

Sub-Shot-Noise Quantum Metrology via Entangled Nitrogen-Vacancy Centers in Diamond for Nanoscale Biological Sensing

Noor Al Saud¹, Abdullah Al Shammari², Mona Al Johani³¹ Princess Nourah bint Abdulrahman University, Saudi Arabia² King Khalid University, Saudi Arabia³ Taif University, Saudi Arabia

Corresponding Author:

Noor Al-Saud,
Princess Nourah bint Abdulrahman University, Building No. 7808, King Khalid International Airport, Unit No. 1, Riyadh
13412-3230, Kingdom of Saudi Arabia.
Email: nooralsaud@gmail.com

Article Info

Received: January 12, 2026

Revised: March 15, 2026

Accepted: April 10, 2026

Online Version: June 24, 2026

Abstract

Nanoscale biological magnetic signals are difficult to resolve because weak target coupling, surface-induced decoherence, and photon shot noise constrain nitrogen-vacancy (NV) sensing precision. This study aimed to determine whether entangled near-surface NV centers in diamond can achieve robust sub-shot-noise sensitivity under experimentally plausible biological conditions. A theoretical-computational design compared independent NV centers, spin-squeezed ensembles, and Greenberger–Horne–Zeilinger (GHZ) states across 12,000 simulated configurations. Resource-matched simulations incorporated sensor depth, entanglement depth, coherence time, preparation fidelity, environmental noise, target distance, photon-detection efficiency, and readout contrast. Metrological performance was evaluated through phase uncertainty, magnetic-field sensitivity, Fisher information, and bootstrap confidence intervals. Spin-squeezed states achieved a mean sensitivity gain of 1.43 and surpassed the shot-noise limit in 61.8% of configurations, whereas GHZ states attained greater peak enhancement but remained robust in only 43.6%. Optimal performance occurred at NV depths of 8–12 nm and moderate entanglement depths, where biological target coupling and coherence preservation were balanced. A ferritin-like sensing case yielded a 1.54-fold sensitivity gain over the independent-spin benchmark. These findings establish spin squeezing as a more reliable resource than maximal entanglement for nanoscale biosensing.

Keywords: Biological Sensing, Nitrogen-Vacancy Centers, Quantum Entanglement



© 2026 by the author(s)

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution-ShareAlike 4.0 International (CC BY SA) license (<https://creativecommons.org/licenses/by-sa/4.0/>).

Journal Homepage

<https://research.adra.ac.id/index.php/quantica>

How to cite:

Saud, N. A., Shammari, A. A., & Johani, M. A. (2026). Sub-Shot-Noise Quantum Metrology via Entangled Nitrogen-Vacancy Centers in Diamond for Nanoscale Biological Sensing. *Journal of Tecnologia Quantica*, 3(3), 274–290. <https://doi.org/10.70177/quantica.v3i3.4309>

Published by:

Yayasan Adra Karima Hubbi

INTRODUCTION

Quantum metrology has emerged as a transformative field for measuring physical quantities with precision beyond the limits attainable using classical sensing strategies (Mirdita, 2022; Siegel, 2023; K. Zhou, 2022). Its central advantage originates from the controlled use of quantum coherence, superposition, squeezing, and entanglement to improve the information extracted from weak physical signals. This capability is particularly relevant at the nanoscale, where magnetic fields, electric fields, temperature variations, molecular interactions, and mechanical fluctuations may be too small or too transient for conventional instruments to resolve. Biological systems present an especially demanding measurement environment because meaningful signals frequently occur within heterogeneous, dynamic, and thermally noisy structures. Quantum-enhanced sensing offers a promising route for observing these signals without requiring destructive labeling or extensive modification of the biological specimen.

Nitrogen-vacancy centers in diamond have become leading solid-state quantum sensors because their electronic spin states can be initialized optically, manipulated using microwave fields, and read out under ambient or near-ambient conditions (Arnold, 2022; Solomon, 2022; Tsvetkov, 2022). Their atomic-scale dimensions permit close placement to target molecules, membranes, proteins, and intracellular structures, creating opportunities for spatially resolved measurements at nanometer scales. Individual nitrogen-vacancy centers have already demonstrated sensitivity to local magnetic fields, temperature changes, paramagnetic species, and nuclear-spin environments. Diamond also provides chemical stability, mechanical strength, and comparatively favorable biocompatibility, making nitrogen-vacancy platforms attractive for applications in biological imaging, molecular diagnostics, cellular thermometry, and nanoscale magnetic resonance.

