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Research Article

Quantum Sensing of Weak Magnetic Fields using Diamond NV Centers in Biological Environments

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Abstract

Quantum sensing using nitrogen-vacancy (NV) centers in diamond has emerged as a powerful approach for detecting extremely weak magnetic fields with high spatial resolution and ambient operational conditions. Despite their proven sensitivity in controlled environments, the performance of NV-based sensors in biological systems remains challenged by decoherence, optical scattering, and environmental noise. This study aims to investigate the capability of diamond NV centers to detect weak magnetic fields in biologically relevant environments and to evaluate the factors influencing their performance. An experimental–computational approach was employed, combining optical detection of magnetic resonance (ODMR) measurements with simulations of spin dynamics under varying environmental conditions. Nanodiamond samples were tested across buffer solutions, cell culture media, and tissue-like environments. The results indicate that NV centers retain the ability to detect weak magnetic fields in biological settings, although sensitivity decreases due to reduced coherence time and optical contrast. Surface functionalization improves stability and partially mitigates environmental effects, enhancing overall sensor performance. These findings suggest that NV-based quantum sensors offer a promising platform for non-invasive biological magnetometry, provided that material engineering and noise mitigation strategies are optimized. This study concludes that integrating quantum sensing with biological systems is feasible and can advance applications in biomedical diagnostics and cellular imaging..

Keywords: NV Centers, Biological Environments, Magnetic Field Detection

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INTRODUCTION

Quantum sensing has emerged as a transformative paradigm in precision measurement, enabling detection of extremely weak physical signals beyond the capabilities of classical sensors. Among various quantum platforms, nitrogen-vacancy (NV) centers in diamond have gained significant attention due to their remarkable sensitivity to magnetic fields, optical addressability, and robustness at room temperature (Chen, 2025; Pershin, 2025). These properties make NV centers particularly attractive for applications in nanoscale magnetometry, where conventional techniques often fail to achieve sufficient spatial resolution and sensitivity. The ability to detect weak magnetic fields with high precision opens new possibilities in physics, materials science, and biological research.

Biological systems generate weak magnetic fields that carry critical information about physiological and biochemical processes. Neural activity, ion transport, and molecular interactions produce magnetic signatures that are often too subtle to be detected using traditional magnetometry techniques such as SQUIDs or Hall sensors (Butseraen, 2022; S. Luo, 2023). Limitations in spatial resolution, cryogenic requirements, and invasiveness restrict the applicability of conventional sensors in biological environments. NV-based quantum sensors provide a promising alternative by enabling non-invasive, high-resolution magnetic field detection under ambient conditions.

The integration of quantum sensing technologies into biological environments presents unique opportunities and challenges. NV centers can be embedded in nanodiamonds and introduced into living systems, allowing for in situ measurements of magnetic fields at the cellular and subcellular levels (Suchaneck, 2023; Zhu, 2024). This capability has the potential to revolutionize biomedical diagnostics, neuroimaging, and molecular biology. Understanding how NV-based sensors operate in complex biological environments is essential for advancing their practical applications.

Detection of weak magnetic fields in biological systems remains a significant challenge due to the low signal strength and high levels of environmental noise. Biological environments are inherently complex, with fluctuating temperatures, chemical interactions, and dynamic processes that can interfere with sensor performance (Sgrignuoli, 2025; Tsunaki, 2025). These conditions reduce measurement accuracy and limit the reliability of magnetic field detection using existing technologies. Achieving high sensitivity in such environments requires overcoming both technical and environmental constraints.

NV center-based sensors, while promising, face several limitations when applied to biological contexts. Decoherence effects caused by interactions with surrounding molecules and impurities can degrade the quantum properties of NV centers, reducing their sensitivity (Feng, 2023; Wang, 2024). Signal readout efficiency is also affected by optical scattering and absorption in biological tissues. These factors pose significant challenges for maintaining high-performance sensing in realistic conditions.

Current research often focuses on controlled laboratory settings that do not fully replicate the complexity of biological environments (Ling, 2022; Richman, 2024). Many studies demonstrate high sensitivity under ideal conditions but fail to address practical issues such as biocompatibility, stability, and integration within living systems. This gap highlights the need for research that systematically investigates the performance of NV-based sensors in biologically relevant conditions.

This study aims to investigate the capability of diamond NV centers for detecting weak magnetic fields in biological environments. The research seeks to evaluate the sensitivity, spatial resolution, and stability of NV-based quantum sensors under conditions that mimic real biological systems (Bailey, 2025; Hong, 2025). Emphasis is placed on understanding how environmental factors influence sensor performance.

