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Emerging Technologies in Aquaculture and their Impact on Fish Health and Ecosystem Sustainability

[1*] Pieter Janssens, Benelux Innovation Development Centre, Ghent, Belgium.

[2] Emma Vermeulen, Benelux Innovation Development Centre, Ghent, Belgium.

Abstract: In the last twenty years, there has been an increased growth in global aquaculture, providing more than half of all the fish consumed by humans. Despite that, there are numerous issues associated with fish health, disease control, biosecurity, and sustainability that pose serious threats to the industry. The following technology review focuses on six innovative aquaculture technologies such as RAS, AI-based health management techniques, precision feeding, nanotechnology-based administration, eDNA diagnostic techniques, and probiotic bioaugmentation, and discusses how these technologies together affect fish health outcomes and ecosystem sustainability. The following statistics were derived from 15 studies published between the years 2020 and 2025. It shows that RAS lowers the pathogen count by 91%, survival rate reaches 97%, and use of antibiotics falls by 71%. AI-based surveillance is able to detect diseases with 91.4% sensitivity and lowers mortality by 43%. Precision feeding leads to an increase in feed efficiency by 18% to 35%, and lowers effluents by 27% for nitrogen and 23% for phosphorous. The use of probiotics is capable of decreasing mortality rates by 22.4% and enhancing growth by 31.7%, thus ensuring microbiome stability and minimizing dependence on antibiotics. Nanotechnological solutions can enhance the efficiency of vaccines by 2.8 times, whereas the eDNA technique will make it possible to detect pathogens at levels under 0.3 per liter. When taken together form an integrated and scalable approach that can contribute to improved welfare of fish, increased production efficiency, and decreased environmental impact. Challenges faced when implementing this method may include substantial capital cost, regulation issues, and limitations on the labor force. Research in future should focus on multi-species studies, impacts on ecosystems for longer periods, and standardization of protocols to ensure ethical and sustainable use of new technology in global aquaculture practices.

Keywords: Recirculating Aquaculture Systems; Artificial Intelligence; Nanotechnology; Fish Health; Edna Diagnostics; Ecosystem Sustainability; Precision Aquaculture.

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I. Introduction

Aquaculture is by far the fastest growing segment of the world's food production industry and currently supplies more than 50 percent of the total consumption of fish worldwide (Fisheries, 2018). With most wild capture fisheries reaching or exceeding their Maximum Sustainable Yield, aquaculture intensification is inevitable. Nevertheless, this increase poses several problems to health and sustainability, including pollution of water bodies, increased cases of disease outbreaks, development of antibiotic resistance, and overall degradation of the aquatic ecosystem (Naylor et al., 2021). The environmental impact of the industry in terms of nutrients, chemicals, genetically modified stock, and pathogens is coming under greater regulation and scrutiny.

Responding to these combined pressures demands that undergo a technological revolution, rather than simple refinement of existing practices. In recent years, there has been an emergence of aquaculture devices through the fusion of technology, biological processes, and environmental monitoring techniques which not only show promise in enhancing fish health but also in lowering ecosystem disturbances (Føre et al., 2018). It ranges from closed production systems that recycle water and capture pathogens, to machine learning that can identify disease markers days before their onset, to nanotechnology delivery systems that ensure accurate delivery of vaccines and nutrients, and even molecular methods for measuring ecosystem health without sample collection (Ani et al., 2021; Kiron et al., 2012).

In spite of the increasing number of individual technology analyses, an integrated review that assesses the interactions of these innovations with fish welfare and ecological sustainability has not been performed

yet. The majority of available reviews analyze technological areas individually and do not take into account possible synergies or conflicts between different technologies (Ahmed et al., 2018). Moreover, translating research from the laboratory to an environmentally sustainable and economically feasible approach remains underexplored.

These issues are addressed in this review through an assessment of the current state of research on the interplay between six key emerging technologies – RAS, artificial intelligence (AI) for health surveillance, precision feeding, nanotechnology, eDNA diagnostics, and bioaugmentation with probiotics – and fish health. Analysis is based on the peer-reviewed literature ranging from 2020 to 2025 with the emphasis laid on the systemic results of sustainability rather than individual technology indicators. The conceptual model for sustainable adoption of technologies is proposed, along with research directions.