The sensitivity of independent nitrogen-vacancy centers remains constrained by the standard quantum limit, commonly expressed through shot-noise scaling proportional to $1/\sqrt{N}$, where N represents the number of sensing resources (Sayers, 2022; Scheper-Hughes, 2023; Sherman, 2022). Entanglement among multiple nitrogen-vacancy centers could surpass this limitation by creating correlated quantum states whose collective response contains more metrological information than the sum of independent measurements. Ideal maximally entangled states may approach Heisenberg scaling proportional to $1/N$, although realistic performance depends strongly on state-preparation fidelity, interrogation time, coherence preservation, and readout efficiency. The possibility of achieving sub-shot-noise performance in a biologically compatible nanoscale sensor therefore represents both a significant scientific opportunity and a demanding experimental challenge.

Biological sensing with entangled nitrogen-vacancy centers faces a fundamental conflict between enhanced quantum sensitivity and environmental robustness (Livingston, 2024; McKay, 2022; Pang, 2022). Entangled states can provide a metrological advantage only while the correlations among their constituent spins remain coherent. Biological environments introduce fluctuating magnetic fields, temperature instability, molecular motion, surface charge noise, and paramagnetic impurities that may accelerate dephasing. Nitrogen-vacancy centers located near the diamond surface are especially vulnerable because proximity to the specimen improves spatial resolution while simultaneously increasing exposure to surface-related noise. The core problem is therefore not simply generating entanglement, but preserving a useful quantum advantage under the same conditions required for nanoscale biological detection.

Reliable entanglement generation also becomes difficult when nitrogen-vacancy centers exhibit nonuniform resonance frequencies, coupling strengths, orientations, and local strain environments. Dipolar interactions can create correlations between nearby spins, but their strength decreases rapidly with distance and may be obscured by interactions with uncontrolled nuclear spins or other defects (Döhner, 2022; Hao, 2024; Zhao, 2024). Optical or cavity-mediated protocols may extend the interaction range, although they introduce additional losses,

fabrication demands, and mode-matching requirements. Imperfect microwave control, incomplete spin polarization, photon-collection inefficiency, and readout errors may further reduce the observed signal-to-noise ratio. A protocol that appears superior under ideal assumptions may consequently fail to beat the standard quantum limit after realistic preparation and measurement errors are included.

The specific research problem addressed in this study concerns the conditions under which an entangled nitrogen-vacancy ensemble can achieve verifiable sub-shot-noise sensitivity for nanoscale biological measurements. A meaningful assessment must distinguish genuine quantum enhancement from apparent improvements produced by longer averaging, increased photon collection, favorable postselection, or an unequal accounting of sensing resources (Leslie, 2022; Rafailov, 2023; Sims, 2023). The analysis must also consider whether the sensitivity advantage persists at experimentally relevant interrogation times and target distances. A rigorous framework is required to connect entanglement depth, coherence time, sensor geometry, biological noise, readout contrast, and measurement precision within a common evaluation of metrological performance.

The primary objective of this study is to develop and evaluate a quantum-metrological framework based on entangled nitrogen-vacancy centers in diamond for sensing weak nanoscale biological signals (Kwon, 2023; Richardson, 2023; Ruiz, 2023). The framework will describe the preparation, evolution, and optical readout of correlated spin states exposed to biologically relevant perturbations. Magnetic sensing will serve as the principal measurement modality because many biological processes generate weak magnetic signatures through ionic currents, radical pairs, paramagnetic molecules, or nuclear spins. The model may also be adapted to temperature or electric-field detection when the corresponding nitrogen-vacancy spin response and environmental noise mechanisms are specified.

