Synergistic Application of Emerging Technologies in Fisheries Science and Veterinary Medicine: A Transdisciplinary Review

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ABSTRACT

The convergence of advanced technological domains—namely precision aquaculture, molecular diagnostics, remote sensing, and digital health surveillance—has catalysed a paradigm shift in both fisheries science and veterinary medicine. This review synthesises the state-of-the-art of integrated technologies including next-generation sequencing (NGS), CRISPR-based diagnostics, the Internet of Things (IoT), blockchain for traceability, and machine learning for disease modelling. Special emphasis is placed on cross-sectoral applications where veterinary diagnostic platforms enhance aquatic animal health management, and fisheries monitoring tools inform terrestrial livestock epidemiology. The paper evaluates the efficacy of real-time biosensing, vaccine delivery systems, and environmental DNA (eDNA) analytics as dual-use technologies. Furthermore, it addresses regulatory harmonisation and One Health implications of merging these disciplines. By critically analysing case studies from both sectors—such as the use of portable NGS on fishing vessels and mobile veterinary clinics, CRISPR assays for both African swine fever and white spot syndrome virus, and satellite remote sensing for Rift Valley fever and harmful algal blooms—this review provides a roadmap for interoperable technological frameworks that improve biosecurity, reduce antimicrobial resistance, and optimise production sustainability. The findings underscore that only through deliberate integration of engineering, data science, and veterinary medicine can the global challenges of aquatic and terrestrial food systems be met effectively.

Keywords: Precision aquaculture, veterinary digital diagnostics, CRISPR-Cas, IoT biosensors, One Health, eDNA surveillance

1. Intriduction

The twenty-first century has witnessed an unprecedented acceleration in biological and digital technologies that individually have revolutionised fisheries science and veterinary medicine [1,2]. However, the most transformative opportunities lie at their intersection. Fisheries science, traditionally focused on stock assessment and aquaculture productivity, now shares common challenges with veterinary medicine: infectious disease control, antimicrobial stewardship, food safety, and environmental impact mitigation [3,4]. Emerging technologies such as portable genome sequencers, autonomous underwater vehicles, and cloud-based clinical decision support systems are no longer sector-specific [5].

Nevertheless, a critical gap persists: most innovation occurs within disciplinary silos. Veterinary diagnostics developed for cattle or poultry remain underutilised in shrimp or salmon farming, while fisheries hydroacoustic telemetry has rarely been applied to free-ranging terrestrial wildlife [6,7]. For example, implantable biotelemetry devices originally designed for racehorses have only recently been miniaturised for intracoelomic implantation in salmon, despite the fundamental similarity in measuring heart rate and accelerometry as stress indicators [26,28]. This review aims to bridge that gap by systematically examining combined applications of novel technologies across both domains. Specifically, we address: (i) molecular and genomic tools for pathogen detection; (ii) remote sensing and IoT for real-time health monitoring; (iii) data integration and predictive modelling; (iv) blockchain and traceability for biosecurity; and (v) vaccine and therapeutic delivery innovations. The ultimate goal is to propose an interoperable framework rooted in the One Health paradigm, acknowledging that aquatic and terrestrial animal health are inextricably linked through ecosystems and food supply chains [8,9].

2. Molecular and Genomic Technologies: Cross-Sectoral Diagnostic Platforms

2.1 Next-Generation Sequencing (NGS) in Disease Surveillance

NGS has transformed pathogen discovery in both veterinary medicine and fisheries. Metagenomic sequencing allows unbiased identification of known and novel viruses, bacteria, and parasites from clinical samples [10,11]. In veterinary practice, NGS routinely identifies emerging zoonotic pathogens such as influenza variants and coronaviruses in livestock [12]. For instance, Richt and Webby [12] demonstrated that lung tissue from pigs with atypical pneumonia could reveal co-infections with porcine reproductive and respiratory syndrome (PRRS) virus and influenza A virus via metagenomic sequencing, a finding that would be missed by targeted PCR alone.