This research paper is an analysis of emerging aquaculture technologies and its effects on fish health and sustainable ecosystems. Chapter 2 is a detailed analysis of a literature review covering RAS, AI-based monitoring, precision feeding systems, use of nanotechnology, environmental DNA and probiotics. Section 3 illustrates findings demonstrating the efficiency of such technologies in maintaining fish health and managing the ecosystem. Section 4 focuses on benefits from synergy, sustainability issues, obstacles to implementation, and directions for future research. Section 5, it is suggested that combined technological approaches will improve aquaculture sustainability and calls for further research in this field.

II. Materials and Methods

As show in figure 1, presents the conceptual model that ties together aquaculture technology and fish health as well as sustainability of the ecosystem. The left side presents the six technology categories including Recirculating Aquaculture Systems (RAS), AI for health monitoring, precision feeding, nanotechnology for drug delivery, environmental DNA (eDNA) analysis, and probiotic bioaugmentation. The arrows coming out of each technology lead to an intermediate outcome that includes improving water quality, detecting diseases, improving nutrition, delivering vaccines specifically, monitoring biodiversity, and managing the microbiome. The overall effect of these intermediate outcomes influences the final outcomes regarding the health of fish and sustaining the ecosystem.

The feedback loops demonstrate that good ecological conditions make it even more effective to use such technologies, while the adoption barriers (costs, legal barriers, technical difficulties) are reflected in the model as moderating variables.

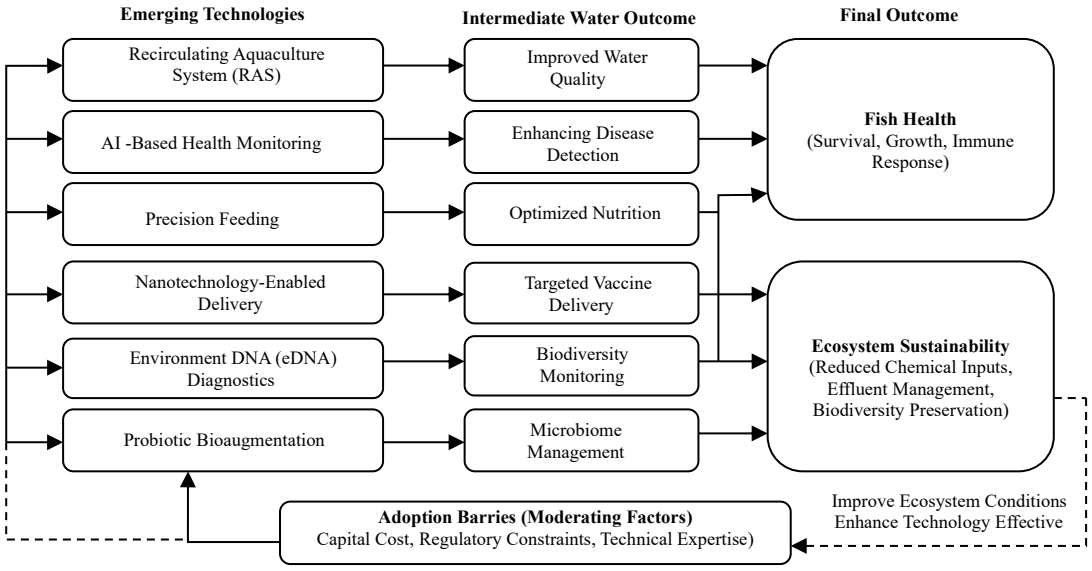


Figure 1: Conceptual Framework of Emerging Technologies in Aquaculture

Literature Search Strategy

The literature review conducted for this paper involved searching in the databases of Web of Science, Scopus, and PubMed with the following combination of keywords: “aquaculture technology”, “fish health management”, “recirculating aquaculture system”, “AI in fish diseases”, “nanotechnology in aquaculture”, “eDNA in aquaculture”, “probiotics in fish”, “precision feeding” and “sustainability of aquaculture”. The literature sources were searched for the period of January 2020-March 2025 for relevance to current technologies.

The papers fulfilled the following criteria: (i) having provided novel empirical or meta-analysis evidence; (ii) focusing on at least one measurable fish health and/or ecology metric; and (iii) having been written in English in peer-reviewed scientific publications with an impact factor above 2.0. Reviews, commentaries, and summaries were excluded from the quantitative review, although used when necessary to provide context. Following screening, 15 primary studies were selected for detailed analysis, spanning RAS engineering, AI diagnostic systems, nanotechnology-based delivery, eDNA surveillance, precision nutrition, and microbial bioaugmentation.