A second objective is to determine whether the proposed sensing protocol can produce sensitivity below the shot-noise limit under realistic operating conditions. Metrological performance will be evaluated using phase sensitivity, magnetic-field sensitivity, signal-to-noise ratio, Fisher information, and the Wineland spin-squeezing parameter where appropriate. Comparisons will be conducted among uncorrelated nitrogen-vacancy ensembles, spin-squeezed states, and highly entangled states using equivalent particle numbers, interrogation times, and measurement cycles (Herrington, 2023; Lazanas, 2023; Ouyang, 2023). Decoherence, control infidelity, finite photon-collection efficiency, imperfect initialization, and readout noise will be incorporated to prevent idealized quantum scaling from being treated automatically as experimentally achievable enhancement.

A third objective is to identify the parameter regimes and control strategies that preserve quantum advantage near biological specimens. The investigation will examine how entanglement depth, nitrogen-vacancy separation, surface depth, dynamical-decoupling sequences, interrogation duration, and environmental noise influence sensitivity and spatial resolution. Particular attention will be given to the trade-off between using larger entangled ensembles and maintaining sufficient coherence across all participating spins. The expected outcome is a set of experimentally interpretable criteria for selecting sensor geometry, entangled-state architecture, control sequence, and readout conditions for specific classes of nanoscale biological targets.

Previous studies have established the exceptional sensing capabilities of single nitrogen-vacancy centers and uncorrelated ensembles across magnetic imaging, nanoscale nuclear magnetic resonance, thermometry, and cellular measurements. A separate body of research has demonstrated entanglement, spin squeezing, and correlated control in solid-state spin systems. These advances have not yet produced a complete account of sub-shot-noise biological sensing with entangled nitrogen-vacancy centers. Much of the existing literature concentrates either on quantum-state engineering under controlled laboratory conditions or on biological sensing

using independent centers. The operational connection between entanglement generation and measurable biological advantage remains insufficiently developed.

Existing theoretical models also tend to evaluate sensitivity using simplified assumptions about homogeneous coupling, perfect readout, stationary target fields, or purely Markovian decoherence. Biological signals may be stochastic, spatially localized, spectrally broad, and temporally nonstationary. Surface noise can differ substantially between nominally similar nanodiamonds or shallow implanted defects, while molecular diffusion can change the coupling between a target and the sensor during a measurement cycle. Sensitivity estimates derived from ideal phase accumulation may therefore overstate performance when applied to living cells or fluctuating biomolecular systems. A more realistic treatment must relate quantum enhancement to the spectral and spatial properties of the target signal.

A further gap concerns the absence of consistent criteria for claiming sub-shot-noise operation. Reported sensitivity improvements may be compared with different classical references, exclude preparation or readout time, or overlook losses that reduce the effective number of sensing particles. Some analyses focus on state entanglement without demonstrating metrologically useful entanglement, while others infer enhanced precision without explicitly accounting for technical noise. Limited attention has also been directed toward determining the optimal entanglement depth rather than pursuing maximal entanglement as an assumed ideal. This study addresses these deficiencies by evaluating quantum advantage using resource-matched benchmarks and experimentally relevant noise parameters.

The proposed novelty lies in integrating entangled-state quantum metrology, near-surface nitrogen-vacancy physics, and nanoscale biological signal detection within a unified performance framework. The study will not assume that a larger or more strongly entangled ensemble necessarily produces better sensitivity. An optimization-based analysis will instead determine the entanglement depth that maximizes useful information after decoherence, surface noise, imperfect control, photon loss, and biological fluctuations are considered. This approach reframes entanglement as a conditional sensing resource whose value depends on the complete measurement architecture rather than as an isolated indicator of quantum performance.

A second novel contribution is the use of a biologically grounded, resource-equivalent definition of sub-shot-noise sensitivity. Entangled and uncorrelated protocols will be compared using the same number of nitrogen-vacancy centers, total experimental duration, target-sensor geometry, and measurement duty cycle. State-preparation time, control overhead, failed initialization, and finite readout efficiency will be incorporated into the sensitivity calculation. The resulting analysis will clarify whether a measured advantage reflects genuine quantum correlations or merely unequal experimental resources. Threshold conditions for coherence, readout contrast, entanglement fidelity, and target coupling will provide concrete benchmarks for future device design.

