Aquaculture Biosecurity: Future Pathways for Sustainable Disease Prevention

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Abstract

Aquaculture biosecurity is a critical component of sustainable aquaculture development, ensuring disease prevention, environmental protection, and product safety. This study synthesizes current regulatory frameworks, technological innovations, and management practices shaping aquaculture biosecurity. It highlights the importance of risk-based approaches, stakeholder collaboration, and compliance with international and national guidelines. Emerging technologies such as next-generation sequencing, metagenomics, and remote sensing are advancing pathogen detection and environmental monitoring, while probiotics, vaccines, and genetic engineering offer new strategies for disease prevention. Sustainable practices, including recirculating aquaculture systems (RAS) and integrated multitrophic aquaculture (IMTA), reduce ecological impacts, while traceability systems and rapid diagnostics enhance food safety and consumer confidence. The future outlook emphasizes integrating technological innovation, sustainability, and social responsibility within strong regulatory frameworks to ensure resilient and ethical aquaculture production.

Keywords: Recirculating aquaculture systems (RAS); integrated multitrophic aquaculture (IMTA); next-generation sequencing; probiotics; food safety; risk-based management

Biosecurity

Biosecurity refers to the set of practices and measures aimed at preventing the introduction and spread of diseases, pests and harmful biological agents that threaten human, animal and plant health. In the face of rising pandemics, emerging infectious diseases and bioterrorism risks, biosecurity has become a cornerstone of global health and food security. Its primary goals include preventing the entry of new diseases through quarantine, screening and surveillance, while also reducing transmission within populations through vaccination, hygiene practices and protective equipment. These measures not only safeguard public health but also protect food supplies and ecosystems, ensuring resilience against biological threats. Continued investment in biosecurity is therefore critical, as it strengthens our ability to control infectious diseases, maintain economic stability in agriculture and aquaculture and preserve biodiversity and natural environments for future generations.

History of Biosecurity

Biosecurity has a long and evolving history, rooted in ancient efforts to control the spread of infectious diseases among humans and animals. Over time, the concept has been shaped by scientific and technological advancements, as well as the growing awareness of risks posed by disease outbreaks. The development of epidemiology in the nineteenth century, marked by John Snow's work during the cholera outbreak in London, laid the foundation for modern disease control. Breakthroughs such as vaccines and antibiotics in the nineteenth and twentieth centuries brought optimism, with many infectious diseases appearing to decline due to improved hygiene, medical treatments and preventive measures. However, the twentieth and twenty-first centuries have witnessed the persistence and re-emergence of infectious diseases, with a striking majority being zoonotic in origin 61% of re-emerging diseases and 75% of newly identified human pathogens arising from animals. These realities underscore the complexity of biosecurity, which continues to be shaped by major outbreaks and the need for effective prevention strategies. As global health faces ongoing challenges from emerging diseases and the demand for sustainable production practices, the importance of biosecurity will only grow, reinforcing its role in protecting populations, food systems and ecosystems.

Main Categories of Aquaculture Biosecurity

Aquaculture biosecurity prevents pathogens from entering and spreading within or between facilities. It is generally grouped into three categories: physical, biological and operational.

1. **Physical biosecurity measures**

Physical biosecurity measures in aquaculture are designed to block pathogens from entering systems, thereby reducing disease risks and protecting stock health. These include barriers such as fences, nets and screens to keep out predators and disease vectors, with effectiveness depending on barrier type, strength and facility location. Such measures also prevent farmed fish from escaping, which helps avoid the spread of pathogens to wild populations. In addition, closed systems like recirculating aquaculture systems (RAS) and flow-through units provide strong protection by limiting external contamination and maintaining controlled environments. Together, these physical strategies form a critical foundation for disease prevention and sustainable aquaculture.

2. **Biological biosecurity measures**

Biological biosecurity measures in aquaculture focus on strengthening the natural defenses of aquatic animals and reducing disease risks. One key approach is the use of disease-resistant species, such as specific pathogen-free (SPF) or pathogen-resistant (SPR) stocks, which lower susceptibility to infections. Probiotics are also widely applied, as they enhance immunity, improve growth and survival and help control bacterial diseases. Similarly, immunostimulants boost the immune response, increasing resilience against pathogens and supporting better performance in culture systems. Together with other microbial-based interventions like bacteriophages and vaccines, these strategies promote healthier stocks, reduce outbreaks and contribute to sustainable aquaculture production.

3. **Operational biosecurity measures**

Operational biosecurity measures in aquaculture focus on daily practices that maintain animal health and prevent disease spread. Key strategies include proper feed management, such as using high-quality, contaminant-free feeds and ensuring correct storage to avoid spoilage. Regular monitoring of water quality checking parameters like temperature, pH, oxygen and ammonia is equally critical, since poor conditions can stress animals and increase disease risks. Hygiene and sanitation protocols, including cleaning and disinfecting equipment, tanks and vehicles, help limit pathogen transfer, while staff training and the use of protective gear further strengthen defenses. Modern technologies such as sensors, drones and artificial intelligence now enhance these measures by enabling real-time monitoring, facility surveillance and predictive modeling of potential outbreaks. Together, these operational practices form a vital layer of biosecurity, ensuring sustainable and resilient aquaculture systems.