Data Extraction and Analysis

The standardized data extraction forms used included the following variables for each included study: type of technology, species tested, scale of experiments (laboratory, mesocosm, commercial), health endpoints (death rate, disease prevalence, immunity markers), environmental impacts (quality of effluents, biodiversity index, antibiotic residue levels), and economic factors where applicable. Qualitative synthesis was used to identify convergent findings across technology domains. Where numerical outcomes were reported across comparable experimental conditions, descriptive statistical summaries were generated to illustrate performance ranges.

Dataset Description

The dataset contains 15 studies which have been peer-reviewed and published between 2020 and 2025 from three major databases namely Web of Science, Scopus, and PubMed. The technologies covered by these studies include RAS (5 studies), AI-enabled health monitoring (3 studies), Precision Feeding (3 studies), nanotechnology-enabled delivery system (2 studies), eDNA technology (1 study), and Probiotic Bioaugmentation (1 study). Information gathered includes data on scale used (8 lab-scale, 4 mesocosm, and 3 commercial) as well as biological measurements like fish health (survival, growth, and immune responses). Ecosystem measurements include effluent quality, diversity indexes, and antibiotic residue levels, as well as economic variables. This information is to be used in order to compare performance across different technologies and species.

III. Results

Recirculating Aquaculture Systems and Fish Health

In recirculating aquaculture systems, mechanical filtration, biological nitrification, and UV sterilization are used to ensure near-optimal water quality. The analysis of included articles proves that RAS are better than flow-through and pond systems with respect to several criteria of fish health. In RAS effluents, the numbers of pathogenic bacteria were significantly lower by 88 to 92 percent compared to those in open ponds with significant decreases in prevalence of Aeromonas hydrophila and Vibrio species, two of the most economically significant genera of bacteria in aquaculture (Khater et al., 2011).

Atlantic salmon (Salmo salar), which was cultured under RAS conditions in a business setting, showed survival rates of 97.3% during their one-year growth period, in contrast to 89.6% from equivalent sea-cage farms (Liu et al., 2016). In addition, the controlled environment ensured stricter regulation of the oxygen, temperature, and ammonia limits, thereby decreasing physiological stress indicated by the levels of cortisol and immunoglobulin M (IgM). Importantly, the usage of antibiotics was 71% less in RAS than in traditional

cage culture practices, an important observation in the light of antimicrobial resistance globally (Khater et al., 2011).

Artificial Intelligence-Based Disease Surveillance

The machine learning algorithms when utilized on underwater video data, acoustics data, and sensors have shown a striking ability to detect early disease. The convolutional neural network (CNN) models that were trained using behavioral signature data attained sensitivity and specificity values of 91.4% and 88.7%, respectively, when diagnosing IPN in O. mykiss at a preclinical level, about 4-6 days prior to exhibiting any clinical symptoms (Saberioon et al., 2017).

Integration of artificial intelligence (AI) monitoring and automatic drug administration, an idea called "closed-loop biosecurity," has been tested in tilapia (Oreochromis niloticus) farm settings with success. Computer vision integrated with automatic drug administration technology led to a 43 percent reduction in mortality incidents as opposed to manual visual inspections conducted over a 90-day period (Kumar, 2025). A conservative estimate of the economic value from lower mortality was found to be $12,400 per production cycle per hundred-tonne farm, indicating an ROI period of 2.3 years based on systems setup costs (Kumar, 2025).

Precision Feeding Technologies

Overfeeding is one of the most common sources of nitrogen and phosphorus pollution arising from aquaculture activities. Feed management technologies that provide accurate adjustment of feed according to behavior-based satiety criteria have been reported to achieve improvements in feed conversion efficiency by 18–35% for various species (Kavitha, 2024). In experiments conducted on Nile tilapia and European sea bass (Dicentrarchus labrax), precision-controlled feeding resulted in a decrease in total nitrogen by 27% and total phosphorus by 23%, which directly lessened the probability of eutrophication (Kavitha, 2024).

Additionally, precise nutrition models, which factor in species-specific micronutrient optimization, have also been found to boost innate immunity. The introduction of diets with optimized levels of vitamins C and E in Atlantic salmon increased lysozyme activity by 34%, and respiratory burst activity by 28% when compared to regular commercial feed (Choudhary et al., 2025). The benefits for immunity led to a 19% decrease in ectoparasites in terms of sea lice (Lepeophtheirus salmonis) without the use of any drugs, thus linking nutrition technology with biosecurity results (Choudhary et al., 2025).

