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ARTICLE

Novel Quantum Materials: Transformative Tools for Advancing Aquaculture and Marine Biotechnology

Aisha B. Alvarez*

Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92093, USA

ABSTRACT

Novel quantum materials, including topological insulators, 2D nanomaterials, and strongly correlated systems, are revolutionizing aquaculture and marine biotechnology through unparalleled sensing sensitivity, environmental stability, and biocompatibility. This review integrates recent advancements (2022–2025) in quantum material-based platforms for marine biosensing, water quality monitoring, and aquaculture management. We highlight silicon quantum dots for heavy metal detection, bismuth telluride topological insulators for biomolecule sensing, and samarium nickelate-based systems for marine organism monitoring. Key applications include real-time Hg^{2+} detection in aquaculture waters (detection limit: 3 nmol/L) and label-free biomolecule analysis via topological THz biosensors. Challenges such as scalability and long-term seawater stability are addressed, with perspectives on intelligent aquaculture integration.

Keywords: Quantum materials; Topological insulators; 2D nanomaterials; Marine biosensing; Aquaculture monitoring; Strongly correlated systems

*CORRESPONDING AUTHOR:

Aisha B. Alvarez, Scripps Institution of Oceanography, University of California San Diego; Email: aisha.alvarez@ucsd.edu

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1. Introduction

Aquaculture and marine biotechnology face escalating demands for precision monitoring, environmental sustainability, and biosecurity amid global climate change and expanding seafood production. Traditional analytical tools—including chromatography and standard electrochemical sensors—are limited by high cost, bulky instrumentation, and slow response times, hindering real-time oversight of aquaculture systems and marine ecosystems. Novel quantum materials, defined by their quantum mechanical properties (e.g., topological surface states, tunable bandgaps, and correlated electron behavior), offer transformative solutions to these limitations.

Three classes of quantum materials have emerged as particularly impactful: topological materials (e.g., bismuth telluride), 2D nanomaterials (e.g., graphene quantum dots), and strongly correlated systems (e.g., samarium nickelate). These materials exhibit unique characteristics—such as high charge carrier mobility, photostability, and seawater corrosion resistance—that address critical gaps in marine biotechnology. For instance, silicon quantum dots (SiNPs) enable portable heavy metal detection in aquaculture waters within 15 minutes [1], while topological THz biosensors achieve label-free biomolecule detection without sample drying [8].

This review synthesizes the latest research on quantum material applications in marine environments, emphasizing practical implementations in aquaculture management, pollutant monitoring, and biosensing. We first overview the fundamental properties of key quantum material classes, then detail their specific applications, and conclude with strategies for translational development.

2. Fundamental Properties of Quantum Materials for Marine Applications

2.1 Topological Materials

Topological materials are distinguished by protected surface states that remain conductive even when the bulk material is insulating, a property rooted in non-trivial band topology. Bismuth telluride (Bi_2Te_3), a well-studied topological insulator, exhibits highly delocalized surface states that facilitate efficient interfacial charge transfer—critical for electrochemical sensing [3]. This unique electronic structure reduces charge transfer barriers at the material-aqueous interface, enabling ultrasensitive detection of biomolecules like hydrogen peroxide (H_2O_2) at concentrations as low as 16 nM [3].

Recent advancements in topological THz biosensors have further expanded applications. These devices utilize topologically protected evanescent fields with an out-of-plane extent of $0.3\lambda_0$, enhancing interaction with aqueous analytes despite strong THz wave absorption by water [8]. Unlike conventional THz sensors, topological waveguide cavity systems maintain sensitivity over extended periods, making them suitable for long-term marine biomolecule monitoring [8].

2.2 2D Quantum Materials

2D quantum materials, including graphene quantum dots (GQDs) and carbon quantum dots (CQDs) derived from marine biomass, combine atomic-scale thickness with tunable optical properties. Marine biomass-based CQDs (AB-CDs)—synthesized from algae, fish scales, or crustacean shells—exhibit high quantum yields, surface functionalizability, and biocompatibility [5]. Their synthesis via hydrothermal carbonization or microwave-assisted methods minimizes environmental impact, aligning with sustainable aquaculture goals [7].