Components of aquaculture biosecurity

Aquaculture biosecurity includes several essential elements that work together to protect animal health and ensure sustainable operations. These elements form a comprehensive plan designed to minimize the introduction and spread of pathogens, reduce the risk of outbreaks and safeguard productivity. By integrating physical, biological and operational measures, aquaculture systems can maintain resilience and positively support long-term sustainability.

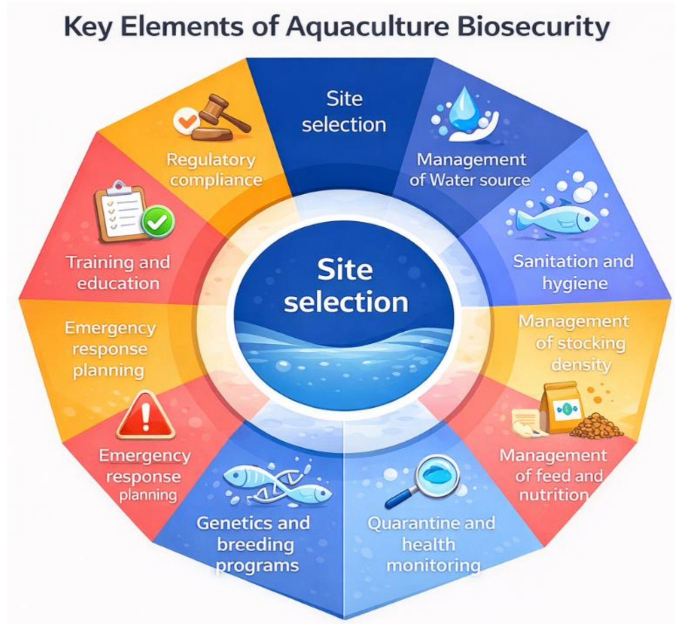

Fig. 1. Key elements of aquaculture biosecurity

1. **Site selection**

Site selection is a critical element of aquaculture biosecurity, as it directly influences the risk of disease introduction, environmental impact and overall sustainability of operations. Choosing the right location ensures optimal growing conditions while minimizing exposure to pathogens, pests and pollutants. Key considerations include water quality such as temperature, pH, oxygen and nutrient levels as well as freedom from contaminants like heavy metals or pesticides. Accessibility to transport and reliable infrastructure further supports efficient operations. Proximity to other aquaculture facilities or wild aquatic environments must be carefully evaluated to reduce cross-contamination risks, while closed or semi-closed systems can enhance protection. Topography and geology also play a role, with stable substrates and safe terrain reducing erosion, sedimentation and natural hazards. Finally, environmental impact

Fig. 2. Site selection as an element for aquaculture biosecurity

assessments are essential to prevent pollution and safeguard surrounding ecosystems. By carefully selecting sites, farmers can optimize production, protect aquatic health and strengthen long-term biosecurity.

2. Water source management

Water source management is a vital component of aquaculture biosecurity, as it directly influences stock health and disease prevention. Regular monitoring of water quality parameters such as temperature, pH, dissolved oxygen and nutrient levels helps maintain optimal conditions and reduces stress in aquatic animals. Treatment and filtration systems, along with physical barriers like screens and filters, can prevent the entry of pathogens and invasive species. Effective practices also include disinfection, quarantine and testing of new stock before introduction. To avoid cross-contamination, facilities should separate production units and enforce strict hygiene protocols, including equipment disinfection and proper staff practices. Emerging technologies such as sensors, remote monitoring, drones and AI further enhance water management by enabling real-time detection and predictive modeling of risks. By ensuring clean and secure water sources, aquaculture operations can minimize disease outbreaks, protect animal welfare and support long-term sustainability.

3. Sanitation and hygiene

Sanitation and hygiene are vital components of aquaculture biosecurity, helping to prevent disease outbreaks and maintain healthy stocks. Regular cleaning and disinfection of tanks, equipment and facilities reduce bacterial loads and limit pathogen transmission. Proper waste management further minimizes contamination risks within systems. Training staff in hygiene and biosecurity practices strengthens compliance and ensures consistent facility cleanliness. In addition, emerging approaches such as the xuse of probiotics and prebiotics have shown promise in lowering bacterial loads and improving fish health, offering innovative support to traditional sanitation measures. Together, these practices form a strong foundation for disease prevention and sustainable aquaculture operations.

4. Quarantine and health monitoring

Quarantine is a fundamental biosecurity measure in aquaculture, involving the isolation of new or returning animals to prevent disease introduction. Its duration depends on species, facility location and local disease history and should allow time for accurate health assessments using diagnostic tools like PCR or LAMP. Alongside quarantine, health monitoring programs combining passive surveillance of abnormal behavior and mortality with active sampling and testing are essential for early detection. Advances in digital technologies, including remote monitoring, machine learning and mobile applications, now enhance disease diagnosis and outbreak prevention. Together, quarantine and health monitoring provide a strong framework for protecting stock health and ensuring sustainable aquaculture operations.

