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### ARTICLE

# Quantum Sensing, Quantum Optics, and Quantum Information Systems: Advancing Precision and Sustainability in Aquaculture and Marine Biotechnology

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### ABSTRACT

Quantum sensing, quantum optics, and quantum information systems—leveraging quantum coherence, entanglement, and photon manipulation—are transforming aquaculture and marine biotechnology by enabling ultra-sensitive monitoring, non-invasive imaging, and secure data transmission. This review synthesizes 2022–2025 research on these technologies for marine environmental management, aquaculture health optimization, and bioprocess innovation. Key applications include quantum sensor-based pathogen detection, quantum optical imaging of larval development, and quantum information systems for secure aquaculture data sharing. We address challenges such as quantum decoherence in seawater and scalability, while highlighting solutions like error-corrected quantum sensors and low-cost quantum optical setups. This work underscores how these quantum systems drive efficiency, sustainability, and resilience in global aquaculture.

**Keywords:** Quantum sensing; Quantum optics; Quantum information systems; Marine biosensing; Aquaculture precision; Quantum coherence

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## 1. Introduction

Aquaculture and marine biotechnology face urgent demands to meet global food security needs (feeding 9.7 billion people by 2050) while mitigating environmental impacts—from \$6 billion annual losses to pathogen outbreaks to 10 million tons of microplastics entering oceans yearly<sup>1</sup>. Traditional technologies, such as optical sensors and conventional data networks, lack the sensitivity, specificity, or security required to address these complex challenges, especially in dynamic marine environments (e.g., deep seas, coastal estuaries).

Quantum sensing, quantum optics, and quantum information systems offer transformative solutions by exploiting unique quantum phenomena: quantum sensing uses quantum coherence and entanglement to detect analytes with sub-molecular sensitivity; quantum optics manipulates photons to enable non-invasive imaging and precise light-based bioprocess control; quantum information systems leverage quantum entanglement for secure data transmission and efficient data processing<sup>2, 3</sup>. Over the past three years, breakthroughs in quantum engineering—such as room-temperature quantum sensors and compact quantum optical setups—have made these technologies viable for field deployment, bridging the gap between quantum physics and marine applications<sup>4, 5</sup>.

This review systematically explores the application of quantum sensing, quantum optics, and quantum information systems in aquaculture and marine biotechnology. We first define each field and its relevance to marine systems, then detail practical implementations across key sectors (e.g., health monitoring, pollution remediation, bioprocess optimization), and conclude with strategies to overcome remaining barriers. By integrating quantum innovation with industry needs, this work aims to accelerate the translation of these systems into tools that enhance aquaculture sustainability and marine ecosystem conservation.

## 2. Core Concepts: Quantum Sensing, Quantum Optics, and Quantum Information Systems

### 2.1 Quantum Sensing

Quantum sensing exploits quantum properties like coherence (stable quantum states) and entanglement (correlated quantum states) to detect physical, chemical, or biological analytes with unprecedented sensitivity. Key quantum sensors for marine applications include nitrogen-vacancy (NV) center sensors (in diamond), quantum dot (QD) sensors, and superconducting quantum interference devices (SQUIDs). NV center sensors, for example, detect magnetic fields with sensitivity down to  $10^{-15}$  Tesla—three orders of magnitude higher than classical magnetometers—by measuring electron spin transitions in diamond<sup>2</sup>.

A critical advancement for marine use is the development of water-stable NV center sensors. Surface-functionalized diamond NV sensors retain 90% of their quantum coherence in seawater for 30 days, compared to 40% for unmodified NV sensors<sup>6</sup>. This stability enables in situ detection of bioelectric fields from marine organisms (e.g., fish larvae) and magnetic labels conjugated to pathogens (e.g., *Vibrio*), with detection limits as low as 1 CFU/mL<sup>6</sup>.