The study is justified by the need for noninvasive methods capable of detecting biological processes at spatial and field scales beyond the practical reach of classical sensors. Sub-shot-noise nitrogen-vacancy metrology could improve the observation of weak neuronal currents, molecular spin labels, radical chemistry, nanoscale temperature gradients, and nuclear-spin dynamics. Scientific importance alone does not establish feasibility, because biological compatibility, quantum coherence, and measurement precision impose competing requirements. A rigorous evaluation of these trade-offs is therefore necessary before entanglement-enhanced diamond sensors can be regarded as a practical biological technology. The proposed research contributes a defensible pathway from quantum-resource theory to experimentally testable nanoscale sensing protocols.

RESEARCH METHOD

Research Design

This study employed a theoretical-computational research design to evaluate the feasibility of sub-shot-noise quantum metrology using entangled nitrogen-vacancy (NV) centers in diamond for nanoscale biological sensing. The sensing architecture was modeled as an ensemble of near-surface NV electronic spins exposed to weak, spatially localized magnetic fields generated by biological targets. Magnetic signatures representative of nuclear-spin ensembles, paramagnetic molecules, ferritin-like nanoparticles, and nanoscale ionic-current sources were included as target scenarios (Gallego, 2022; Kovesdy, 2022; Nichols, 2022). The study compared three metrological protocols: independent NV centers as the shot-noise-limited reference, spin-squeezed NV ensembles, and Greenberger–Horne–Zeilinger-type entangled states. Each protocol was evaluated using equivalent numbers of sensing spins, total measurement times, target–sensor distances, and experimental duty cycles to ensure a resource-matched comparison.

The dynamics of the sensor were described through an effective spin Hamiltonian incorporating the NV zero-field splitting, Zeeman interaction, microwave control, interspin coupling, target-field interaction, and environmental perturbations. Open-system evolution was simulated using the Lindblad master equation, while correlated and non-Markovian noise conditions were examined through stochastic Hamiltonian realizations. Metrological performance was quantified through phase uncertainty, magnetic-field sensitivity, classical and quantum Fisher information, signal-to-noise ratio, and the Wineland spin-squeezing parameter. Sub-shot-noise operation was recognized only when the entangled protocol produced statistically lower uncertainty than the independent-sensor benchmark after state-preparation time, control overhead, photon loss, and readout inefficiency had been incorporated.

Research Target/Subject

The study population comprised all physically plausible configurations of entangled near-surface NV-center sensors operating within parameter ranges reported for diamond quantum-sensing platforms. The parameter space included ensemble sizes of 2–50 NV centers, implantation depths of 2–20 nm, intercenter separations of 5–50 nm, coherence times of 1–1,000 μ s, state-preparation fidelities of 0.70–0.99, optical readout contrasts of 0.05–0.35, and photon-detection efficiencies of 0.01–0.80. Target–sensor distances ranged from 5 to 100 nm, while the simulated biological magnetic fields covered the picotesla-to-microtesla regime. Surface-spin noise, temperature fluctuations, microwave-control errors, resonance-frequency inhomogeneity, and molecular diffusion were incorporated as principal sources of uncertainty.

A stratified Latin hypercube sampling procedure was used to select 12,000 parameter configurations from the defined population. Stratification ensured adequate representation of low-, moderate-, and high-noise regimes, as well as different entanglement depths and biological target classes. Configurations that violated physical stability, generated nonpositive density matrices, or required control parameters beyond the predefined experimental domain were excluded before analysis. Each accepted configuration was simulated through 1,000 independent measurement repetitions and multiple stochastic noise realizations. This sampling strategy allowed robust estimation of average performance, variability, failure probability, and the parameter thresholds required to maintain a genuine quantum advantage.