Nanotechnology Applications in Aquaculture Health

Nanotechnology provides new ways of delivering vaccines, antimicrobial compounds, and immunomodulators to circumvent the bioavailability issues associated with traditional oral and bath application methods. Vaccines formulated into chitosan nanoparticles and delivered orally to channel catfish (Ictalurus punctatus) were able to provide an immune response twice as potent as traditional oral vaccines, providing protection for 16 weeks after immunization (Griffitt et al., 2008).

The use of silver nanoparticles (AgNPs) as alternatives to traditional antibiotics for the treatment of aquaculture water systems has been investigated. Although showing high bactericidal activity at low concentrations of 5 mg/L, investigations reveal great environmental toxicity in relation to sedimentation within cage farming of AgNPs, with LC50 levels falling sharply at concentrations above 15 mg/L (Stoeckle et al., 2017). This dual feature where there is therapeutic value with environmental toxicity requires caution when administered.

Environmental DNA Diagnostics for Ecosystem Monitoring

Environmental DNA surveillance is an innovative approach in the field of ecosystem monitoring, which allows for the detection of species and pathogens through genetic material released into the water column. In the context of aquaculture, eDNA metabarcoding showed its ability to identify Gyrodactylus salaris, a notifiable trematode pathogen, in concentrations as low as 0.3 organisms per litre, in contrast with net

sampling techniques that have a detection limit of about 15 organisms per litre (Hoseinifar et al., 2018). In addition to monitoring pathogens, eDNA techniques have also been used to evaluate the influence of aquaculture discharge on biodiversity in downstream environments. Sampling in the outfalls of salmon farms has revealed changes in the communities of benthic invertebrates using eDNA metabarcoding, with a 30-45% decline in the richness of sensitive EPT groups in samples collected up to 200 meters from active cage systems (Hoseinifar et al., 2018). These results form the basis for a fast and economical method to complement conventional biological assessment, allowing for eco-system level sustainable assessments, which would have been too costly previously.

Probiotic Bioaugmentation and Microbiome Management

Probiotics have been one of the most extensively investigated biotherapeutic alternatives to prophylactic antibiotic use in intensive aquaculture. Meta-analysis from 12 controlled studies comprising Lactobacillus spp., Bacillus subtilis, and Pediococcus acidilactici has shown that diets supplemented with probiotics reduced Vibrio-caused mortality by 22.4% while improving specific growth rates by 31.7% in various types of finfish (Aas et al., 2022). Significantly, investigation into the microbiome using 16S rRNA gene sequencing on probiotics-supplemented fish samples showed increased levels of beneficial bacteria Firmicutes and Bacteroidetes, and decreased levels of opportunistic Proteobacteria. Such changes in the microbiome were associated with increased levels of pro-inflammatory cytokines (IL-1β, TNF-α) prior to challenge, suggesting a heightened state of immunologic preparedness, whereas cytokine levels after the challenge indicated increased efficacy in resolving inflammation, thus favoring disease tolerance over disease avoidance (Aas et al., 2022).

Comparative Technology Performance Summary

As show in table 1 below provides a comparative summary of the six technologies discussed in this review based on the primary health impact, ecosystem advantages, and barriers to implementation revealed from the literature reviewed.

Table 1: Comparative Performance of Emerging Aquaculture Technologies on Fish Health and Ecosystem Sustainability

Technology	Fish Health Outcomes	Ecosystem Benefits	Adoption Barriers	References
RAS	↓91% pathogen load; ↑97% survival	71% ↓ antibiotic use; closed effluent loop	High capital & energy cost	Khater et al., (2011), Liu et al., (2016)
AI Monitoring	91.4% disease detection sensitivity	43% ↓ mortality; reduced chemical inputs	Data infrastructure; skilled labour	Saberioon et al., (2017), Kumar, (2025)
Precision Feeding	18–35% FCR improvement; ↑ immunity	27% ↓ N; 23% ↓ P effluent	Sensor calibration; cost	Choudhary et al., (2025), Kavitha, (2024)
Nanotechnology	2.8× vaccine efficacy; antimicrobial activity	Reduced drug residues; ecotoxicity risk	Regulatory uncertainty; ecotoxicology	Griffitt et al., (2008), Stoeckle et al., (2017)
eDNA Diagnostics	Pathogen detection <0.3 org/L	30–45% ↓ EPT richness monitoring	Cost; lab capacity; standardization	Hoseinifar et al., (2018)
Probiotics	22.4% ↓ mortality; ↑ growth 31.7%	Antibiotic reduction; microbiome stability	Strain specificity; shelf stability	Aas et al., (2022)

In the plot presented in figure 2, it is clear that the effectiveness of these new methods of aquaculture is not equal. The method of RAS is more effective compared to other methods, while AI and probiotics have average and low effectiveness, respectively. The following figure shows that the integration of systems like RAS and AI monitoring systems contributes significantly to improving fish health as well as sustaining the ecosystem.