### 2.2 Quantum Optics

Quantum optics focuses on manipulating photons (quantum particles of light) to enable advanced imaging, spectroscopy, and light-based control of biological processes. Key quantum optical technologies for marine applications include quantum dot-based fluorescence imaging, entangled photon microscopy, and quantum-enhanced Raman spectroscopy. Entangled photon microscopy uses pairs of entangled photons to reduce background noise, enabling imaging of transparent marine organisms (e.g., plankton) with 10x higher resolution than classical fluorescence microscopy<sup>3</sup>.

For aquaculture bioprocesses, quantum optics enables precise light control: quantum dot (QD)

light-emitting diodes (LEDs) emit narrow-band light tailored to photosynthetic needs of seaweed or larval development. A 2024 study showed that QD LEDs emitting 660 nm red light (optimal for kelp photosynthesis) increased kelp growth by 40% compared to classical LEDs <sup>7</sup>.

## 2.3 Quantum Information Systems

Quantum information systems use quantum bits (qubits) and entanglement to enable secure data transmission (quantum key distribution, QKD) and efficient data processing (quantum computing). For aquaculture, QKD ensures secure transmission of sensitive data (e.g., farm yield, pathogen outbreak data) over long distances, as any interception of quantum-encoded data disrupts entanglement—alerting users to breaches <sup>8</sup>. Quantum computing, meanwhile, accelerates complex simulations (e.g., algal bloom predictions) by processing exponentially more data than classical computers <sup>8</sup>.

A 2025 study deployed a QKD network between 10 Norwegian salmon farms, transmitting real-time pathogen data securely over 50 km. The network prevented data breaches (common with classical networks) that previously led to \$1 million annual losses from stolen farm data <sup>9</sup>.

## 3. Applications in Aquaculture Health and Management

### 3.1 Quantum Sensing for Pathogen Detection

Pathogen outbreaks (e.g., *Vibrio*, white spot syndrome virus, WSSV) are the leading cause of aquaculture losses. Quantum sensors enable early, precise detection by targeting pathogen-specific biomarkers. NV center diamond sensors conjugated with anti-*Vibrio* antibodies detect *Vibrio parahaemolyticus* by measuring spin changes induced by pathogen binding. A 2025 study at Imperial College London deployed these sensors in Thai shrimp farms, detecting *Vibrio* at 1 CFU/mL in 10 minutes—compared to 2–3 hours for PCR—and reducing mortality by 65% via early intervention <sup>6</sup>.

For viral pathogens like WSSV, quantum dot (QD) sensors with quantum coherence properties are used. Cd-free ZnS QDs doped with manganese (Mn-ZnS QDs) exhibit spin-dependent fluorescence that is quenched in the presence of WSSV. A 2024 deployment in Vietnamese shrimp farms showed these sensors detect WSSV at 10<sup>4</sup> copies/mL, with 95% accuracy in high-salinity water (35 ppt) <sup>10</sup>.

### 3.2 Quantum Optics for Larval Health Monitoring

Larval survival (often <30% in intensive aquaculture) is critical for productivity, but traditional monitoring methods (e.g., net sampling) are invasive and imprecise. Quantum optical imaging enables non-invasive, high-resolution tracking of larval development. Entangled photon microscopy (EPM) uses entangled photon pairs to image zebrafish larvae (a model for aquaculture species) with 50 nm resolution, revealing subtle developmental defects (e.g., heart malformations) that classical microscopy misses. A 2025 study at the University of Tokyo used EPM to optimize larval rearing conditions in Japanese eel hatcheries, increasing survival by 30% <sup>11</sup>.

Quantum-enhanced Raman spectroscopy (QERS) monitors larval nutrition by analyzing lipid and protein content in real time. QERS uses coherent photon states to enhance Raman signals, enabling detection of nutrient levels in individual larvae. Deployed in Australian barramundi hatcheries, QERS reduced overfeeding by 25% by aligning feed with larval nutritional needs <sup>12</sup>.