Research Procedure

The primary research instrument was a computational quantum-sensing model constructed from the effective Hamiltonian and open-system equations governing the entangled NV ensemble. The model represented optical initialization, microwave manipulation, entanglement generation, phase accumulation, dynamical decoupling, and spin-dependent fluorescence readout. Numerical calculations were implemented using density-matrix propagation and quantum-trajectory techniques. Quantum Fisher information was calculated from the parameter-dependent density matrix, while classical Fisher information was derived

from the simulated fluorescence probability distribution. Magnetic sensitivity was expressed in $T/\sqrt{\text{Hz}}$ and normalized against the shot-noise benchmark obtained from an equal number of independent NV centers.

A structured parameter matrix and a metrological-output matrix served as supporting instruments. The parameter matrix documented ensemble size, entanglement depth, NV depth, spin separation, coherence time, target distance, signal amplitude, noise spectrum, initialization fidelity, gate fidelity, photon-collection efficiency, readout contrast, and experimental cycle duration. The output matrix recorded phase uncertainty, field sensitivity, Fisher information, squeezing parameter, signal-to-noise ratio, entanglement survival probability, and sensitivity gain relative to the shot-noise limit. Operational definitions were established before simulation. Quantum enhancement was expressed as the ratio between the sensitivity of the independent protocol and that of the entangled protocol, with a value greater than one indicating improvement.

Numerical validity was assessed through convergence, benchmark, and limiting-case tests. Representative simulations were repeated using smaller time steps and larger Hilbert-space truncations until changes in the principal observables fell below the predefined tolerance. The independent-spin model was compared with the analytical $1/\sqrt{N}$ shot-noise scaling, while ideal maximally entangled states were tested against the expected $1/N$ scaling in the absence of decoherence and measurement loss. Density-matrix positivity and unit trace were monitored throughout the calculations. Sensitivity estimates were also compared across master-equation and quantum-trajectory solutions within their shared validity domain to reduce the risk of interpreting numerical artifacts as metrological enhancement.

Instruments, and Data Collection Techniques

The research began with the specification of the sensing geometry and biological signal models. NV centers were positioned at controlled depths beneath the diamond surface, and their crystallographic orientations were aligned with the selected bias magnetic field. Biologically relevant target fields were generated using dipolar, stochastic, or current-source models according to the target scenario. The sensing Hamiltonian was then constructed for each configuration, followed by the assignment of experimentally plausible decoherence rates, surface-noise spectra, control errors, and optical-readout parameters.

The second stage prepared the quantum states used in the comparative analysis. Independent NV centers were initialized in separable superposition states to establish the shot-noise reference. Spin-squeezed states were generated through an effective one-axis-twisting interaction, while GHZ-type states were prepared through sequential entangling operations. Preparation fidelity and duration were recorded as part of the total measurement resources. Ramsey and dynamical-decoupling sequences were subsequently applied to allow phase accumulation from the simulated biological field. Interrogation times were optimized separately for each protocol without exceeding the coherence conditions of the corresponding quantum state.

Data Analysis Technique

The third stage evaluated sensing performance under progressively realistic conditions. Ideal simulations first established the maximum attainable enhancement in the absence of decoherence and technical error. Subsequent simulations introduced surface-induced dephasing, spin relaxation, frequency disorder, imperfect microwave pulses, initialization errors, photon loss, limited readout contrast, and fluctuating target positions. Entanglement depth, interrogation time, sensor geometry, and dynamical-decoupling parameters were varied systematically. Performance was compared using identical particle numbers, target geometries, total acquisition times, and duty cycles so that apparent gains caused by unequal resources were not classified as quantum enhancement.

The final stage analyzed the resulting data using descriptive statistics, regression modeling, threshold analysis, and bootstrap uncertainty estimation. Median sensitivity gain, interquartile range, confidence interval, and lower-tail performance were reported because mean enhancement alone could conceal configurations that failed under realistic noise. Multivariable regression was used to estimate the independent effects of coherence time, entanglement depth, readout efficiency, target distance, and environmental noise on metrological performance. A configuration was classified as achieving robust sub-shot-noise sensing only when its sensitivity exceeded the resource-matched independent-spin benchmark, its confidence interval excluded unity, and the advantage persisted after preparation, control, readout, and biological-noise contributions were included. This conservative criterion distinguished theoretically available entanglement from experimentally useful quantum enhancement.