Chlorine-doped GQDs derived from seaweed represent a notable innovation, offering high-intensity white fluorescence and clear cell imaging at 633 nm excitation [11]. These 2D materials avoid the toxicity of heavy metal-based quantum dots (e.g., cadmium selenide), making them ideal for in situ marine organism studies [11]. Additionally, CQDs derived from marine polysaccharides (e.g., alginate, chitosan) naturally incorporate heteroatoms (N, S, O), enhancing their sensing selectivity for marine toxins and pesticides [7].

2.3 Strongly Correlated Systems

Strongly correlated electron systems, where electron-electron interactions dominate material behavior, exhibit phase transitions that can be exploited for sensing. Samarium nickelate ($SmNiO_3$), a perovskite-related quantum material, undergoes a temperature-dependent metal-insulator transition that enables ultra-sensitive detection of electrical signals [2]. Unlike conventional sensors, $SmNiO_3$ maintains stability in cold seawater and resists corrosion, mimicking the electroreceptive capabilities of shark ampullae of Lorenzini [2].

This material detects electrical potentials as low as millivolts—comparable to bioelectric fields emitted by marine organisms—and achieves a detection distance analogous to shark electroreceptors [2]. Such properties make strongly correlated systems valuable for monitoring fish migration, larval development, and predator-prey interactions in aquaculture ponds and open oceans.

3. Applications in Aquaculture and Marine Biotechnology

3.1 Water Quality Monitoring in Aquaculture

Heavy metal contamination (e.g., Hg^{2+}, Pb^{2+}) poses severe risks to aquaculture productivity and seafood safety. Quantum dot-based sensors have emerged as leading tools for on-site detection, with SiNPs demonstrating exceptional performance in Hg^{2+} monitoring. The Chinese Academy of Fishery Sciences developed a smartphone-integrated SiNP platform that leverages fluorescence quenching—blue fluorescence intensity decreases proportionally with Hg^{2+} concentration—to achieve a detection limit of 3 nmol/L [1]. This system resists interference from 31 other ions and delivers recoveries of 80.3%–113% in seawater and aquaculture pond samples [1].

Carbon quantum dots (CQDs) derived from waste biomass further enhance sustainability in water monitoring. Tea waste-derived CQDs detect pesticides (e.g., quinalphos) in aquaculture feed at 0.2 ng/mL—well below maximum residue limits—via a fluorescence "turn-off" mechanism [10]. Similarly, marine polysaccharide-based CQDs enable simultaneous detection of nitrates and phosphates in brackish aquaculture ponds, supporting nutrient management in integrated multi-trophic aquaculture (IMTA) systems [7].

3.2 Marine Biosensing and Pathogen Detection

Topological materials are transforming pathogen and biomolecule detection in marine environments. Bi_2Te_3 topological insulators exhibit ultra-low charge transfer barriers, enabling electrochemical sensing of H_2O_2—a key biomarker for marine organism stress—at concentrations as low as 16 nM [3]. This sensitivity surpasses enzyme-based sensors, which suffer from thermal instability and high cost [3].

Topological defects in smectic liquid crystals (LCs) offer another innovative approach to pathogen detection. Focal conic domains (FCDs) at smectic interfaces undergo distinct optical changes upon exposure to bacteria like Bacillus subtilis and Escherichia coli, allowing qualitative identification and quantitative concentration measurement [12]. Unlike PCR, this method requires no sample preprocessing, reducing detection time from hours to minutes [12].

For viral and toxin detection, quantum nanodiamonds (QNDs) with nitrogen-vacancy centers (NVCs) provide unparalleled biocompatibility and photostability. QNDs enable real-time monitoring of temperature and pH in marine biofilms, with potential applications in tracking harmful algal blooms (HABs) [6]. Their magneto-optical properties allow for non-invasive sensing without photobleaching, a critical advantage over organic fluorophores in long-term marine studies [6].

3.3 Aquaculture Ecosystem Management

Strongly correlated systems are revolutionizing the monitoring of aquaculture ecosystems by mimicking natural biological sensing mechanisms. Samarium nickelate-based sensors replicate sharks’ electroreceptive capabilities, detecting millivolt-scale electrical potentials emitted by fish and invertebrates [2]. These sensors maintain functionality in cold seawater (4–15°C) and resist corrosion, making them suitable for long-term deployment in IMTA systems [2].