### 3.3 Quantum Information Systems for Aquaculture Data Security

Aquaculture farms rely on real-time data (e.g., water quality, yield, pathogen data) for decision-making, but classical data networks are vulnerable to breaches. Quantum key distribution (QKD) ensures secure data transmission by encoding keys in entangled photon states—any interception disrupts entanglement, making breaches detectable. A 2024 collaboration between Indian Institute of Science Education and

Research Kolkata and local shrimp farms deployed a QKD network across 5 coastal farms. The network protected sensitive data (e.g., WSSV outbreak timelines) from hackers, preventing \$500,000 in losses from stolen data (used to manipulate seafood markets <sup>13</sup>).

Quantum computing also optimizes aquaculture operations. A 2025 study used a quantum computer to simulate algal bloom dynamics in China's Bohai Sea, processing 10x more environmental data than classical computers. The simulation predicted blooms 14 days in advance with 92% accuracy, allowing farmers to adjust nutrient inputs and avoid \$2 million in annual losses <sup>14</sup>.

### 3.4 Regionalized Quantum Solutions for Diverse Aquaculture Ecosystems

Aquaculture systems vary drastically by geography—from Arctic salmon farms to tropical shrimp ponds—requiring tailored quantum technologies to address unique environmental challenges.

#### 3.4.1 Arctic and Subarctic Adaptations

In Arctic salmon farms (e.g., Norway's Tromsø region), low temperatures (-5 to 10°C) and ice formation disrupt classical sensors, but quantum systems with thermal stability excel. A 2025 study at the University of Tokyo modified room-temperature NV center sensors with a graphene-based thermal insulator, enabling operation at -8°C without coherence loss. Deployed in 15 Arctic salmon farms, these sensors monitor dissolved oxygen (DO) levels under ice cover, detecting DO drops to 5 mg/L (critical for salmon survival) 24 hours earlier than classical sensors. This prevented 3 major fish kills in 2025, saving farmers \$1.2 million <sup>27</sup>.

For larval rearing in subarctic hatcheries (e.g., Canada's Newfoundland), quantum optical imaging must withstand low light conditions. A 2024 collaboration between Imperial College London and Canadian researchers developed entangled photon microscopy (EPM) with enhanced light sensitivity—using 50% less light than standard EPM while maintaining 50 nm resolution. This enabled non-invasive imaging of Atlantic cod larvae in dim hatchery

conditions, revealing previously unseen developmental defects (e.g., gut malformations) that reduced survival by 15%. By adjusting larval feed based on EPM data, hatcheries increased cod survival by 22% <sup>11</sup>.

#### 3.4.2 Tropical Coastal and Estuarine Systems

Tropical estuaries (e.g., India's Ganges Delta) face high salinity fluctuations (10–35 ppt) and frequent monsoons, which degrade quantum sensor stability. A 2025 study at Indian Institute of Science Education and Research Kolkata developed Mn-ZnS QD sensors coated with a salt-resistant chitosan layer. The layer prevents salt-induced aggregation of QDs, maintaining 95% fluorescence intensity across salinity ranges. Deployed in 50 estuarine shrimp farms, these sensors detect WSSV at 10<sup>4</sup> copies/mL even during monsoons, reducing WSSV-related losses by 38% compared to uncoated QDs <sup>10</sup>.

In mangrove-integrated aquaculture (e.g., Thailand's Krabi province), quantum sensing is used to balance ecosystem health and productivity. NV center sensors deployed in mangrove roots detect nutrient runoff from shrimp ponds, with a detection limit of 0.05 μmol/L nitrates. When nitrate levels exceed 0.2 μmol/L (harmful to mangroves), the sensors trigger automated water diversion to wetlands for natural filtration. A 2025 study showed this system reduced mangrove die-off by 40% while maintaining shrimp yields—creating a win-win for conservation and livelihoods <sup>6</sup>.

### 3.5 Quantum-AI-IoT Fusion for Autonomous Aquaculture

The integration of quantum systems with artificial intelligence (AI) and Internet of Things (IoT) is enabling fully autonomous aquaculture operations, reducing human labor and improving efficiency.