5. Management of stocking density

Effective management of stocking density is a vital aspect of aquaculture biosecurity, as it directly impacts animal health, welfare and economic performance. Overcrowding can cause stress, increase disease outbreaks and reduce growth rates, while maintaining appropriate densities helps minimize pathogen transmission and improve survival. Strategies include using separate tanks or ponds for different life stages, applying biofilters and recirculating systems to maintain water quality and adjusting densities based on species-specific needs and environmental conditions. Studies consistently show that reducing stocking density improves growth, feed efficiency and disease resistance, making it a critical measure for sustainable and profitable aquaculture operations.

6. Feed and nutrition management

Feed and nutrition management are central to aquaculture biosecurity, as they directly influence the health, growth and disease resistance of cultured species. High-quality, well-formulated feeds ensure balanced nutrition, while poor-quality or contaminated ingredients can introduce pathogens and compromise stock health. Although fishmeal and fish oil remain common components, they carry risks of disease transmission if not properly processed, making strict quality control and the use of alternative protein and lipid sources important safeguards. Beyond formulation, feeding practices also matter overfeeding or underfeeding can cause stress, reduce immunity and increase disease susceptibility. Proper handling and storage of feed are equally critical to prevent contamination. Together, these measures help maintain animal welfare, reduce disease risks and support sustainable aquaculture operations.

7. Genetics and breeding programs

Genetics and breeding programs are increasingly important for aquaculture biosecurity, as they help reduce disease risks and improve the resilience of farmed stocks. Selective breeding focuses on traits such as growth, survival and disease resistance, while advances in genomics and genetic engineering allow identification and modification of genes linked to immunity and performance. Transgenic fish and marker-assisted selection have shown promise in enhancing resistance to common pathogens. However, these approaches also raise concerns, including potential impacts on wild populations if escapees occur and reduced genetic diversity that may increase vulnerability to other stresses. To balance benefits and risks, breeding strategies must prioritize genetic diversity, sustainability and responsible use under clear regulatory frameworks.

8. Emergency response planning

Emergency response planning is a vital element of aquaculture biosecurity, designed to minimize the impact of disease outbreaks, natural disasters and other critical incidents on fish health, production systems and the environment. Effective planning involves clear, tailored protocols for identifying and reporting emergencies, controlling disease spread and safeguarding stock welfare. Strong communication and collaboration among stakeholders producers, government agencies and support networks ensure coordinated responses and resource sharing. Risk assessment and management strategies further strengthen preparedness by identifying vulnerabilities and implementing preventive measures, such as backup systems and enhanced biosecurity. Regular training and simulation exercises are essential to keep stakeholders familiar with procedures, improve response efficiency and ensure rapid action when emergencies occur. Together, these measures protect aquaculture operations from major disruptions and support long-term sustainability.

9. Training and education

Training and education are essential components of aquaculture biosecurity, ensuring that stakeholders understand and can effectively implement protocols. These efforts may include classroom instruction to build foundational knowledge, on-the-job training for practical application and simulations to test emergency response plans. Collaboration among producers, agencies and organizations enhances resource sharing and preparedness, especially during large-scale emergencies. In addition to formal programs, global organizations such as the FAO and the Global Aquaculture Alliance provide guidelines, manuals, webinars and courses that promote awareness and strengthen biosecurity practices across the industry.

10. Regulatory compliance

Regulatory compliance is a critical element of aquaculture biosecurity, ensuring that production systems operate safely, responsibly and sustainably. It covers key areas such as water quality, fish health, animal welfare and environmental protection, helping to safeguard both public health and ecosystems. International frameworks like the FAO's *Code of Conduct for Responsible Fisheries* provide broad guidelines, while national regulations such as the U.S. EPA's NPDES program set specific requirements for waste management and water discharge. Compliance relies on coordinated efforts among government agencies, industry organizations and producers, supported by certification programs and monitoring mechanisms. Regular inspections, audits and reporting requirements, coupled with consistent enforcement, are essential to deter violations and maintain a level playing field. By adhering to these frameworks, aquaculture operations can reduce risks, prevent disease outbreaks and ensure long-term sustainability.

Future Prospects and Vision of Aquaculture Biosecurity

Aquaculture biosecurity is set to become a foundation for sustainable industry growth, driven by innovation, risk-based management and strong regulation. Future strategies emphasize rapid pathogen detection through tools like next-generation sequencing, metagenomics and AI-based monitoring, alongside genetic breeding, vaccines and microbial treatments to reduce reliance on antibiotics. Sustainability will be advanced through closed systems (RAS), integrated multitrophic aquaculture (IMTA) and practices that minimize waste and ecosystem impact. Social responsibility ensuring fair labor and ethical practices will complement environmental goals. Regulatory frameworks with clear standards, monitoring and transparency will ensure compliance, product safety and consumer confidence. Together, these measures create a resilient, responsible and forward-looking biosecurity system for aquaculture.

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