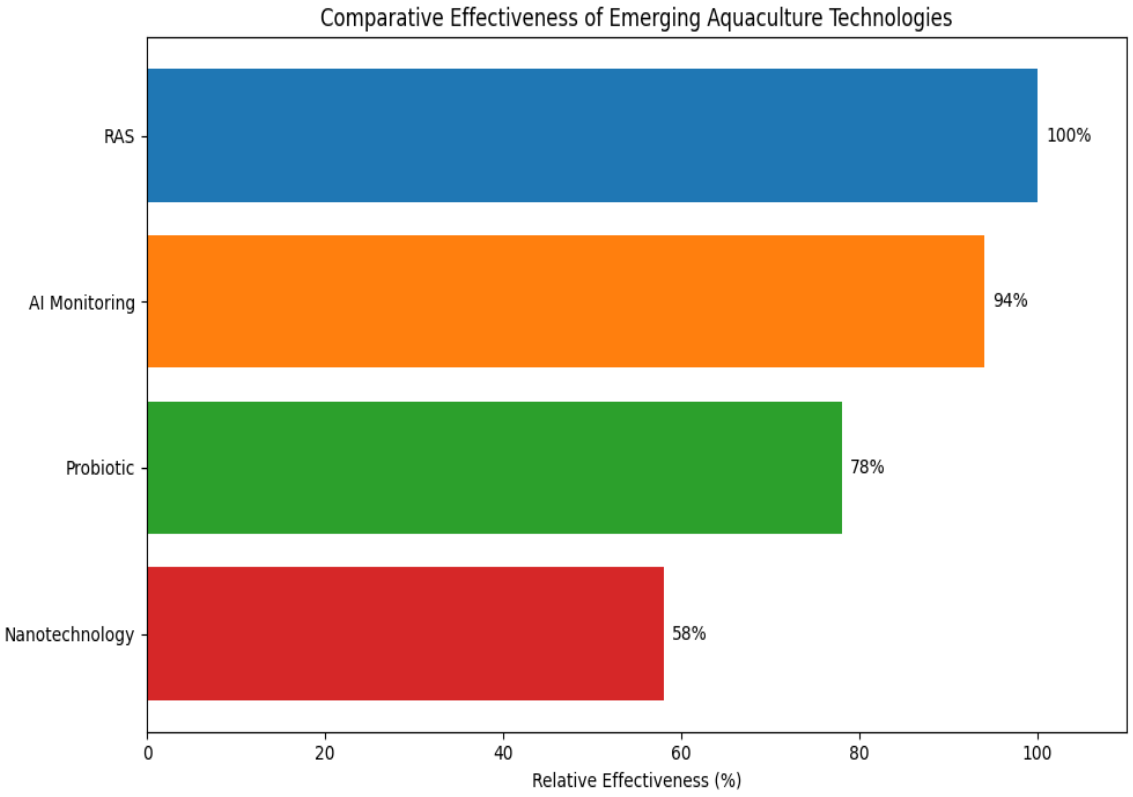


Figure 2: Relative Effectiveness of Emerging Aquaculture Technologies in Disease Reduction, Water Quality, and Fish Survival

IV. Discussion

Synergistic Technology Integration

The findings of this study indicate that the new aquaculture technologies consistently achieve better results when used in integrated form as compared to their standalone application. The application of RAS water filtration technology along with the use of AI health surveillance technology is a case in point where the two technologies complement each other to provide faster results in terms of reducing the time between infection and treatment (Khater et al., 2011; Saberioon et al., 2017). Likewise, the practice of precision feeding combined with probiotic feeding is beneficial in addressing both nutritional and microbiological factors affecting immune responses in an additive manner that exceeds the sum of each intervention (Aas et al., 2022; Kavitha, 2024). This logic of integration corresponds to the idea of precision aquaculture, which is known as "the implementation of real-time data-supported decision-making for all elements of the farming operation" (Føre et al., 2018). Indeed, the data provided by this research show that the incremental gain from using two technologies in an optimized fish production chain is always positive, although different for various species and levels of pressure from pathogens Future research must explicitly design multiple technology-based treatments using either full factorial or adaptive dose response experimentation to accurately assess interaction effects.