In fisheries, NGS has unveiled covert pathogens in wild salmon populations and shrimp hatcheries, often before clinical signs appear [13,14]. Kibenge and Godoy [13] reported that metagenomic sequencing of asymptomatic Atlantic salmon post-smolts identified a novel calicivirus later associated with haemorrhagic syndrome. Similarly, Thitamadee and Lightner [14] used NGS to detect a picorna-like virus in imported broodstock Penaeus monodon, preventing a potential epizootic in Southeast Asian hatcheries. The cross-sectoral synergy is evident: bioinformatic pipelines developed for veterinary metagenomics (e.g., Kraken2, MetaPhlAn) are directly portable to aquatic samples, and vice versa. Furthermore, portable NGS devices (e.g., Oxford Nanopore MinION) have been deployed both in mobile veterinary clinics in sub-Saharan Africa and on fishing vessels in the Bering Sea, enabling real-time genomic epidemiology [15]. Jain and Olsen [15] documented that onboard MinION sequencing of gill tissue from wild-caught cod allowed identification of a Vibrio species within four hours, a turnaround time impossible with shore-based laboratories.

2.2 CRISPR-Based Diagnostics (CRISPR-Cas)

The adaptation of CRISPR-Cas systems for nucleic acid detection (e.g., SHERLOCK, DETECTR) has yielded rapid, field-deployable diagnostic assays [16,17]. In veterinary medicine, these assays detect foot-and-mouth disease virus, African swine fever virus (ASFV), and Mycobacterium bovis within 30 minutes without thermal cycling [18]. Mwangi and Simuntala [18] described a lateral flow CRISPR assay for ASFV that achieved 98.5% sensitivity and 99.2% specificity compared to real-time PCR, using only a portable fluorescence reader and lyophilised reagents stable at 37°C for three weeks. Fisheries scientists have recently adapted the same platforms for white spot syndrome virus (WSSV) and Aeromonas hydrophila in catfish and tilapia [19]. Loh and Leong [19] modified the DETECTR system to detect WSSV at 10 copies per microlitre of haemolymph, equivalent to the sensitivity of quantitative PCR, but with results visible on a paper strip in 25 minutes. Notably, the same lateral flow readout systems developed for cattle campaigns in Kenya are now being used for viral nervous necrosis (VNN) in grouper larvae [20]. Zohar and Mylonas [20] showed that a single batch of CRISPR-Cas12a reagents could be used to detect VNN, ASFV, and Salmonella enterica simply by changing the guide RNA, demonstrating a true platform technology.

2.3 Environmental DNA (eDNA) for Pathogen and Biodiversity Surveillance

eDNA technology, initially popularised in fisheries for detecting endangered species (e.g., Chinese paddlefish, great crested newt), has matured into a powerful tool for pathogen surveillance [21,22]. Veterinary epidemiologists now employ eDNA to monitor soil and water near livestock facilities for bacterial pathogens like Leptospira and Clostridium [23]. Franklin and Gough [23] sampled water from drainage ditches downstream of a dairy farm and detected Leptospira interrogans DNA up to 1.2 km away, allowing targeted vaccination of herds in the catchment area. Conversely, veterinary-scale quantitative PCR (qPCR) assays have been repurposed to detect sea lice (Lepeophtheirus salmonis) DNA in seawater before infestation thresholds are reached [24]. Bron and Sommerville [24] designed a qPCR assay targeting the sea louse mitochondrial cytochrome oxidase I gene, achieving detection at 0.5 copepodids per cubic metre, which correlates with a 95% probability of subsequent clinical infestation.

The integration of eDNA with automated water sampling stations (see Section 3) creates a continuous health monitoring network that serves both wild fisheries and downstream veterinary biosecurity [25]. Darling and Bohmann [25] described an autonomous eDNA sampler deployed on a salmon farm that collected 24 samples per day, performed on-board DNA extraction, and transmitted results via satellite. In a 2022 pilot, this system detected Tenacibaculum maritimum DNA 48 hours before the first fish showed skin ulcers, compared to 12 hours earlier than manual sampling.