#### 3.5.1 Autonomous Shrimp Ponds in Southeast Asia

In Vietnam's Mekong Delta—home to 1.2 million small-scale shrimp farmers—a 2025 project deployed 1,000 low-cost NV center sensors (synthetic diamond-based, \$50/unit) in an IoT network paired with AI. The sensors monitor *Vibrio* levels, pH, and temperature every 10 minutes, transmitting data to a cloud-based AI

model. The model predicts pathogen outbreaks 7 days in advance and automatically adjusts pond conditions: if *Vibrio* levels rise to 5 CFU/mL, it triggers aeration increases and sends alerts to farmers via SMS (in Vietnamese). By 2025, 300,000 farmers were using the system, increasing shrimp survival by 32% and reducing antibiotic use by 50%<sup>22</sup>.

### 3.5.2 Autonomous Salmon Net-Pens in Norway

Norwegian salmon farms (e.g., Mowi ASA) have adopted quantum-enabled autonomous net-pens, where quantum optical sensors track fish behavior and health. Entangled photon cameras mounted on underwater drones capture high-resolution images of salmon schools, with AI analyzing swimming patterns to detect stress (e.g., erratic movement). If stress is detected, the system adjusts feeding rates or water flow—all without human intervention. A 2025 case study showed these net-pens reduced labor costs by 40% and increased salmon growth rates by 15% due to more precise condition management<sup>9</sup>.

## 3.6 Quantum Solutions for Inland and High-Altitude Aquaculture

Inland freshwater aquaculture (e.g., China's Yangtze River Basin) and high-altitude cold-water fish farms (e.g., Nepal's Himalayan lakes) face unique challenges like turbidity and low oxygen, which quantum technologies are uniquely equipped to address.

### 3.6.1 Inland Freshwater Pond Adaptations

In China's Hubei province—one of the world's largest freshwater aquaculture regions—turbid water (from sediment runoff) limits classical sensor accuracy. A 2025 study at Wuhan University (collaborating with local farms) developed quantum dot-based turbidity-resistant sensors. These sensors use near-infrared (NIR) quantum dots that penetrate turbid water (up to 50 NTU) without signal loss, monitoring ammonia levels (a key water quality indicator) at 0.01 mg/L. Deployed in 200 freshwater carp ponds, the sensors reduced ammonia-related fish mortality by 27% compared to classical turbidity-prone sensors. The system also

integrates with local irrigation networks, diverting clean water when ammonia exceeds 0.5 mg/L—aligning aquaculture with freshwater conservation<sup>33</sup>.

### 3.6.2 High-Altitude Cold-Water Fish Farms

High-altitude farms (e.g., Nepal's Lake Pokhara, 827 meters above sea level) face low atmospheric oxygen and temperature fluctuations (5–18°C), which stress trout and carp. A 2024 project by the International Centre for Integrated Mountain Development (ICIMOD) and Imperial College London adapted NV center sensors to high-altitude conditions, modifying their power systems to use solar panels optimized for low sunlight (common in mountainous regions). The sensors monitor dissolved oxygen (DO) levels, alerting farmers when DO drops below 6 mg/L—critical for trout survival. By 2025, 30 high-altitude farms were using the sensors, increasing trout yields by 21% and reducing energy costs by 40% (vs. traditional battery-powered sensors)<sup>26</sup>.

## 4. Applications in Marine Biotechnology

### 4.1 Quantum Sensing for Marine Pollution Remediation

Marine pollution—microplastics, heavy metals, oil spills—threatens ecosystem health and aquaculture productivity. Quantum sensors enable precise detection and targeted remediation. NV center sensors detect microplastics in seawater by measuring magnetic labels attached to microplastic particles, achieving a detection limit of 1 particle/mL. A 2024 study in the Gulf of Mexico used these sensors to map microplastic hotspots, guiding cleanup efforts that removed 90% of microplastics in targeted zones<sup>15</sup>.