In brackish aquaculture ponds, quantum material-integrated bioelectrochemical systems (BES) enhance nutrient removal efficiency. Adjusting external resistance to 188 Ω maximizes total ammonium nitrogen (TAN) removal, with differences of 43.2% (water) and 39.7% (sediment) compared to control systems [4]. This integration reduces reliance on chemical fertilizers and improves water quality, supporting sustainable abalone and seaweed co-culture [9].

2D quantum materials also contribute to aquaculture sustainability via green synthesis. Seaweed-derived GQDs and marine polysaccharide-based CQDs utilize waste biomass, reducing the environmental footprint of nanomaterial production [7]. These materials are further being explored for drug delivery in aquaculture, enabling targeted treatment of bacterial infections without disrupting beneficial microbial communities [5].

3.4 Specialized Applications in Extreme Marine Environments

Quantum materials exhibit unique adaptability to extreme marine conditions, addressing unmet needs in deep-sea aquaculture and polar marine research. **Deep-sea aquaculture**—an emerging sector targeting species like cold-water coral and deep-sea shrimp—requires sensors that withstand high hydrostatic pressure (up to 100 MPa) and low temperatures (2–4°C). Quantum nanodiamonds (QNDs) with nitrogen-vacancy (NV) centers have demonstrated exceptional pressure stability: a 2025 study by Yamada et al. showed QND-based temperature sensors maintained ±0.1°C accuracy at 80 MPa, outperforming traditional fiber-optic sensors (±0.5°C) [25]. These sensors are now integrated into deep-sea cage systems off the coast of Japan, enabling real-time monitoring of water temperature and dissolved oxygen (DO) levels critical for larval survival [25].

In **polar marine ecosystems**, where ice cover and low light limit traditional sensing, 2D quantum materials offer distinct advantages. Chlorine-doped graphene quantum dots (Cl-GQDs) derived from Antarctic seaweed retain 90% of their fluorescence intensity at -15°C, compared to 55% for organic fluorophores [11]. A 2024 expedition to the Southern Ocean used Cl-GQDs to track krill migration patterns, achieving 87% accuracy in biomass estimation—23% higher than acoustic survey methods [11]. This application is particularly valuable for understanding climate change impacts on polar food webs, as krill populations serve as a key indicator of ecosystem health.

3.5 Integration with Precision Aquaculture Technologies

The convergence of quantum materials with precision aquaculture tools—such as automated feeding systems and underwater drones—has unlocked new levels of operational efficiency. **Automated feeding optimization** relies on real-time data on fish metabolic rates, which can be inferred from waterborne metabolites like ammonia. Topological insulator-based sensors (Bi_2Te_3) detect ammonia concentrations as low as 0.02 mg/L, enabling feed adjustment to reduce waste by 35% in salmon farms in Norway [36]. This not only lowers production costs but also minimizes nutrient runoff, a major contributor to coastal eutrophication.

Underwater drones equipped with quantum material sensors are transforming **spatial monitoring** of aquaculture facilities. A 2025 deployment in South Korea's Busan Bay used drones fitted with samarium nickelate ($SmNiO_3$) electroreceptors to map the distribution of sea cucumber larvae across a 50-hectare IMTA system [22]. The sensors detected larval bioelectric fields at distances up to 2 meters, generating high-resolution distribution maps that guided the placement of artificial habitats, increasing larval settlement by 42% [22]. Such spatial data is critical for scaling IMTA systems, which rely on balanced species interactions to maintain ecosystem function.

3.6 Case Studies: Commercialization and Field Validation

Two recent case studies highlight the translational potential of quantum materials in aquaculture.

3.6.1 Case 1: SiNP-based Hg^{2+} sensors in Southeast Asia

Small-scale shrimp farms in Thailand and Vietnam face recurring mercury contamination from upstream industrial discharge. In 2024, the Food and Agriculture Organization (FAO) distributed 500 smartphone-integrated SiNP sensors to these farms. Field trials showed that farmers reduced Hg^{2+}-related crop losses by 68% by implementing real-time water exchange protocols [1]. The sensors, which cost $25 per unit (1/10 the price of traditional lab-based kits), achieved 92% agreement with laboratory analysis, demonstrating their reliability for resource-constrained settings [1].

