Quantum-Enhanced BioMEMS for Ultra-Sensitive Detection of Pathogens in Clinical Diagnostics

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***Abstract*—Rapid and accurate detection of pathogens at very low concentrations is crucial for protecting public health, especially during outbreaks. In this project, I explore how ideas from quantum physics can be combined with biological microelectromechanical systems (BioMEMS) to build more sensitive diagnostic devices. The main goal is to help these chips pick up extremely weak signals from viruses or bacteria while reducing noise and false readings. The work focuses on three approaches: quantum tunneling, spin-based readout (such as nitrogen-vacancy centers in diamond), and quantum-enhanced biophotonic techniques. Using simple computational simulations and conceptual models, I examine how these methods could lower detection limits in microfluidic chips and make the data more reliable. A focused review of recent research on BioMEMS, nanomaterials, and quantum biophotonics is also carried out to understand current challenges and realistic design options. Overall, the project suggests that quantum-enhanced BioMEMS could help create smaller, faster, and more affordable diagnostic tools. Such devices support the United Nations Sustainable Development Goals for better health (SDG 3) and innovation in industry and infrastructure (SDG 9) by making advanced healthcare technology more accessible around the world.**

Emerging infectious diseases and global outbreaks show how important it is to detect pathogens quickly and accurately (Srivastava, Kumar, Wani, Robinson, & Ahmad, 2025). In many cases, the first samples contain only a very small number of viruses or bacteria. Traditional biosensors often cannot detect such low concentrations, so infections may only be discovered at a later stage.

BioMEMS (biological micro-electromechanical systems) are small chips that combine microfluidic channels, biological recognition elements, and electronic readout on the same platform (Welburn, Javadi, Nguyen, & Desai, 2025). They are promising for point-of-care testing because they can work with tiny sample volumes and can, in principle, be produced at low cost. However, current BioMEMS devices still struggle with signal-to-noise ratio, thermal noise, and other sources of interference at the nano-scale.

Quantum sensing offers a new way to push the limits of sensitivity. By using quantum effects such as superposition, entanglement, and spin coherence,

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quantum sensors can measure physical quantities with extremely high precision (Khorsheed & Altaei, 2025). Examples include quantum tunneling–based detection, spin readout using nitrogen-vacancy (NV) centers in diamond, and quantum biophotonic techniques (Moreva et al., 2025; Torabi, Shirani, & Reilly, 2025).

In this project, I investigate how these quantum ideas could be integrated into BioMEMS architectures for ultra-sensitive pathogen detection. The work is mainly conceptual: I combine a literature review with basic simulations and CAD drawings of device layouts. The project also connects to the UN Sustainable Development Goals by exploring diagnostic tools that could support SDG 3 (Good Health and Well-Being) and SDG 9 (Industry, Innovation, and Infrastructure) (Aghili, Abbariki, Daneshgar, Edrisi, & Rabiee, 2025).

Methods

Literature Review

I first carried out a qualitative review of recent research on:

- Quantum-enhanced sensing and its physical principles (Khorsheed & Altaei, 2025),
- Quantum photonics and biophotonics for biosystems (Moreva et al., 2025),
- BioMEMS and their use in clinical diagnostics (Welburn et al., 2025; Abhinav et al., 2025), and
- New biosensor designs using nanomaterials and multicolor readouts (Aghili et al., 2025).

The aim of the review was to identify current limits of BioMEMS, to see where quantum methods already show an advantage, and to collect ideas for combining both fields in one device.

Conceptual and Computational Modeling

Next, I created simple conceptual models and basic computational simulations of microfluidic channels. These models were used to:

- Visualize how a sample flows through the chip,
- Estimate how long pathogens stay in the sensing region, and
- Think about how quantum readout (for example, spin-based sensing) could change the detection threshold.

The simulations were not meant to give exact numbers, but to support intuition about channel geometry, sensor placement, and noise.

CAD-Based Device Concepts and Mentor Feedback

Using CAD software, I drew several possible device architectures. Each concept included:

- Microfluidic pathways,
- A biological recognition layer (such as antibodies or aptamers),
- A quantum sensing layer (for example, NV centers in a thin diamond film or tunneling junctions), and
- Electronic or optical readout components.

I discussed these sketches with academic mentors to check if the designs were realistic and if they aligned with basic clinical requirements, such as reproducibility and potential for mass production.

Results

Proposed Device Architecture

From the modeling and review, a common architecture emerged with four main layers:

- Microfluidic layer: guides the biological sample over the sensing area.
- Recognition layer: captures the target pathogen using specific binding molecules.
- Quantum sensing layer: converts tiny physical changes near the surface (for example, magnetic fields, refractive index, or tunneling currents) into quantum signals.
- Readout layer: uses electronics and, where needed, light sources and detectors to read and process the quantum signal.

Placing the quantum sensors very close to the recognition layer appears important because it increases the chance that each binding event creates a measurable change.

Expected Advantages (Qualitative)

Based on values reported in the literature and the conceptual models, quantum-enhanced BioMEMS are expected to offer:

- Lower detection limits: potentially down to femtomolar or even attomolar levels, depending on the sensor type and noise.
- Improved signal-to-noise ratio: quantum readout can help reduce classical noise and improve stability.
- Faster detection: because fewer molecules are needed to generate a detectable signal, waiting time for sufficient binding may be shorter.

These points are qualitative predictions, but they show why combining quantum sensing with BioMEMS is attractive for early pathogen detection.

Challenges Identified

The study also highlights several challenges:

- Quantum coherence can be easily disturbed in warm, complex biological samples.
- Some quantum materials may be difficult to integrate with biocompatible surfaces.
- Multi-layer fabrication that includes microfluidics, quantum structures, and electronics may be complex and expensive.

These issues must be addressed before any real clinical device can be built.

Discussion

The results suggest that quantum-enhanced BioMEMS could play an important role in early disease detection. If such devices can detect pathogens at very low concentrations, clinicians may be able to diagnose infections sooner and choose treatments more quickly. This could help slow down outbreaks and improve patient outcomes.

From a broader perspective, compact and energy-efficient quantum-enhanced chips could be used not only in large hospitals, but also in smaller clinics or resource-limited areas. In this way, the project supports SDG 3 by focusing on better health and SDG 9 by pointing toward innovative, scalable diagnostic technologies.

At the same time, the work reminds us that technology alone is not enough. Issues such as cost, accessibility, and fair distribution will decide whether these advanced tools truly benefit global health.

Conclusion

This project presents a conceptual study on how quantum sensing can be integrated with BioMEMS for ultra-sensitive pathogen detection. Using a literature review, simple simulations, and CAD-based designs, it outlines possible device architectures and their expected advantages, such as lower detection limits and improved signal-to-noise ratio.

Although no physical prototypes were built, the study helps map out the main opportunities and challenges in this emerging area. Future work could focus on building simple test devices, measuring their performance in realistic samples, and exploring how these quantum-enhanced signals can be combined with modern data analysis tools to support clinical decision-making.

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