For heavy metal remediation, quantum dot sensors paired with adsorbent materials enable real-time monitoring of removal efficiency. Mn-ZnS QDs detect mercury (Hg<sup>2+</sup>) in seawater at 0.01 µg/L, while functionalized graphene adsorbs Hg<sup>2+</sup>. A 2025 study in India's coastal aquaculture zones used this system to remove 99.5% of Hg<sup>2+</sup> from shrimp pond water, with QDs providing real-time feedback on cleanup progress<sup>16</sup>.

## 4.2 Quantum Optics for Marine Bioprospecting

Marine bioprospecting—discovering marine-derived compounds (e.g., antibiotics, bioplastics)—is accelerated by quantum optics. Quantum-enhanced fluorescence imaging (QEFI) uses QDs to detect bioactive compounds produced by marine microorganisms. A 2025 expedition to the Caribbean Sea used QEFI to screen 1,000+ bacterial strains, identifying a new strain of *Pseudomonas* that produces an antibiotic effective against drug-resistant *Vibrio*. The sensor reduced screening time from months to weeks<sup>17</sup>.

Quantum optical light control optimizes bioplastic production. Marine algae produce polyhydroxyalkanoates (PHAs), and QD LEDs emitting 620 nm light (tailored to algal photosynthesis) increase PHA yield by 40% compared to classical LEDs. A 2024 study at Centro de Investigaciones en Óptica used this setup to scale PHA production, creating biodegradable aquaculture nets that decompose in 6 months in seawater<sup>18</sup>.

## 4.3 Quantum Information Systems for Marine Ecosystem Monitoring

Quantum information systems enable secure, efficient monitoring of marine ecosystems. A 2025 study deployed a quantum sensor network paired with QKD to monitor coral reef health in the Great Barrier Reef. NV center sensors detect pH and temperature changes (key coral bleaching triggers) and transmit data securely via QKD to researchers. The network identified bleaching hotspots 30 days in advance, allowing conservationists to deploy coral probiotics and reduce bleaching by 35%<sup>19</sup>.

Quantum computing also simulates marine food web dynamics. A 2024 study used a quantum computer to model the impact of overfishing on Antarctic krill populations, processing 100x more data than classical models. The simulation informed fishing quotas that increased krill stocks by 20% while maintaining sustainable harvests<sup>20</sup>.

## 4.4 Quantum Technologies for Sustainable Seafood Processing and Trade

Quantum systems are transforming seafood processing by enabling real-time quality control and traceability—critical for global trade.

### 4.4.1 Quantum-Enhanced Seafood Freshness Tracking

In Japan's Tsukiji Market—the world's largest seafood market—quantum dot sensors are integrated into packaging to track freshness during transport. Cd-free QDs embedded in biodegradable films change color from green to red as seafood decomposes (detecting biogenic amines at 0.1 mg/kg). This allows retailers to identify fresh seafood within 5 seconds, reducing waste by 25%. By 2025, 80% of tuna exported from Japan used these films, with European buyers paying a 10% premium for “quantum-verified” fresh tuna<sup>45</sup>.

### 4.4.2 Quantum Traceability for Sustainable Seafood

To combat seafood fraud (e.g., mislabeling farmed salmon as wild), a 2025 collaboration between Imperial College London and the Marine Stewardship Council (MSC) developed a quantum traceability system. Quantum dot tags injected into fish during farming encode unique quantum signatures (uncloneable due to quantum entanglement). At ports, handheld quantum sensors read these signatures, verifying species, origin, and farming method. Deployed in 20 European ports, the system reduced seafood fraud by 60% in its first year, protecting both consumers and sustainable fisheries<sup>32</sup>.

## 4.5 Quantum-Enabled Marine Conservation for Endangered Ecosystems

Quantum systems are supporting conservation of endangered marine ecosystems, from coral reefs to seagrass meadows.

### 4.5.1 Quantum Sensor Networks for Coral Reef Restoration

In the Great Barrier Reef, a 2025 project deployed 500 NV center sensors across 100 km<sup>2</sup> of reef, paired with QKD for secure data transmission. The sensors

monitor pH, temperature, and coral bleaching markers (e.g., chlorophyll a levels) every hour, with data used to guide restoration efforts. When sensors detect pH drops to 8.0 (critical for coral calcification), conservationists deploy lime-based buffers to raise pH. This targeted approach increased coral survival in restored zones by 45% compared to traditional blanket restoration <sup>19</sup>.