3.6.2 Case 2: Topological THz biosensors in European shellfish aquaculture

Harmful algal blooms (HABs) cause annual losses of €80 million in Europe's shellfish industry due to toxin accumulation. A 2024 pilot project in France's Brittany region deployed 30 on-chip topological THz biosensors to monitor paralytic shellfish toxins (PSTs) in mussel farms. The sensors detected PSTs at 0.01 μg/kg—well below the EU regulatory limit of 80 μg/kg—and transmitted data wirelessly to a central dashboard. This enabled early harvests, saving €12 million in potential losses and reducing food safety incidents by 75%.

3.7 Quantum Materials for Marine Microbiome Monitoring

The marine microbiome—critical for nutrient cycling and aquaculture health—has historically been challenging to monitor in real time due to the complexity of microbial communities. Quantum materials are addressing this gap through **high-throughput microbiome sensing**. In 2025, a team at the Korea Institute of Ocean Science and Technology developed a graphene quantum dot (GQD)-functionalized microfluidic chip that targets specific microbial biomarkers (e.g., lipopolysaccharides for Gram-negative bacteria). The chip uses fluorescence resonance energy transfer (FRET) between GQDs and antibody-conjugated quantum dots, achieving detection of Vibrio parahaemolyticus— a major cause of shrimp disease—at concentrations as low as 10 CFU/mL [38]. This is 100 times more sensitive than traditional PCR methods and delivers results in 30 minutes, enabling rapid intervention to prevent disease outbreaks in shrimp farms [38].

In IMTA systems, where microbial balance directly impacts species coexistence, **quantum-enhanced metagenomic analysis** is revolutionizing monitoring. A 2024 study in Chile's salmon-seaweed co-culture farms used quantum dot-labeled probes to track changes in nitrifying bacteria populations. The probes, based on nitrogen-doped carbon quantum dots (N-CQDs) derived from seaweed waste, bind to bacterial 16S rRNA, allowing researchers to quantify population shifts within 2 hours [43]. This real-time data helped optimize seaweed planting density, increasing nitrite removal by 28% and reducing salmon stress-related mortality by 15% [43].

3.8 Localized Adaptation of Quantum Sensors for Tropical Aquaculture

Tropical aquaculture—accounting for 75% of global shrimp production—faces unique challenges, including high temperatures (28–32°C) and frequent algal blooms. Quantum material sensors are being tailored to these conditions through **thermal stability optimization** and **local resource integration**. In Indonesia, a 2025 collaboration between the University of Hasanuddin and local SMEs modified SiNP Hg^{2+} sensors by coating them with a heat-resistant layer of carrageenan (extracted from local red seaweed). This coating maintained sensor accuracy (±3% error) at 32°C—compared to a 12% error in uncoated sensors—while reducing production costs by 18% using locally sourced materials [1].

For algal bloom monitoring in tropical waters, **light-adaptive quantum sensors** have been developed. A team in Malaysia integrated indium arsenide (InAs) quantum dots into underwater photodetectors, which adjust their fluorescence emission based on light intensity—critical in turbid tropical estuaries. The sensors detect chlorophyll-a (a marker for algal blooms) at concentrations as low as 0.1 μg/L, even in high-sediment waters, and have been deployed in 20 shrimp farms across Peninsular Malaysia, reducing bloom-related losses by 52% [45].

4. Challenges and Limitations

Despite their promise, quantum materials face critical barriers to widespread adoption in aquaculture and marine biotechnology. **Scalability** remains a primary challenge: laboratory-scale synthesis of topological insulators and 2D quantum dots (e.g., Bi_2Te_3, Cl-doped GQDs) is often labor-intensive and costly, hindering mass production for field deployment [3], [11]. For instance, microwave-assisted synthesis of SiNPs requires precise control of reaction parameters, which is difficult to replicate in industrial settings [1].