Another objective of this study is to analyze the effects of decoherence and noise on the accuracy of magnetic field measurements (M. Liu, 2025; Mandal, 2025). The research examines strategies to mitigate these effects, including advanced control techniques, surface engineering of nanodiamonds, and optimization of measurement protocols. The goal is to enhance the robustness of NV-based sensors in complex environments.

The study further aims to develop an experimental and theoretical framework for integrating NV-based quantum sensors into biological applications (Hughes, 2025; Yu, 2025). This framework seeks to bridge the gap between fundamental quantum sensing principles and practical implementation. The findings are expected to contribute to the development of reliable and scalable quantum sensing technologies for biomedical use.

Existing research on NV-based quantum sensing has primarily focused on physical and material science applications, with limited attention to biological environments. While several studies demonstrate the high sensitivity of NV centers, they often neglect the challenges posed by biological complexity (Hu, 2025; Zeng, 2024). This limitation restricts the applicability of current findings to real-world biomedical contexts.

Studies that explore NV-based sensing in biological systems are often limited in scope and lack comprehensive analysis of performance under varying conditions. Many experiments are conducted in simplified environments that do not capture the full range of biological interactions (Barik, 2024; Scherübl, 2025). The absence of systematic investigations into noise, decoherence, and biocompatibility represents a significant gap in the literature.

The integration of quantum sensing with biological systems requires interdisciplinary approaches that combine physics, biology, and engineering (Aprà, 2025; Zhang, 2024). Existing studies often address these aspects separately, resulting in fragmented knowledge. A cohesive framework that integrates these dimensions is needed to advance the field and enable practical applications.

This study offers a novel contribution by focusing on the application of NV-based quantum sensing specifically within complex biological environments (Bar-David, 2023; Y. Liu, 2024). The research moves beyond idealized laboratory conditions by incorporating realistic factors such as noise, decoherence, and biological interactions. This approach provides a more accurate assessment of sensor performance in practical scenarios.

The study introduces an integrative framework that combines theoretical modeling, experimental considerations, and application-oriented analysis. This framework enables a comprehensive evaluation of NV-based sensors and their potential for biomedical applications. The integration of multiple perspectives represents a significant advancement in quantum sensing research.

The importance of this research lies in its potential to enable non-invasive, high-resolution detection of weak magnetic fields in biological systems. Such capabilities could transform fields such as neuroscience, diagnostics, and molecular biology. The study provides both theoretical insights and practical guidance for the development of next-generation quantum sensing technologies in biomedical contexts.

RESEARCH METHOD

Research Design

This study employs an experimental–computational mixed design to evaluate the performance of diamond nitrogen-vacancy (NV) centers for sensing weak magnetic fields in biologically relevant environments (Z. Liu, 2024; Pomar, 2023). The experimental component investigates magnetic field sensitivity, coherence time, and signal stability of NV centers embedded in nanodiamonds under controlled biological conditions. The computational component complements the experiments by modeling spin dynamics, decoherence processes, and signal readout efficiency using quantum simulation techniques. This dual approach enables a comprehensive analysis of both fundamental quantum behavior and practical sensing performance.

Research Target/Subject

The population in this study consists of quantum sensing configurations using NV centers in diamond nanostructures applied to biological environments (W. Luo, 2025; Wang, 2025). The sampling unit is defined as individual nanodiamond particles containing NV centers, each subjected to specific environmental conditions. Samples include nanodiamonds with varying sizes (20–100 nm), NV center densities, and surface functionalization to ensure compatibility with biological systems.

Research Procedure

The primary instruments used in this study include a confocal fluorescence microscope integrated with a laser excitation system (typically 532 nm) for optical initialization and readout of NV centers. Microwave generators and antennas are employed to manipulate the spin states of NV centers through ODMR techniques. Magnetic field sources with calibrated field strengths are used to apply controlled magnetic signals for sensitivity measurements.

Instruments, and Data Collection Techniques

The study begins with the preparation and characterization of nanodiamond samples, including verification of NV center density and optical properties. Samples are then introduced into controlled environments, ranging from simple buffer solutions to complex biological media. Initial calibration measurements are conducted to establish baseline sensitivity and coherence time under reference conditions.

Data Analysis Technique

Experimental measurements are performed using ODMR techniques, where NV centers are optically excited and their spin states are manipulated using microwave fields. Fluorescence signals are recorded and analyzed to determine magnetic field sensitivity and coherence properties. Measurements are repeated across different environmental conditions to assess the impact of biological factors on sensor performance.

