development over the last three decades (FAO, 2019, 2020a). Despite extensive efforts by national competent authorities, industry, academia, and development institutions, inadequate implementation of biosecurity practices results in costly reactive actions, highlighting the need for preventative measures.

Four stages of the PMP for improving aquatic biosecurity are given in Figure 2.

The Progressive Management Pathway for Improving Aquaculture Biosecurity (PMP/AB) was developed by FAO and partners, as a "paradigm shift" after analyzing the pathways and factors to disease emergence and seeing a need for strategic planning to further guide and support countries toward achieving sustainable aquaculture biosecurity and health management systems. The PMP/AB is an extension of FAO's "Progressive Control Pathways" (PCP) approach, which has been internationally adopted to assist countries to develop risk mitigation strategies that reduce or prevent losses from major livestock diseases. However, whereas most PCPs focus on the control of specific diseases, the PMP/AB focuses on diseases faced by aquaculture at the commodity and enterprise levels. The PMP/AB uses a comprehensive, holistic approach to improving aquaculture biosecurity and supporting sustainable development.

The PMP/AB is progressive, collaborative, and risk-based. The four stages of PMP-AB involve strong public and private stakeholder input to promote the application of risk management at the sector level as part of a national approach. Countries decide the appropriate entry point, how far, and how fast to progress to the next stage. Due to the diverse range of farmed species in every country, aquaculture sectors may advance independently, at different speeds, or with different goals but a common requisite is strong cooperation between government and industry, such as a public-private sector partnership (PPP). This is necessary to ensure clarity on roles and responsibilities, identify key gaps requiring improved capacity and infrastructure, and increase awareness of the cost/benefits of biosecurity along the whole value chain. Risk analysis is a key aspect of all stages of the PMP/AB. Risk hotspots (critical control points) are identified for biosecurity investment (training, diagnostic capacity, etc.). All this feeds into the development of a National Strategy on Aquatic Animal Health (NSAAH) or national aquaculture biosecurity strategy, which sets the foundation for ongoing review and updating as the industry develops (see Figure 3).

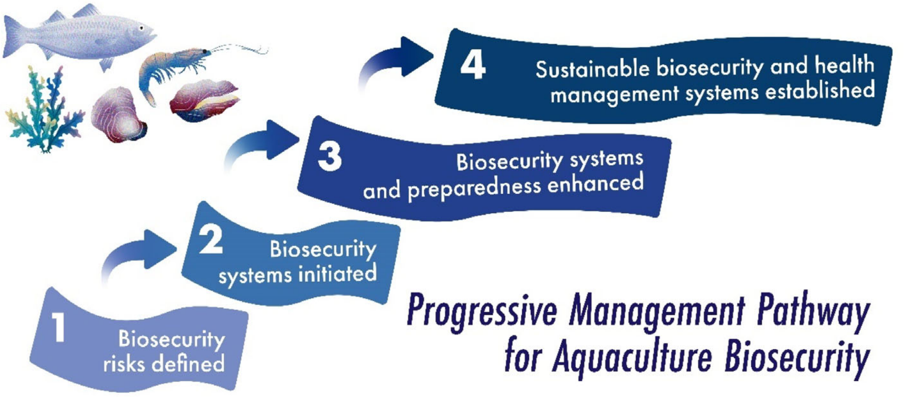

FIGURE 2 The four stages of the Progressive Management Pathway for Aquaculture Biosecurity (PMP-AB). It follows the principles of being risk-based, progressive, and collaborative.