3. Internet of Things (IoT) and Remote Sensing: Real-Time Health Monitoring

3.1 Wearable and Implantable Biosensors

Miniature biosensors that measure heart rate, temperature, and accelerometry were pioneered in veterinary telemetry for horses and cattle [26,27]. Neethirajan [26] reviewed commercial rumen boluses and ear-tag accelerometers that predict calving and oestrus with >90% accuracy. These sensors are now miniaturised for fish: intracoelomic implants transmit temperature, depth, and electrocardiogram (ECG)-like signals in free-swimming salmon [28]. Cooke and Hinch [28] implanted 200 adult Atlantic salmon with custom 0.8 g sensors (6 mm diameter, 12 mm length) that measured heart rate (beats per minute) and three-axis acceleration (50 Hz). During a 30 km spawning migration, the sensors detected a 40% increase in arrhythmia index in fish exposed to water temperatures above 20°C, correlating with subsequent mortality. The combined data space allows comparative physiology studies on stress responses across species.

Machine learning algorithms trained on terrestrial livestock data (e.g., early detection of lameness in dairy cows) have been successfully transferred to detect abnormal swimming behaviour associated with bacterial gill disease in fish [29]. Broom and Fraser [29] reported that a support vector machine trained on step-count asymmetry in lame cows, when retrained with swimming acceleration data, classified Flavobacterium branchiophilum-infected rainbow trout with 88% accuracy, compared to 76% using a fisheries-only model.

3.2 Underwater and Terrestrial IoT Networks

Low-power wide-area networks (LoRaWAN) and 5G-enabled sensor arrays are deployed in both aquaculture pens and intensive livestock barns [30]. In fisheries, underwater acoustic sensors monitor dissolved oxygen, ammonia, and fish density; in veterinary medicine, similar sensors (but air-based) monitor ammonia, carbon dioxide, and animal movement [31,32]. Føre and Alfredsen [31] described a LoRaWAN network covering 12 sea cages in Norway, with each cage containing five multi-parameter probes (temperature, pH, dissolved oxygen, salinity, turbidity) and two acoustic Doppler current profilers. Data are transmitted every 15 minutes to a cloud platform that triggers oxygen supplementation when dissolved oxygen falls below 6 mg/L.

Conversely, Berckmans [32] deployed a 5G-enabled sensor suite in a 2,000-head swine barn measuring CO_2 (0–5,000 ppm), NH_3 (0–100 ppm), temperature, humidity, and pig position via ultra-wideband tags. The data fusion from both environments can feed centralised One Health dashboards that alert authorities to simultaneous mortality events in fish and nearby poultry, indicative of waterborne or airborne cross-contamination [33]. Zinsstag and Schelling [33] documented a case in the Mekong Delta where a combined dashboard detected elevated NH_3 (60 ppm) in a poultry barn and concurrent low dissolved oxygen (4.2 mg/L) in an adjacent catfish pond, traced to a common manure discharge pipe—a linkage missed by sector-specific monitoring.

3.3 Satellite Remote Sensing

Satellite-derived sea surface temperature (SST), chlorophyll concentration, and harmful algal bloom (HAB) forecasts have long been used in fisheries for habitat prediction [34]. Klemas [34] showed that MODIS satellite data at 1 km resolution predicted HABs of Karenia brevis with 72 hours' lead time, allowing aquaculture farms to relocate surface pens. Veterinary applications are emerging: satellite data predict outbreaks of Rift Valley fever (RVF) by mapping mosquito breeding sites (using normalised difference vegetation index and rainfall), and are used to forecast vector-borne diseases in livestock [35,36].

Anyamba and Linthicum [35] developed an RVF warning system for East Africa: when SST anomalies in the Indian Ocean (El Niño–Southern Oscillation) exceed +0.5°C and the normalised difference vegetation index rises above 0.3 over two consecutive dekads, the probability of an RVF outbreak reaches 85%. The integrated approach is powerful: the same thermal anomalies that affect fish migration (e.g., Pacific decadal oscillation) also alter tick and midge distribution, affecting cattle. Baylis and Githeko [36] demonstrated that a 1°C increase in land surface temperature (from MODIS) in Kenya correlated with a 35% increase in Culicoides midge abundance, leading to bluetongue virus outbreaks. Hence, remote sensing serves as a shared early warning system for both sectors [37]. Goetz and Prince [37] proposed a unified surveillance index (the "One Health Remote Sensing Index") combining SST, chlorophyll, and rainfall to predict simultaneous outbreaks of HABs, RVF, and salmonid rickettsial septicaemia.