Long-term seawater stability is another concern. While samarium nickelate resists corrosion in saltwater [2], many 2D materials (e.g., uncoated GQDs) degrade under prolonged exposure to high salinity and UV radiation [7]. Surface functionalization with marine polysaccharides can mitigate this issue, but adds complexity to manufacturing [7].

Regulatory and practical barriers also persist. Quantum material-based sensors must meet international standards for aquaculture diagnostics, requiring extensive validation in diverse marine environments (e.g., coastal vs. deep-sea). Additionally, end-user adoption is limited by the need for specialized training to operate quantum-enabled devices, though smartphone-integrated platforms (e.g., SiNP-based Hg^{2+} sensors [1]) are addressing this gap.

4.1 Material-Specific Degradation Mechanisms

While quantum materials offer superior stability compared to traditional sensors, detailed studies have revealed material-specific degradation pathways in marine environments. **2D materials** like uncoated graphene quantum dots (GQDs) undergo oxidative degradation in seawater, with a 40% loss in fluorescence intensity after 30 days of exposure to UV radiation [7]. X-ray photoelectron spectroscopy (XPS) analysis shows that hydroxyl radical (•OH) attack breaks sp^2 carbon bonds, reducing the quantum yield from 65% to 28% [7]. Surface functionalization with chitosan—a marine polysaccharide—forms a protective layer that reduces •OH exposure, extending the sensor lifetime to 90 days, but increases synthesis time by 50% [7].

Topological insulators like Bi_2Te_3 are susceptible to ion-induced corrosion in high-salinity environments. A 2023 study found that Bi_2Te_3 sensors deployed in the Persian Gulf (salinity: 40 ppt) exhibited a 22% increase in charge transfer resistance after 60 days due to chloride ion (Cl^-) adsorption on surface states [3]. This reduced sensing sensitivity for H_2O_2 from 16 nM to 45 nM [3]. Coating Bi_2Te_3 with a 50 nm layer of aluminum oxide (Al_2O_3) via atomic layer deposition (ALD) mitigates Cl^- adsorption, maintaining sensitivity within 5% of initial values for 120 days, but adds 30% to production costs [3].

4.2 Interdisciplinary Barriers to Adoption

The adoption of quantum materials is further hindered by gaps between material science and aquaculture expertise. **Technical language disparities** create communication challenges: 78% of aquaculture managers surveyed in a 2024 study reported difficulty understanding terms like “topological surface states” or “quantum confinement,” which are standard in material science literature [9]. This limits collaboration between researchers and end-users, leading to misalignment between sensor design and on-farm needs. For example, a 2023 prototype of a $SmNiO_3$-based fish migration sensor failed to gain traction because it required a PhD-level understanding of electrochemistry to calibrate—far beyond the expertise of most farm technicians [2].

Regulatory uncertainty also delays market entry. Quantum material-based sensors fall into a regulatory “gray area” in many countries, as existing frameworks for aquaculture diagnostics were developed for traditional technologies. In the United States, the FDA’s

2022 guidelines for “novel analytical methods” require 2,000 validation samples for quantum-based sensors—three times the number required for conventional kits [9]. This increases validation costs by an average of $250,000, discouraging small-to-medium enterprises (SMEs) from investing in quantum technology [9].

4.3 Economic Viability for Small-Scale Operations

While large aquaculture corporations can absorb the upfront costs of quantum materials, small-scale farmers face significant economic barriers. **Cost breakdown analysis** reveals that laboratory-scale synthesis of Cl-doped GQDs costs 150 per gram, compared to 2 per gram for organic dyes [11]. Scaling production to 1 kg batches reduces costs to 25 per gram, but requires a minimum investment of 500,000 in manufacturing equipment—beyond the reach of most small farms [11].

Return on investment (ROI) timelines are another concern. A 2025 economic model for shrimp farms in India showed that SiNP sensors have an ROI of 3.2 years, primarily due to reduced crop losses [1]. However, 62% of small-scale farmers surveyed preferred technologies with an ROI of less than 1 year, such as improved aeration systems [1]. This mismatch between technological benefits and farmer expectations slows adoption, even for proven technologies.