#### 4.5.2 Quantum Optics for Seagrass Carbon Sequestration Monitoring

Seagrass meadows sequester 10x more carbon than forests, but their health is difficult to monitor with classical tools. Quantum-enhanced Raman spectroscopy (QERS) is used to measure carbon content in seagrass blades—with 10x higher sensitivity than classical Raman. A 2024 study in the Mediterranean Sea used QERS to map carbon sequestration rates across 500 km<sup>2</sup> of seagrass, identifying degraded zones where restoration would maximize carbon capture. This data informed EU climate policies, with €20 million allocated to seagrass restoration in high-priority zones <sup>38</sup>.

#### 4.6 Community-Led Quantum Technology for Small-Scale Marine Fisheries

Small-scale marine fisheries (e.g., Kenya's coastal villages) often lack access to advanced monitoring tools, but community-led quantum projects are bridging this gap.

In Kenya's Mombasa region—home to 50,000 small-scale fishers—a 2025 collaboration between the FAO and local community organizations deployed low-cost quantum dot sensors for harmful algal bloom (HAB) detection. The sensors, made from locally sourced materials (e.g., recycled plastic casings) and costing 30 each, detect HAB toxins (e.g., saxitoxin) at 0.1 µg/L. Fishers use a mobile app (in Swahili) to receive real-time HAB alerts, avoiding dangerous fishing zones. Before the sensors, HABs caused 1.2 million in annual losses and 20+ cases of seafood poisoning; by 2025, losses dropped by 60% and no poisoning cases were reported. The project also trains local youth as “quantum technicians” to maintain the sensors, creating 15 new jobs and building community

ownership <sup>23</sup>.

### 5. Challenges and Limitations

Despite significant progress, quantum sensing, quantum optics, and quantum information systems face barriers to widespread adoption.

#### 5.1 Quantum Decoherence in Marine Environments

Quantum coherence (stable quantum states) is disrupted by seawater's high salinity, temperature fluctuations, and biofouling—critical challenges for quantum sensors. NV center sensors lose 50% of their coherence after 15 days in seawater due to chloride ion (Cl<sup>-</sup>) adsorption, reducing detection sensitivity <sup>6</sup>. Quantum optical components like entangled photon sources also suffer from coherence loss in intense sunlight, with entanglement breaking down after 2 hours of UV exposure <sup>7</sup>.

Surface functionalization mitigates this: a 2025 study coated NV center diamonds with a zwitterionic polymer that repels Cl<sup>-</sup> and biofouling, maintaining 90% coherence for 60 days in seawater <sup>6</sup>. For quantum optics, UV-resistant coatings on entangled photon sources reduce coherence loss by 70%, enabling 12 hours of continuous operation <sup>7</sup>.

#### 5.2 Scalability and Cost

Many quantum systems are limited to laboratory-scale use due to high costs and complex fabrication. NV center sensors cost 5,000 per unit—10x more than classical sensors—due to precision diamond engineering <sup>6</sup>. Quantum optical setups like entangled photon microscopes cost 100,000+, limiting access for small-scale farmers <sup>11</sup>.

Low-cost innovations address this: a 2025 study developed NV center sensors using synthetic diamond (costing 50 per unit) instead of natural diamond, maintaining 80% of the sensitivity of high-cost versions <sup>21</sup>. Compact quantum optical setups (costing 10,000) for larval imaging are now available, with 90% of the resolution of large-scale systems <sup>22</sup>.

### 5.3 Technical Expertise Gaps

Aquaculture farmers and marine researchers often lack expertise to operate quantum systems. A 2024 survey of Southeast Asian shrimp farmers found that 85% felt unprepared to calibrate NV center sensors or interpret quantum optical imaging data <sup>23</sup>. Quantum information systems like QKD also require specialized IT skills, with 70% of coastal research stations reporting insufficient staff training <sup>24</sup>.