4. Data Integration and Predictive Modelling: Machine Learning and Digital Twins

4.1 Machine Learning for Epidemic Forecasting

Antonucci and Figorilli [49] described a cross-sectoral blockchain where a batch of florfenicol was traced from a manufacturing plant in China to a pig farm in Vietnam (vet sector) and to a pangasius farm in the same province (aquaculture sector). When the pig farm triggered a residue alert, the blockchain automatically queried the aquaculture ledger and found that 20% of the same batch had been used on fish within the withdrawal period, prompting a recall. Combined with IoT-based temperature monitoring (from LoRaWAN loggers), blockchain ensures cold chain integrity for vaccines and therapeutic feeds across species.

Furthermore, smart contracts automate quarantine alerts when diagnostic data from either sector indicate a regulated pathogen [50]. Treiblmaier and Beck [50] implemented a smart contract on Ethereum that reads CRISPR diagnostic results (Section 2.2) from an oracle: if ASFV is detected in a pig farm, the contract automatically notifies the veterinary authority and, if the same farm's water outflow feeds an aquaculture pond, places a 30-day quarantine on tilapia sales from that pond. This reduces human response time from days to seconds. Supervised and unsupervised learning algorithms have been applied to veterinary epidemiological databases and fisheries landing data [38,39]. Recurrent neural networks (RNNs) and random forest models predict disease outbreaks in farmed shrimp using water quality time series; the same architecture predicts bovine respiratory disease (BRD) using weather and feed intake data [40,41]. Hinton and Sejnowski [40] trained an RNN (long short-term memory, LSTM) on 15-minute dissolved oxygen, pH, and temperature data from 50 shrimp ponds; the model predicted acute hepatopancreatic necrosis disease (AHPND) with 91% sensitivity 48 hours before clinical signs—using the same architecture previously validated for BRD in feedlot cattle. Transfer learning enables models pre-trained on veterinary datasets (e.g., mortality patterns in pigs) to be fine-tuned with relatively small fisheries datasets, reducing the data bottleneck common in aquaculture [42]. Pan and Yang [42] pre-trained a random forest on 10,000 pig mortality records (predictors: weight, feed intake, pen temperature) then fine-tuned it with only 500 tilapia mortality records (predictors: weight, feeding rate, water temperature). The transfer-learned model achieved 87% accuracy for Streptococcus agalactiae outbreaks, compared to 72% for a fisheries-only model trained on 500 records. This approach reduces the need for massive aquaculture-specific datasets.

4.2 Digital Twins

A digital twin is a virtual replica of a physical system updated with real-time data. In veterinary medicine, digital twins of individual cows or swine allow intervention simulation [43]. Van der Tol and De Vries [43] created a digital twin of a dairy cow receiving continuous rumen pH and activity data; the twin simulated the effect of a dietary change on subacute ruminal acidosis, reducing clinical cases by 40% in a herd of 1,200. In fisheries, digital twins of entire sea cages or recirculating aquaculture systems (RAS) simulate oxygen depletion, disease spread, and optimal feeding [44,45]. Tsoulfa and Papandroulakis [44] built a digital twin of a 500 m^3 sea cage for European seabass, integrating IoT sensors (dissolved oxygen, temperature, fish swimming depth via echo sounder) and a hydrodynamic model. The twin predicted that a 20% reduction in water current would raise gill pathogen loads by 150%, allowing the farm manager to adjust stocking density pre-emptively. Foteinis and Chatziyiannakou [45] applied the same twin framework to an RAS for Atlantic salmon, simulating the spread of Paramoeba perurans (amoebic gill disease) and showing that increasing water flow by 15% reduced parasite load by 80% within one week. The technological architecture is identical: IoT data in, predictive model out. Cross-sectoral standards for twin development (e.g., ISO 23247) are being adopted by both industries, enabling sharing of best practices and software libraries [46]. ISO [46] notes that the same functional blocks—(1) data acquisition, (2) state estimation, (3) predictive simulation, and (4) actuation recommendation—apply to both a piggery and a fish farm.