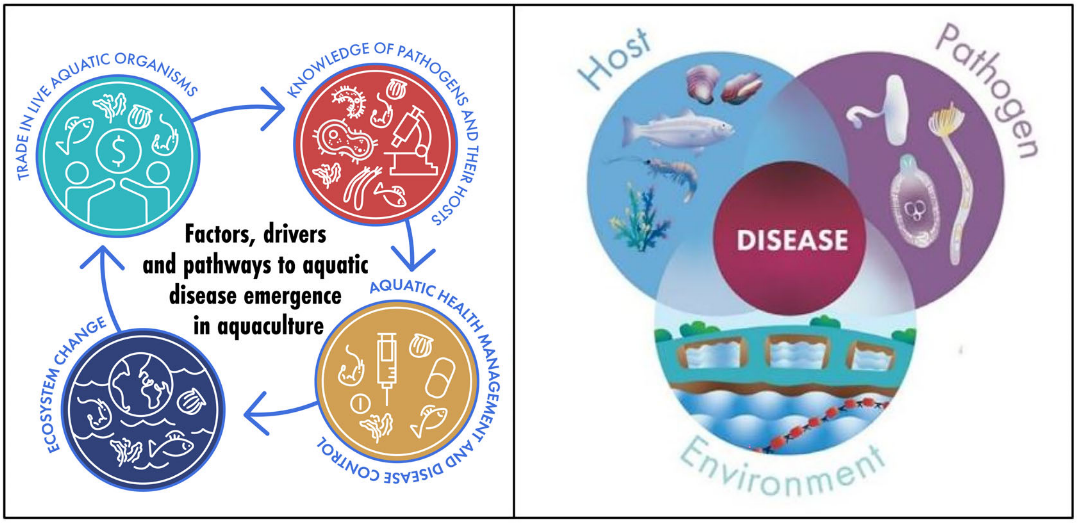

FIGURE 3 The Progressive Management Pathway for Aquaculture Biosecurity (PMP-AB) relies on a good understanding of the factors, drivers, and pathways to disease emergence and the epidemiological triad (Snieszko Circle) showing the relationship between pathogen and susceptible aquatic population in a suitable environment that allows transmission of the pathogen and development of the disease.

Key focus and outcomes of the four stages of the PMP are given in Table 2.

The benefits of the PMP/AB can be summarized as follows:

- It builds on management capacity using bottom-up and top-down approaches, is evidence-based, and is supported by transparent and ongoing reviews. The co-management approach ensures problems are clearly defined and management solutions have a common understanding and buy-in.
- The PMP/AB provides a degree of consistency between participating countries or regions that is essential for reducing risks from trade, as well as addressing biosecurity-related trade challenges.
- The PMP/AB provides a framework that is adaptable and can respond to changes in aquaculture production scope and objectives (small to large-scale; local to international industries), as well as to environmental and anthropological changes that impact aquaculture production.

As countries and aquaculture enterprises advance along the pathway, the following outcomes are expected: reduced burden of diseases, improved aquatic (organism and environmental) health at the farm and national levels, minimized the international spread of diseases, improved socio-economic benefits from aquaculture, increased investment in aquaculture, and achievement of One Health goals (FAO, 2020b, 2020c; Stentiford et al., 2020); all of which provide benefits at the enterprise, national, regional, and global level. Recognizing the importance of aquatic plants as a contributor to food and wealth, the seaweed sector is included in the PMP/AB discussions. PMP/AB is a work in progress and is at an advanced stage of development, and guidance documents and other toolkits are being prepared. It has been welcomed, endorsed, and supported by the FAO's Committee on Fisheries and the Sub-Committee on Aquaculture during its 10th and 34th sessions, respectively.

2 | FUTURE

Aquaculture is a very dynamic, complex sector. It encompasses diverse production systems in open and closed water systems in marine and freshwater environments. Both low and high-value species are cultured, produced at small and

TABLE 2 Key focus and outcomes of the four stages of PMP.