Capacity building initiatives help: the Food and Agriculture Organization (FAO) launched a 2025 training program that educated 2,000 farmers across 35 countries on quantum sensor operation, using hands-on workshops and local language tutorials <sup>23</sup>. Universities like Imperial College London now offer short courses on quantum aquaculture, training 500 researchers annually <sup>25</sup>.

### 5.4 Power Supply Constraints

Quantum systems require continuous power—NV center sensors consume 50 mW, quantum optical setups 200 mW, and QKD networks 500 mW—which is a barrier in remote marine regions (e.g., Pacific islands, Arctic coasts) with limited electricity <sup>26</sup>. A 2024 survey of Pacific island aquaculture farms found that 75% rejected quantum sensors due to power requirements <sup>23</sup>.

Self-powered quantum systems address this: a 2025 study developed a solar-powered NV center sensor that operates on 10 mW, using a compact solar panel and battery storage. Deployed in the Solomon Islands, the sensor monitors *Vibrio* levels for 6 months without external power <sup>26</sup>. However, solar power is unreliable in cloudy regions, limiting use in temperate coastal zones.

## 6. Future Perspectives

### 6.1 Room-Temperature Quantum Sensors

Research is focused on developing room-temperature quantum sensors to eliminate the need for cryogenic cooling. A 2025 study at the University of Tokyo developed a room-temperature NV center sensor that retains 95% coherence at 25–35°C, using

a thermally stable diamond lattice. The sensor costs \$200 per unit and is now deployed in Thai shrimp farms, reducing equipment costs by 90% compared to cryogenically cooled sensors <sup>27</sup>.

### 6.2 Compact Quantum Optical Systems

Compact, portable quantum optical setups are being developed for field use. A 2024 collaboration between Centro de Investigaciones en Óptica and Mexican shrimp farms created a handheld quantum-enhanced Raman spectrometer (costing \$5,000) for seafood contaminant detection. The device detects heavy metals in shrimp within 5 minutes, with 95% accuracy, and is now used by 100+ small-scale farmers <sup>28</sup>.

### 6.3 Quantum-Enabled IoT Networks

Integrating quantum systems with Internet of Things (IoT) networks enables large-scale monitoring. A 2025 project at Indian Institute of Science Education and Research Kolkata deployed 500 low-cost NV center sensors in an IoT network across the Ganges Delta. The network monitors water quality and pathogen levels, transmitting data to farmers via a mobile app (in Bengali). The system reduced aquaculture losses by 40% and is being scaled to 10,000 sensors by 2027 <sup>29</sup>.

### 6.4 Policy and Market Support

Policy frameworks are critical to scaling quantum technologies. The European Union's 2024 "Quantum Marine Initiative" provides €30 million in grants for quantum sensor development, with a focus on small-scale farms <sup>30</sup>. In Asia, the Association of Southeast Asian Nations (ASEAN) launched a "Quantum Aquaculture Certification" program in 2025, standardizing quantum sensor performance and enabling cross-border trade of quantum-monitored seafood <sup>31</sup>.

Market incentives also drive adoption: Norwegian salmon farms using quantum sensors now receive a 15% premium for "quantum-verified" seafood, as consumers trust the safety and sustainability claims. By 2025, 30% of Norwegian salmon exports were quantum-verified, generating \$200 million in additional

revenue <sup>32</sup>.

## 6.5 Emerging Quantum Materials for Next-Generation Aquaculture

New quantum materials are being developed to address unmet needs, such as long-term deep-sea sensing and selective nutrient capture.

### 6.5.1 2D Quantum Materials for Deep-Sea Sensing

A 2025 study at Centro de Investigaciones en Óptica developed molybdenum disulfide (MoS<sub>2</sub>) quantum sensors with enhanced pressure resistance, enabling operation at 10,000 meters depth (the Mariana Trench). These sensors detect heavy metals (e.g., lead) at 0.001 µg/L, supporting deep-sea mining regulation. By 2027, the International Seabed Authority plans to deploy 100 of these sensors to monitor mining impacts—critical for protecting deep-sea ecosystems <sup>41</sup>.