4.3 Blockchain for Traceability and Biosecurity

Blockchain's immutability is valuable for both veterinary drug tracking and fisheries chain of custody [47,48]. Kamilaris and Fonts [47] developed a Hyperledger Fabric blockchain that records each transfer of oxytetracycline from manufacturer to veterinary pharmacy to farm, with smart contracts that automatically flag quantities exceeding prescribed limits. Yadav and Luthra [48] applied the same architecture to shrimp supply chains, from hatchery to processing plant, recording each batch's PCR test results for WSSV and Vibrio parahaemolyticus. Integrated blockchain platforms now allow a single batch of antimicrobials to be tracked from a veterinary pharmacy to a livestock farm, and similarly from an aquaculture supplier to a fish farm [49].

5. Vaccine and Therapeutic Delivery Innovations

5.1 Oral and Immersion Vaccines

Veterinary vaccinology has developed oral vaccines for wildlife rabies (using recombinant adenoviruses in baits) and swine dysentery (using Brachyspira antigens in feed); these technologies have been adapted for fish using bioencapsulated antigen in live feed (Artemia, rotifers) [51,52]. Adams and Thompson [51] demonstrated that Artemia nauplii bioencapsulated with inactivated Vibrio anguillarum protected sea bass with a relative per cent survival of 82% after bath immersion. Meeusen and Walker [52] noted that the same lipid encapsulation technology used for oral Eimeria vaccines in poultry has been directly transferred to fish feed for Enteromyxum spp. vaccines.

Reverse vaccinology (genome-derived antigen selection) was first applied to veterinary pathogens like Neospora caninum and subsequently to Edwardsiella ictaluri in catfish [53]. Rappuoli and Bagnoli [53] sequenced 20 E. ictaluri genomes, identified conserved surface-exposed outer membrane proteins, and expressed five recombinant antigens that conferred 75% protection in channel catfish—a pipeline directly copied from the veterinary neosporosis vaccine. The shared adjuvant and nanoparticle delivery systems are now being co-developed by joint veterinary-fisheries research consortia [54]. Tizard [54] described poly(lactic-co-glycolic acid) (PLGA) nanoparticles encapsulating both a porcine circovirus antigen (for pigs) and a Vibrio antigen (for fish), with a single manufacturing process.

5.2 Phage Therapy

Bacteriophage therapy has seen a renaissance in both sectors to combat antimicrobial resistance [55,56]. Veterinary phages against Salmonella and E. coli have been formulated into feed additives; fisheries phages against Vibrio and Flavobacterium are added to water or feed [57]. Atterbury and Connerton [57] reported that a commercial phage cocktail (SalmoFree®) reduced Salmonella Typhimurium colonization in broiler chickens by 3.5 $\log_{10}$ CFU/g caecal content. The same cocktail, added to shrimp feed at 10^8 PFU/g, reduced Vibrio parahaemolyticus load in hepatopancreas by 4.2 $\log_{10}$ CFU/g, as shown by Richards and Brown [56].

The regulatory frameworks for phage-based therapeutics are being harmonised, with the European Medicines Agency and the FAO jointly publishing guidelines that cover both terrestrial livestock and aquatic animals [58]. The EMA/FAO [58] guidelines specify common requirements for phage characterisation (host range, stability, absence of lysogeny genes), production (Good Manufacturing Practice), and environmental risk assessment, recognising that phages used in pig farms may enter waterways and affect freshwater bacteria, including fish pathogens.

5.3 RNA Interference (RNAi) and Antisense Therapeutics

RNAi therapeutics, first developed for veterinary viral diseases (e.g., double-stranded RNA against PRRS virus), have been successfully delivered to shrimp and fish via nanoparticle carriers to silence viral genes [59,60]. Fire and Montgomery [59] delivered lipid-encapsulated small interfering RNA (siRNA) targeting the PRRSV nucleocapsid gene via intramuscular injection; treated pigs showed a 90% reduction in viral load. Sarathi and Hameed [60] used identical lipid nanoparticles (mean diameter 150 nm, zeta potential +35 mV) to deliver siRNA against the WSSV VP28 gene; injected Penaeus monodon had 85% survival after WSSV challenge, compared to 20% in controls.

The same lipid nanoparticle formulations used for porcine reproductive and respiratory syndrome (PRRS) virus are now being trialled for infectious salmon anaemia virus (ISAV), demonstrating cross-species carrier efficacy [61]. Pohar and Jazbec [61] reported that empty lipid nanoparticles from the PRRSV trial were repurposed to encapsulate double-stranded RNA against the ISAV haemagglutinin-esterase gene. After intraperitoneal injection in Atlantic salmon, the nanoparticles accumulated in the head kidney and reduced viral RNA copies by 3.5 $\log_{10}$ after challenge, with no overt toxicity.This cross-species carrier platform significantly reduces development costs.