Stage description	Key focus	Key outcomes
Stage 1: Biosecurity risks defined	• National strategy that has the confidence and support of the stakeholders (private and public) and a common agreement on a long-term vision • Principal hazards and risks that affect aquaculture health and production: exotic, endemic, emerging diseases (known and unknown); map risks and gaps, identify the negative impact on the ecosystem • Strategic Biosecurity Action Plan which will be the 'gateway pass' to enter **Stage 2**	• Stakeholders are identified and production systems, marketing networks, and associated socio-economic drivers are well described and understood for aquaculture sectors (value chain analysis) • Threats to aquaculture and biosecurity vulnerabilities are identified and described • Risk hotspots and critical control points are identified through risk analysis • An enabling environment for aquaculture biosecurity is reviewed and developed • Risk-based strategies are developed and endorsed at sector and national levels (*Gateway Pass*)
Stage 2: Biosecurity systems initiated	• Implementation of a Biosecurity Action Plan in specific sectors/compartments • Co-management is expected to continue and strengthen the implementation and the improvements • Should this stage move forward additional biosecurity efforts at ports and borders must be included • Countries will need: evidence of Strategic Biosecurity Action Plan implementation, and commitment through a National Biosecurity Management System in order to enter **Stage 3**	• Risk-based strategies developed in Stage 1 are implemented by public and private stakeholders • Management of biosecurity vulnerabilities and occurrence of important pathogens is monitored • Evidence exists that the implementation of risk-based strategies strengthens biosecurity and reduces the impact of pathogens within aquaculture sectors • Enabling environment is further developed, with enhanced cooperation between public and private sectors • Risk-based strategies are enhanced and revised, based on evidence (*Gateway Pass*)
Stage 3: Biosecurity systems and preparedness enhanced	• Zoning, restrictions of movement, and reporting of any disease/emerging problems through constant surveillance should be in place • Once the management system is found to be capable to sustain Aquaculture health by defending and maintaining specific disease freedom it can move forward to **Stage 4**	• Revised risk-based strategies are implemented • Exotic, endemic, and emerging pathogens under continuous surveillance • Disease incidence and impact are reduced • Enabling environment is strengthened • Demonstrated commitment, including investment, from public and private stakeholders to safeguard progress (*Gateway Pass*)
Stage 4: Sustainable biosecurity and health management systems established	• End stage—achievement of a Sustainable and Resilient National Aquaculture System acquired through the capacity to maintain confidence, biosecurity system, emergency preparedness and preventive measures • All these activities must be coordinated and maintained	• Risk management activities are sustained and improved based on evidence • Enabling environment is maintained and continuously improved • Robust socio-economic situation for all (including small-scale producers, and food security) • National and international stakeholders have confidence in national aquaculture and ecosystem health

large scales, and are consumed locally or traded internationally. More than 500 species are produced in aquaculture (compared to more than 150 in terrestrial agriculture), and the culture of each species has differing risks. Addressing these risks poses a great challenge that requires collaboration, innovation, and investment. Strong political will and concerted international action and cooperation and significant resources are required in addressing biosecurity.

Although the aquaculture sector suffered from pathogen incursions and disease outbreaks causing significant production losses and revenue, to date, evidence-based knowledge on the economic (and subsequent social) impacts of diseases in aquaculture is still lacking. FAO is currently calling for concerted action to improve global knowledge on the socio-economic impacts of diseases in aquaculture, and once achieved, will a tremendous contribution toward designing and implementing efficient strategies for improving global aquatic biosecurity.

There are several challenges to the collection of data linked to economic and social loss from episodes of aquatic disease. These include the lack of uniform data collection methods and standardized protocols for data collection across countries and regions, which can result in inconsistent and incomplete data. Collecting and analyzing data on aquatic animal disease can be resource-intensive. Some countries or regions may lack the necessary funding, infrastructure, and trained personnel to collect and analyze data effectively. The sheer volume of aquaculture production sites in each country can be immense, Thailand by way of example, listed 589,893 aquaculture farms in operation in 2020 (Fisheries Statistics of Thailand, 2022). Many countries do not have effective surveillance systems to detect aquatic animal diseases, leading to an under-reporting of the impact of diseases, making it difficult to accurately estimate losses. At the same time, some diseases go unrecognized or undiagnosed, or unreported (Shinn et al., 2015b). Farmers, therefore, may not report on the occurrence of disease or the losses they incur through either fear of negative consequences or a lack of awareness about the importance of reporting.

To overcome these hurdles, data collection methods and protocols need to be standardized across countries and regions to improve data consistency and accuracy. There needs to be an increase in resources—funding, infrastructure, and trained personnel able to collect and analyze data. Surveillance systems need to be strengthened so that they can detect disease and capture losses. There is a need to raise awareness among farmers about the importance of reporting diseases and losses; and there is a need to provide training to support individuals working in the field to improve expertise and accuracy in collecting and analyzing data on aquatic animal diseases, in providing loss estimates, and critically in the diagnosis of disease.

Disease frequency, infection intensity, the effect of the disease on mortality and productivity in animals, and its effects on human health, and efforts to respond to the disease all influence the economic impact of a disease (Rushton et al., 2018). Some of the hurdles in data collection pertain to clarity on the type of data to be collected from the public and private sectors, ownership, commercial sensitivities, data transparency, and confidentiality.