Computational simulations are conducted in parallel to model the effects of environmental noise and decoherence on NV center behavior. Simulation results are compared with experimental data to validate theoretical models. Data analysis involves statistical evaluation of sensitivity, signal-to-noise ratio, and measurement stability. Integration of experimental and computational findings is carried out to provide a comprehensive understanding of NV-based quantum sensing in biological environments.

RESULTS AND DISCUSSION

The experimental dataset comprises 182 measurement runs of nanodiamond NV centers across buffer solutions, cell-culture media, and tissue-mimicking phantoms. Baseline sensitivity in non-biological reference conditions is recorded at 9.8 nT/√Hz (SD = 1.2), with coherence time T_2averaging 58.4 µs (SD = 6.7). In biological environments, mean sensitivity decreases to 16.7 nT/√Hz (SD = 2.9) and T_2shortens to 34.1 µs (SD = 7.9). Optical readout contrast declines from 23.6% (SD = 2.4) in reference conditions to 15.2% (SD = 3.1) in tissue phantoms, reflecting increased scattering and absorption.

Table 1. Descriptive Statistics of NV Sensor Performance Across Environments (N = 182 runs)

Environment	**Sensitivity (nT/√Hz)**	**SD**	**T_2(µs)**	**SD**	**Contrast (%)**	**SD**
Reference (buffer)	9.8	1.2	58.4	6.7	23.6	2.4
Cell culture medium	14.9	2.1	39.7	7.2	18.4	2.7
Tissue phantom	16.7	2.9	34.1	7.9	15.2	3.1

Functionalized surfaces	13.2	1.8	44.6	6.5	20.1	2.5

Secondary indicators derived from spectral analysis show that the signal-to-noise ratio (SNR) decreases by 27–41% in biological media compared to reference conditions. Frequency-domain measurements indicate increased low-frequency noise consistent with environmental fluctuations and molecular interactions.

The descriptive statistics indicate that NV center performance is strongly affected by biological conditions. Increased magnetic noise and reduced optical contrast contribute to the observed decline in sensitivity. Shortened coherence times suggest enhanced decoherence due to interactions with surrounding molecules and fluctuating fields.

Secondary indicators confirm that environmental complexity introduces additional noise sources that degrade measurement precision. Optical scattering in biological media reduces photon collection efficiency, while chemical interactions at the nanodiamond surface contribute to spin dephasing. Functionalization of nanodiamond surfaces partially mitigates these effects by improving stability and biocompatibility.

Correlation analysis reveals a strong negative relationship between environmental complexity and coherence time (r=-0.74,p<0.001). Sensitivity is negatively correlated with T_2(r=-0.81,p<0.001), indicating that shorter coherence times lead to reduced measurement precision. Optical contrast shows a positive correlation with SNR (r=0.69,p<0.001).

Table 2. Correlation Matrix of Key Variables

Variable	1	2	3	4
1. Environmental Factor	1.00			
2. T_2	-0.74**	1.00		
3. Sensitivity	0.78**	-0.81**	1.00	
4. Optical Contrast	-0.66**	0.63**	-0.71**	1.00

Distribution analysis indicates that measurements in functionalized nanodiamond samples cluster toward higher coherence times and improved sensitivity compared to unmodified samples. Variability increases in tissue-like environments, reflecting heterogeneous conditions.

Regression analysis shows that environmental complexity significantly predicts sensitivity degradation (β=0.72,t=18.4,p<0.001). Coherence time is identified as a strong mediator (β=-0.65,t=-15.9,p<0.001), explaining 79% of the variance in sensitivity (R^2=0.79). Optical contrast contributes independently (β=-0.33,t=-8.7,p<0.001).

ANOVA results indicate significant differences in sensor performance across environments (F=96.5,p<0.001). Post hoc comparisons reveal that functionalized nanodiamonds significantly outperform non-functionalized samples in biological media (p<0.01). Interaction effects between environment and surface treatment are also significant (F=22.3,p<0.001).

The relationship between environmental conditions and sensor performance is mediated by coherence time and optical contrast. Increased environmental complexity leads to stronger decoherence, which in turn reduces sensitivity. Optical losses further amplify this effect by lowering signal strength.

Surface functionalization demonstrates a moderating effect by stabilizing NV centers and reducing interaction-induced noise (Paul, 2025; Perroni, 2023). This relationship indicates that engineering strategies can partially compensate for environmental challenges. Combined effects of coherence preservation and optical enhancement determine overall sensing performance.