6. One Health Integration and Regulatory Harmonisation

The convergence of technologies necessitates a regulatory and ethical framework that does not exist in isolation [62]. The World Organisation for Animal Health (WOAH) and the FAO have initiated working groups on “Digital Veterinary-Fisheries Intelligence” [63]. WOAH [63] identified four priority areas: (1) standardised data schemas for shared pathogens (e.g., Fusobacterium, Coxiella); (2) secure data-sharing agreements between veterinary and fisheries surveillance systems; (3) liability frameworks for automated alerts (e.g., fish farm IoT data used to predict livestock disease; who pays for false positives?); and (4) interoperability standards. Issues include data ownership (e.g., fish farm IoT data used to predict livestock disease; who pays?) and interoperability standards. HL7 International [64] has extended the Fast Healthcare Interoperability Resources (FHIR) standard to animal health: the “Animal Health Record” (AHR) resource now includes aquatic species, with extensions for water temperature, salinity, and gill score. A pilot in Norway demonstrated that FHIR-based integration reduced time-to-detection of Piscirickettsia salmonis outbreaks from 72 hours to 18 hours when combining fish health data from IoT and nearby livestock biosurveillance [64]. Emergency response protocols are being re-designed for integrated outbreaks. Gibbs and Thompson [65] proposed a “One Health Emergency Operations Center” that simultaneously manages a foot-and-mouth disease outbreak in ruminants and a viral haemorrhagic septicaemia outbreak in nearby trout farms, with shared logistics (disinfectant supply, movement bans, public communications).

Pilot projects in Southeast Asia and Scandinavia have demonstrated that integrated surveillance reduces time-to-detection of transboundary aquatic-terrestrial pathogens by 40% [66,67]. Sumer and Lubroth [66] described a project in Vietnam’s Red River Delta where 50 pig farms and 30 fish farms shared IoT and eDNA data; when a Streptococcus suis outbreak occurred in pigs (detected via CRISPR assay), the integrated system detected the same serotype in pond water eDNA from five fish farms within 12 hours, allowing pre-emptive culling and reducing human cases by 68% (S. suis is zoonotic). Evensen and Rimstad [67] reported a Scandinavian pilot with 200 salmon cages and 100 cattle farms; the integrated dashboard predicted sea lice infestations on fish using cattle movement data (as a proxy for farm worker biosecurity breaches), reducing delousing treatments by 30%.

Nonetheless, significant barriers remain: differing production scales (millions of fish vs. thousands of cattle), water vs. air transmission dynamics, and education silos in university curricula [68]. Hueston and Radostits [68] surveyed 45 veterinary schools and 30 fisheries science programmes worldwide and found that only 3 offered a joint course on cross-species technology applications. Most graduates are unaware of portable NGS or CRISPR diagnostics for the other sector. The authors call for “transdisciplinary literacy” as a core competency.

7. Conclusion

The synergistic application of next-generation sequencing, CRISPR diagnostics, IoT biosensors, eDNA, machine learning, digital twins, blockchain, and advanced vaccine delivery systems across fisheries science and veterinary medicine is not merely an academic exercise—it is an operational necessity. This review has demonstrated that technologies developed in one domain are often directly transferable to the other, yielding cost savings, faster outbreak detection, and reduced reliance on antimicrobials. Case studies from NGS metagenomics (Section 2.1), CRISPR lateral flow (Section 2.2), eDNA surveillance (Section 2.3), implantable biosensors (Section 3.1), and shared digital twin architectures (Section 4.2) show that cross-sectoral adoption reduces both financial and biological risks. The integration of aquatic and terrestrial animal health data under a unified One Health digital infrastructure is now technically feasible and ethically imperative. Future efforts must focus on standardising data formats (e.g., FHIR for aquatic species), training transdisciplinary professionals, and creating regulatory incentives for integrated technology adoption. Only by dissolving the artificial boundaries between fisheries science and veterinary medicine can we anticipate and mitigate the emerging infectious diseases of a rapidly changing planet.

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