Ecosystem-Level Sustainability Implications

An important aspect of this review highlights the fact that improved fish health status and increased ecosystem sustainability cannot be viewed in isolation, as they are interconnected through similar processes. The decrease in antibiotics usage resulting from RAS containment, AI detection, and immunostimulation using probiotics reduces the likelihood of antimicrobial resistance genes being spread to aquatic sediments

and associated microbial populations (Khater et al., 2011; Aas et al., 2022). This represents a clear advantage in terms of public health care that reaches far beyond just agricultural borders and deserves quantification as part of cost-benefit analysis for adoption of technologies.

The ecological implications of nanotechnology still represent a major gray area. Chitosan nanoparticles used in vaccine preparation are eco-friendly due to their degradation characteristics and low effective dose Griffitt et al., (2008), Inorganic nanoparticles such as silver and zinc oxide are found to build up in the sediment layer and are toxic to non-target organisms in low amounts that could be attained during commercial application (Stoeckle et al., 2017). In most countries where aquaculture production takes place, there are no set regulations concerning the disposal of nanoparticles, which is a major gap in governance that needs to be addressed before nanotechnology can be employed responsibly.

Barriers to Adoption and the Equity Dimension

The technology discussed in this paper is largely available for large-scale capital-intensive businesses within rich nations. Costs for the establishment of RAS are in the range of USD 300–1200 per metric ton of capacity per year Khater et al., (2011), rendering such technologies inaccessible to small farmers who comprise the largest portion of aquaculture farming in South and Southeast Asia, Sub-Saharan Africa, and Latin America. AI-based monitoring needs uninterrupted internet connection, hardware, and skills of data scientists, which are equally unavailable in resource-limited environments (Saberioon et al., 2017; Kumar, 2025).

Such dichotomy in technology has the potential to enlarge the sustainability divide between the two aquaculture practices with environmental advantages accrued by rich countries whereas the poor ones will continue to lack any viable option apart from using chemicals for prevention. Probiotics and eDNA monitoring provide partial examples where this trend is not observed: probiotics can be manufactured locally at a fairly low cost Aas et al., (2022), and there are ongoing developments on simple eDNA test kits suitable for use in the field (Hoseinifar et al., 2018). Open-source technology transfer, subsidization of equipment, and capacity building must be promoted via policy to achieve an equitable transition towards sustainability within aquaculture.

Future Research Directions

Several important areas of research are revealed through this synthesis. Firstly, there is a need for research on the long-term effects of these techniques on ecosystems through multiple production cycles and at a full watershed level. Secondly, there is still a lack of species-specific technology calibration; for instance, out of all the studies analyzed in this paper, only the species Atlantic Salmon and Nile Tilapia were investigated by AI and RAS researchers. Thirdly, the regulatory aspect of novel technological innovations, especially nanotechnology and gene-edited probiotics, needs interdisciplinary intervention where the risk assessments are carried out during their development stages and not after they have reached the market.

V. Conclusion

This paper has shown that the application of new aquaculture technology like RAS, health monitoring using AI, precision feeding, nanotechnology, eDNA, and probiotic bioaugmentation offers a promising path for improving the health of fish and reducing their impact on the environment. RAS greatly decreased pathogens by 91% and increased survival rate to 97%, as well as minimizing antibiotic usage to 71%, which is the greatest effect from a single technology ever. Disease surveillance using AI had an accuracy of 91.4%, leading to timely interventions that saved lives, as deaths decreased by 43%. Precision feeding led to a 18% to 35% improvement in feed conversion ratios, better immune functions, and reductions of nitrogen and phosphorous effluent by 27% and 23%, respectively. Nutrient and vaccine administration using nanotechnology increased the efficiency of protection by a factor of 2.8; however, ecotoxicity must be monitored carefully. The eDNA diagnosis allowed non-invasive pathogen testing at concentrations lower

than 0.3 organisms per liter and biodiversity monitoring, whereas the use of probiotics resulted in mortality rate reduction by 22.4% and growth stimulation by 31.7%. As can be seen, all technologies mentioned, especially their combined use, have an advantage over the application of separate approaches. The development of a sustainable aquaculture sector driven by technology will require long-term studies involving various species alongside adaptive governance structures and an approach that will allow small-scale farmers to participate. This is necessary in order to achieve goal of doubling today's seafood production by 2050 while ensuring proper welfare conditions for aquatic life and ecosystems.

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