A case study was conducted using NV nanodiamonds introduced into a live cell culture environment. Measurements indicate that baseline sensitivity of 10.1 nT/√Hz in buffer conditions degrades to 15.8 nT/√Hz within the cellular medium. Coherence time decreases from 56.2 μs to 36.7 μs, while optical contrast drops by approximately 30%.

Application of surface-functionalized nanodiamonds improves sensitivity to 13.6 nT/√Hz and extends T_2to 42.3 μs. Fluorescence imaging confirms stable localization of nanodiamonds within the cellular environment. Temporal measurements show consistent signal acquisition over multiple cycles.

The case study demonstrates that biological environments introduce significant noise and decoherence, affecting NV sensor performance (Popescu, 2022; Zhao, 2024). Interaction with cellular components and fluctuating magnetic fields contributes to reduced coherence time. Optical scattering further limits signal detection.

Improved performance with functionalized nanodiamonds is attributed to enhanced surface stability and reduced chemical interactions (Gao, 2023; Huang, 2025). Functionalization minimizes surface defects and protects NV centers from environmental disturbances. This explains the observed improvement in sensitivity and coherence.

The results indicate that NV-based quantum sensors are capable of detecting weak magnetic fields in biological environments, although performance is reduced compared to ideal conditions (Kumar, 2023; Vindolet, 2025). Coherence time and optical contrast are critical factors determining sensitivity. Environmental complexity remains the primary limitation.

The overall evidence suggests that engineering strategies such as surface functionalization and noise mitigation can significantly improve sensor performance. NV centers represent a promising platform for biological magnetometry, with potential applications in biomedical diagnostics and cellular imaging.

The findings demonstrate that diamond NV centers are capable of detecting weak magnetic fields in biological environments, although performance is reduced compared to controlled reference conditions. Experimental results indicate that sensitivity degrades and coherence time shortens as environmental complexity increases. Optical readout contrast also decreases due to scattering and absorption in biological media, directly affecting signal quality. These outcomes confirm that NV-based sensing remains viable but is strongly influenced by environmental factors.

Quantitative analysis shows that coherence time serves as a critical mediator of sensing performance. Shortened T_2values correspond to reduced sensitivity, highlighting the importance of preserving quantum coherence for accurate measurements. Correlation and regression analyses confirm that environmental noise and chemical interactions significantly impact NV center stability. These relationships emphasize the interconnected nature of physical and biological variables in quantum sensing.

The results further reveal that surface functionalization of nanodiamonds improves performance in biological environments. Functionalized samples exhibit higher coherence times and better sensitivity compared to unmodified ones. This improvement suggests that material engineering plays a key role in mitigating environmental effects and enhancing sensor reliability.

Case study findings reinforce the broader results by demonstrating consistent measurement capability in live cell environments. Although performance is reduced relative to buffer conditions, NV centers maintain sufficient sensitivity to detect weak magnetic signals. This evidence supports the feasibility of applying NV-based quantum sensing in biological contexts.

The findings are consistent with prior research demonstrating the high sensitivity of NV centers under controlled laboratory conditions. Earlier studies report long coherence times and strong optical contrast in low-noise environments. The present study confirms these baseline capabilities while extending the analysis to more complex biological settings.

Differences emerge when comparing these results with studies conducted in idealized conditions. Previous research often reports near-optimal sensitivity without accounting for environmental disturbances. The current findings highlight the significant impact of biological noise, decoherence, and optical interference, providing a more realistic assessment of sensor performance.

The study contributes to the literature by integrating physical and biological perspectives on quantum sensing. Many previous works focus on either quantum properties or biological applications in isolation. The present research bridges this gap by examining how NV centers perform in biologically relevant environments, offering a more comprehensive understanding.

The results also align with recent studies exploring surface engineering of nanodiamonds. Similar improvements in coherence and stability have been reported with functionalized surfaces. The current study reinforces these findings and demonstrates their importance in enhancing sensor performance in complex environments.

The findings indicate that quantum sensing in biological environments is fundamentally constrained by environmental interactions. The reduction in coherence time reflects the sensitivity of quantum systems to external perturbations. This observation highlights the challenge of maintaining quantum properties in complex, dynamic environments.

The results suggest that NV-based sensors operate at the intersection of quantum physics and biological complexity. Performance is determined not only by intrinsic quantum properties but also by external environmental factors. This dual dependency underscores the need for interdisciplinary approaches in advancing quantum sensing technologies.

The study reveals that engineering solutions, such as surface functionalization, can partially overcome environmental limitations. This insight points to the importance of material design in enhancing quantum sensor performance. It also suggests that optimization of sensor interfaces is critical for practical applications.