The Global Burden of Animal Diseases (GBAD), which includes aquatics, has six key components: disease classification, data collection, disease losses, animal health expenditure, sustainability, and equitability. It is expected to advance the understanding of animal health trends over time and the most effective and efficient means of reducing the burden of animal diseases, with subsequent impacts on human health either directly or indirectly (Huntington et al., 2021; Rushton et al., 2018).

It is important to stress that many of the current aquatic animal health challenges faced by the different aquaculture industries (systems and practices) are part of the natural sequence of knowledge generation and development and are not solely because of intentional malpractice or resistance to comply. In looking to the next decade and with the expansion of aquaculture, there is a need for ongoing adjustments to good aquaculture practices (GAP) with the establishment of regulatory frameworks setting benchmark requirements and the production of standard operating procedures (SOPs) for use at the farm level for each cultured species. This will include, for example, improvements in animal welfare standards (e.g., setting of guidelines regarding stocking densities; mandatory procedures for the transfer of animals, including animal movement documents; in the practice of non-ablation in commercial shrimp production; in water quality and management of the culture system, etc.); in health surveillance and certification throughout production; in vaccination and therapeutic treatments as part of long-term management; in seed and broodstock quality; in new protocols for appropriate microbial management (e.g., preventing secondary pathogens to express virulence); in tight codes of practice regarding wastewater treatment and management; and, in the traceability of stocks. All of these should operate within regulatory frameworks, which are enforced by law, to support production, decrease disease-related losses, and in helping drive toward greater sustainability. National and farm-level biosecurity practices should include risk analyses with the implementation of control points in the production chain to reduce the likelihood of disease events and/or their spread.

While aquaculture moves toward precision farming, the current requirement is not necessarily to move to systems employing greater technological complexity and high-tech analytical tools generating vast amounts of data that need parallel platforms for their analysis and interpretation, but rather to have frameworks that increase farmer accessibility to tools and support services (e.g., access to veterinary support, training in microscopy to conduct basic health assessments, training in the use of pond side diagnostics and devices like oxygen probes, water quality analysis, etc.) that empower them to make real-time management decisions. There is, for example, a need to develop a farm toolbox to support small to medium farmers. Training and education, therefore, will remain a priority in all aspects of aquaculture, the provision of which can be realized through industry-approved online training programs (i.e., have consensus on standard practices). With the development of online platforms, it would be possible to have increased accessibility to veterinary health advice, through centralized, government-approved, and call centers.

Scientific evidence and decades of experience lead us to believe that "healthy and quality seed" is probably the most important input for achieving sustainable and economically viable aquaculture production. Research toward using genetic tools and s in disease prevention and management should receive a higher level of priority. In this review, we took a different approach, substantially deviating from the traditional thematic review process. We looked at major challenges, issues, and opportunities for improving aquatic biosecurity. We concentrated on our decades of experience and the practicalities of strategies used to address biosecurity. We endeavored to understand and describe the complex nature of the problem and try to present a better holistic approach to aquatic animal health management. An all-encompassing ecosystem approach to aquaculture will mitigate impacts on ecosystem services and biodiversity, and provide the necessary resilience to future disease threats, including those exacerbated by climate change.

Improving the health management of cultured species must be a key component of future aquaculture development agenda. At the national level, public-private partnerships are vital in achieving objectives of common benefit. Industry cannot develop effective biosecurity without a clear government strategy and support, specific legislation, which provides an effective framework for safe trade. The improved control of transboundary diseases requires the wider and more consistent implementation of WOAH/OIE standards and other relevant regional voluntary guidelines agreed upon at the regional level, recognizing the importance of putting these measures into the appropriate regional agro-ecological context, conditions, and perspectives.

The PMP/AB is one of the approaches that could be explored as it offers the opportunity to:

- reduce the burden of disease;
- improve health at the farm and national levels;
- minimize the global spread of diseases;
- optimize socio-economic benefits from aquaculture;
- attract investment opportunities into aquaculture; and
- achievement of One Health goals.

Although there is huge potential for aquaculture to continue its rapid growth and increase its contribution to global food security, the sustainable growth of aquaculture is threatened by both known diseases, which we cannot effectively control, and new diseases, which may become pandemics. Recent pandemics have shown that global production systems are epidemiologically connected and, consequently, diseases of cultured aquatic species present a shared global threat that demands global solidarity. The world now depends on a sustainable future for aquaculture and improved aquatic health management is critical to its continued and growing contribution to global food security.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DISCLAIMER

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

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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