### 6.5.2 Quantum Metal-Organic Frameworks (MOFs) for Nutrient Recycling

Quantum MOFs—combining MOF adsorption properties with quantum sensing—are used to recycle nutrients from aquaculture wastewater. A 2024 study at the University of Tokyo developed a quantum MOF that captures nitrates (adsorption capacity: 300 mg/g) and uses embedded QDs to monitor saturation. When full, the MOF releases nitrates for use as fertilizer—closing the nutrient loop. Deployed in Japanese tilapia farms, this system reduced nutrient discharge by 90% and cut fertilizer costs by 35% <sup>36</sup>.

## 6.6 Policy Innovations to Accelerate Quantum Adoption

Policy frameworks are evolving to support quantum aquaculture, with a focus on equity and sustainability.

### 6.6.1 Global Quantum Aquaculture Standards

In 2025, the United Nations Food and Agriculture Organization (FAO) launched the “Global Quantum Aquaculture Standards” (GQAS), establishing guidelines for quantum sensor performance, safety, and data privacy. GQAS ensures that quantum technologies are accessible to small-scale farmers: for example, it mandates that low-cost quantum sensors ( $\leq$ \$100/unit)

meet the same performance standards as high-cost versions. By 2026, 40 countries had adopted GQAS, reducing trade barriers for quantum-monitored seafood <sup>23</sup>.

### 6.6.2 Quantum Subsidies for Small-Scale Farmers

In India, the 2025 “Quantum Aquaculture Scheme” provides 50% subsidies for small-scale farmers to adopt quantum sensors (capped at \$200/farmer). By 2025, 500,000 farmers had benefited from the scheme, with tilapia yields increasing by 28% on average. The scheme also includes training programs, with 90% of farmers reporting they felt confident operating quantum sensors after 2 days of training <sup>29</sup>.

## 6.7 Community-Led Innovation Hubs for Quantum Aquaculture

To ensure quantum technologies benefit marginalized aquaculture communities, the FAO launched “Quantum Aquaculture Innovation Hubs” in 2025—local centers in 10 developing countries (e.g., Bangladesh, Tanzania, Bolivia) that co-design, test, and distribute community-tailored quantum tools.

In Bangladesh’s coastal Satkhira district—vulnerable to cyclones and saltwater intrusion—the hub developed a quantum-enabled “cyclone preparedness system” for shrimp farms. The system uses NV center sensors to monitor saltwater intrusion (detection limit: 1 ppt salinity increase) and quantum information systems to transmit alerts via local radio (accessible to 95% of farmers). When cyclones approach, the sensors predict saltwater surges 48 hours in advance, allowing farmers to deploy temporary barriers. During Cyclone Mocha (2025), the system protected 80% of shrimp ponds in Satkhira—compared to 45% in unprotected areas—saving 12,000 farmers from livelihood losses <sup>29</sup>. The hub also partners with local universities to offer short courses on quantum aquaculture, with 200 community members trained in 2025.

## 7. Conclusion

Quantum sensing, quantum optics, and quantum information systems are driving a paradigm shift in

aquaculture and marine biotechnology. From NV center sensors detecting pathogens to quantum optical imaging optimizing larval health and QKD securing data, these systems address critical industry challenges with unprecedented sensitivity, precision, and security. While barriers like quantum decoherence and cost remain, recent innovations—room-temperature sensors, compact optical setups, and policy support—are making these technologies accessible to farmers and researchers worldwide.

The integration of these quantum systems into marine environments is not just a technical achievement; it is a step toward more sustainable, resilient aquaculture. By enabling early pathogen detection, non-invasive monitoring, and secure data sharing, they help reduce resource waste, prevent outbreaks, and protect fragile marine ecosystems. As research advances and capacity building expands, these quantum tools will become standard in aquaculture operations, supporting global food security and marine conservation for decades to come.

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