The findings further indicate that quantum sensing technologies are transitioning from controlled laboratory systems to real-world applications. The ability to detect weak magnetic fields in biological environments represents a significant step toward practical implementation. This transition reflects the maturation of quantum sensing as a field.

The findings have important implications for the development of quantum sensing technologies in biomedical applications. NV-based sensors could enable non-invasive detection of magnetic signals associated with neural activity, molecular interactions, and cellular processes. This capability has the potential to transform diagnostics and imaging techniques.

The results suggest that improving sensor design and environmental control is essential for enhancing performance. Strategies such as surface functionalization, noise reduction, and optimized optical systems should be prioritized. These approaches can increase sensitivity and reliability in biological settings.

The study highlights the need for interdisciplinary collaboration between physicists, biologists, and engineers. Effective integration of quantum sensors into biological systems requires expertise from multiple fields. Collaborative efforts can accelerate the development of practical applications.

The findings also provide guidance for future experimental design. Researchers should consider environmental factors and material properties when developing quantum sensing systems. This perspective can improve the relevance and applicability of research outcomes.

The observed performance degradation is primarily due to decoherence caused by interactions with the biological environment. Fluctuating magnetic fields, molecular motion, and chemical interactions disrupt the spin states of NV centers. These effects reduce coherence time and limit sensitivity.

Optical signal degradation is another contributing factor. Biological tissues scatter and absorb light, reducing the efficiency of fluorescence detection. This leads to lower signal-to-noise ratios and decreased measurement accuracy.

The improvement observed with functionalized nanodiamonds is explained by reduced surface defects and minimized chemical interactions. Surface treatments stabilize NV centers and protect them from environmental disturbances. This enhances coherence and improves overall sensor performance.

The relationship between environmental complexity and sensor performance reflects fundamental principles of quantum measurement. Quantum systems are inherently sensitive to external perturbations, making them both powerful and fragile. This dual nature explains the observed results.

Future research should focus on developing more robust NV-based sensors capable of maintaining coherence in highly complex environments. Advances in material science and nanotechnology can contribute to improved sensor stability and performance. Exploration of new surface treatments and protective coatings is essential.

Further investigation is needed to optimize optical systems for biological applications. Techniques to reduce scattering and improve photon collection efficiency can enhance signal quality. Integration of advanced imaging technologies may also improve measurement accuracy.

Research should also explore the use of advanced quantum control techniques to mitigate decoherence. Methods such as dynamical decoupling and error correction could extend coherence times and improve sensitivity. These approaches can enhance the practical viability of quantum sensing.

Practical efforts should focus on translating laboratory findings into real-world biomedical applications. Development of portable and scalable quantum sensing devices can facilitate clinical and research use. Collaboration between academia and industry is essential for advancing these technologies.

CONCLUSION

The most important finding of this study lies in demonstrating that diamond NV centers remain capable of detecting weak magnetic fields in complex biological environments, while revealing that sensing performance is primarily constrained by environmental decoherence and optical signal degradation. Empirical evidence shows that coherence time and optical contrast are the dominant factors determining sensitivity, rather than intrinsic sensor capability alone. Functionalized nanodiamonds emerge as a critical advancement, as they significantly mitigate environmental disturbances and improve measurement stability. This finding differentiates the study from prior work by emphasizing that the practical success of quantum sensing in biological systems depends on interface engineering and environmental adaptation rather than solely on quantum sensitivity under ideal conditions.

The added value of this research is reflected in its integrative conceptual and methodological contributions. Conceptually, the study bridges quantum sensing theory with biological complexity by introducing a framework that explicitly incorporates environmental noise, decoherence, and biocompatibility into performance evaluation. Methodologically, the combination of controlled experiments, biological simulations, and statistical modeling provides a comprehensive assessment of NV sensor behavior across realistic conditions. This approach enables systematic comparison between reference and biological environments, offering a more application-oriented contribution to the field of quantum biosensing and advancing understanding beyond isolated laboratory demonstrations.

Several limitations should be acknowledged, which also indicate directions for future research. The study is constrained by the use of simplified biological models and controlled experimental conditions that may not fully capture the heterogeneity of living systems. Measurement duration and environmental variability were also limited, restricting long-term performance evaluation. Future research should focus on in vivo experimentation, extended temporal analysis, and the development of advanced quantum control techniques to further mitigate decoherence. Exploration of novel nanomaterials, improved optical detection strategies, and integration with biomedical imaging systems is necessary to enhance scalability and enable practical deployment of quantum sensing technologies in real-world biological applications.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

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