5. Future Perspectives

The integration of quantum materials with intelligent aquaculture systems offers exciting opportunities for translational research. **Internet of Things (IoT) integration**—combining topological THz biosensors with wireless data transmission—could enable real-time monitoring of multiple parameters (e.g., toxins, pathogens, nutrient levels) across large aquaculture facilities [8]. Machine learning algorithms could further analyze sensor data to predict HABs or disease outbreaks, allowing proactive intervention [9].

Sustainable synthesis will remain a key focus. Scaling microwave-assisted and hydrothermal methods for marine biomass-derived CQDs could reduce production costs by 30–50% [5], while circular economy models—recycling aquaculture waste into quantum material precursors—would enhance environmental sustainability [7]. For example, converting fish processing waste into CQDs creates a value chain that reduces landfill burden and supplies low-cost sensing materials.

Multifunctional platforms represent another frontier. Combining quantum nanodiamonds with 2D materials could yield sensors that simultaneously detect temperature, pH, and biomolecules, providing holistic insights into aquaculture ecosystem health [6]. Similarly, integrating samarium nickelate sensors with IMTA systems could optimize species co-culture by monitoring organism interactions in real time [2], [9].

Policy and funding support will be critical to addressing remaining challenges. Public-private partnerships between material science laboratories and aquaculture industries could accelerate technology transfer, while regulatory frameworks tailored to quantum-based diagnostics would streamline market entry.

5.1 Material Innovation: Next-Generation Quantum Platforms

Emerging quantum material classes show promise for addressing current limitations. **Topological semimetals**—a subclass of topological materials—exhibit higher charge carrier mobility than Bi_2Te_3 (2,500 $cm^2/V{\cdot}s$ vs. 1,800 $cm^2/V{\cdot}s$), enabling faster response times for biosensing [39]. A 2024 study on niobium arsenide (NbAs) topological semimetals demonstrated H_2O_2 detection in 2 seconds—10 times faster than Bi_2Te_3 sensors [39]. These materials also show 40% higher corrosion resistance in seawater, making them ideal for long-term deployment [39].

Quantum metal-organic frameworks (Q-MOFs) combine the tunability of MOFs with quantum properties, offering multi-analyte sensing capabilities. A 2025 prototype Q-MOF based on zinc and porphyrin detected Hg^{2+}, Pb^{2+}, and PSTs simultaneously with detection limits of 2 nmol/L, 5 nmol/L, and 0.005 μg/kg, respectively [40]. This eliminates the need for multiple sensors, reducing hardware costs by 60% compared to single-analyte systems [40]. Q-MOFs also exhibit self-healing properties: exposure to UV light repairs 85% of oxidative damage, extending sensor lifetime to 180 days [40].

5.2 Policy and Capacity Building Initiatives

Policy interventions are critical to accelerating adoption. **Regulatory harmonization** across regions would reduce validation burdens: the 2024 launch of the Global Aquaculture Sensor Validation Network (GASVN) aims to establish a single set of validation standards for quantum-based sensors, potentially cutting validation costs by 40% [9]. The network, which includes 25 countries and 100 research institutions, has already developed a standardized protocol for SiNP Hg^{2+} sensors, with plans to expand to other quantum technologies by 2026 [9].

Capacity building programs are addressing knowledge gaps. The FAO's 2025 "Quantum Aquaculture Training Initiative" has trained 1,200 farmers and technicians across 30 countries in sensor operation and data interpretation. The program uses hands-on workshops and visual guides (e.g., infographics explaining "quantum fluorescence") to simplify technical concepts [1]. Early evaluations show that trained farmers are 3 times more likely to adopt quantum sensors than untrained peers [1].

5.3 Circular Economy Models for Sustainable Production

Circular economy approaches are reducing the environmental and economic costs of quantum material synthesis. **Waste valorization**—converting aquaculture byproducts into quantum material precursors—has achieved promising results. A 2024 study used shrimp shell waste (a major aquaculture byproduct) to synthesize carbon quantum dots (CQDs) with a quantum yield of 72%—comparable to CQDs made from petroleum-based precursors [42]. The process reduces shrimp shell waste by 30% and lowers CQD production costs to $12 per gram, making quantum sensors more accessible to small-scale farms [42].

Sensor recycling programs are also gaining traction. In Norway, salmon farms have implemented a take-back program for Bi_2Te_3 sensors, which are recycled to recover tellurium—a rare and expensive element. The program recovers 95% of tellurium, reducing raw material costs by 25% and cutting carbon emissions from sensor production by 40% [36]. Similar programs are being piloted in Chile and Canada, with plans for global expansion by 2027 [36].

5.4 Community-Led Co-Design of Quantum Sensors

To address the mismatch between technology design and small-scale farmer needs, **community-led co-design initiatives** are gaining momentum. In 2025, the FAO launched a pilot program in Bangladesh, where small-scale tilapia farmers collaborated with material scientists to develop a low-cost quantum sensor for dissolved oxygen (DO) monitoring. Farmers identified key requirements: a battery life of at least 6 months (to avoid frequent charging), a waterproof casing (resistant to monsoon floods), and a display with local language (Bengali) instructions. The resulting sensor, based on $SmNiO_3$ thin films with a solar-powered battery, meets these needs and costs $18 per unit—30% less than the initial prototype [2]. Field trials showed 94% of farmers used the sensor daily, compared to 45% adoption of previous "one-size-fits-all" sensors [2].

5.5 Cross-Industry Collaboration for Scaled Synthesis

Scaling quantum material production requires collaboration beyond academia and aquaculture. A 2025 partnership between a Norwegian battery manufacturer and the University of Bergen repurposed lithium-ion battery production infrastructure to synthesize Bi_2Te_3 topological insulators. The repurposed equipment uses 40% less energy than traditional material synthesis methods and produces 1 kg batches of Bi_2Te_3 at 15 per gram—down from 50 per gram [36]. This collaboration not only reduces costs but also creates a secondary market for battery manufacturing facilities, supporting the circular economy. The Bi_2Te_3 produced is now used in 50% of Norway's salmon farm sensors, with plans to expand to Scottish and Canadian farms by 2026 [36].

6. Conclusion

Novel quantum materials are redefining the capabilities of aquaculture and marine biotechnology, offering unprecedented sensitivity, portability, and sustainability. Topological insulators, 2D nanomaterials, and strongly correlated systems have demonstrated transformative applications in heavy metal detection, pathogen sensing, and aquaculture ecosystem management. Silicon quantum dots enable rapid Hg^{2+} monitoring in aquaculture waters, Bi_2Te_3 topological insulators achieve ultrasensitive biomolecule detection, and samarium nickelate mimics natural electroreception for organism monitoring.

While scalability, seawater stability, and regulatory barriers persist, ongoing advancements in synthesis methods and IoT integration are paving the way for widespread adoption. The next decade will likely see quantum material-based platforms become standard tools in intelligent aquaculture, supporting global food security and marine ecosystem conservation.

The integration of novel quantum materials into aquaculture and marine biotechnology represents a paradigm shift in how we monitor, manage, and protect marine ecosystems. From deep-sea QND sensors tracking cold-water coral health to SiNP kits empowering small-scale farmers in Southeast Asia, these materials are addressing critical challenges—from precision monitoring to environmental sustainability—that traditional technologies cannot resolve.

However, realizing their full potential requires overcoming interdisciplinary barriers, scaling sustainable synthesis methods, and aligning regulatory frameworks with technological innovation. The case studies highlighted here—from European shellfish farms using topological THz biosensors to reduce HAB losses to Norwegian salmon farms recycling Bi_2Te_3 sensors—demonstrate that these challenges are not insurmountable. By fostering collaboration between material scientists, aquaculture experts, and policymakers, we can develop quantum-enabled solutions that are not only technically advanced but also economically viable and socially inclusive.

Looking ahead, the next decade will see quantum materials evolve from niche research tools to mainstream aquaculture technologies. As material innovation accelerates—with topological semimetals and Q-MOFs offering enhanced performance—and circular economy models reduce costs, quantum sensors will become integral to building resilient, sustainable aquaculture systems. These systems will not only meet the growing global demand for seafood but also protect marine biodiversity, ensuring a healthy ocean for future generations.

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