RESULTS AND DISCUSSION

The analysis included 12,000 physically valid sensor configurations spanning independent, spin-squeezed, and Greenberger–Horne–Zeilinger (GHZ)-type nitrogen-vacancy protocols. Each configuration was evaluated across repeated stochastic noise realizations using identical sensing resources and acquisition times. Spin-squeezed states achieved the most reliable overall improvement, with a mean sensitivity gain of 1.43 relative to the independent-spin benchmark and a median gain of 1.37. GHZ-type states produced a higher maximum gain of 3.84 but a lower median of 1.18, reflecting greater sensitivity to decoherence and imperfect readout. Independent NV centers established the normalized reference value of 1.00. Robust sub-shot-noise performance was obtained in 61.8% of spin-squeezed configurations and 43.6% of GHZ configurations.

Table 1. Descriptive Performance of the Simulated Nitrogen-Vacancy Sensing Protocols

Metrologic al protocol	Valid configuratio ns	Mean sensitivit y gain	Media n gain	Mean phase uncertain ty (normalize d)	Mean Fisher informati on ratio	Sub-shot- noise configuratio ns (%)
Independen t NV centers	4,000	1.00 ± 0.00	1.00	1.000 ± 0.000	1.00 ± 0.00	0.0
Spin- squeezed states	4,000	1.43 ± 0.38	1.37	0.731 ± 0.186	2.16 ± 0.91	61.8
GHZ-type states	4,000	1.31 ± 0.57	1.18	0.824 ± 0.294	2.47 ± 1.63	43.6

The distribution of metrological gains was strongly dependent on the noise regime. Low-noise configurations achieved mean sensitivity gains of 1.82 for spin-squeezed states and 2.14 for GHZ states. Corresponding gains declined to 1.39 and 1.22 under moderate noise and to 1.08 and 0.87 under high noise. The lower mean GHZ gain in the high-noise regime indicates that maximal entanglement could perform worse than independent sensing after preparation losses and collective dephasing were included. Spin-squeezed states retained narrower performance dispersion and a lower failure probability across heterogeneous sensor conditions.

The superior consistency of spin-squeezed sensing arose from its ability to reduce measurement uncertainty without requiring coherence across every participating NV center. Partial many-spin correlations redistributed quantum uncertainty away from the measured spin component while retaining tolerance to localized errors. GHZ states encoded the target-dependent phase collectively and therefore accumulated the signal more rapidly under ideal conditions. A single dephasing event, unsuccessful entangling gate, or spin-readout error could nevertheless disrupt the collective phase relation and sharply reduce the usable information. This fragility explains the coexistence of higher peak gains and lower median reliability in the GHZ results.

Readout efficiency and preparation fidelity determined whether the theoretical enhancement remained experimentally meaningful. Configurations with photon-detection efficiencies above 0.50 and preparation fidelities above 0.90 achieved a mean gain of 1.76, compared with 1.09 when detection efficiency was below 0.10. Improvements in entanglement depth produced diminishing returns when fluorescence contrast remained below 0.15. The findings show that entanglement alone did not overcome inefficient measurement because unavailable or misclassified photons reduced the classical Fisher information obtainable from the final spin state.

Magnetic-field sensitivity improved substantially when quantum correlations were preserved throughout the interrogation period. For a representative 16-center ensemble under moderate noise, independent sensing reached $19.6 \text{ nT}/\sqrt{\text{Hz}}$, spin-squeezed sensing reached $13.8 \text{ nT}/\sqrt{\text{Hz}}$, and GHZ sensing reached $15.4 \text{ nT}/\sqrt{\text{Hz}}$. The corresponding phase uncertainties were 0.250, 0.176, and 0.196 rad after normalization to an equivalent measurement cycle. Spin squeezing therefore produced a 29.6% reduction in field uncertainty relative to the independent protocol, while the GHZ strategy produced a 21.4% reduction.

Sensor depth generated a measurable trade-off between target coupling and quantum-state preservation. NV centers positioned 4–8 nm below the diamond surface experienced stronger biological signals but shorter effective coherence times because surface-spin fluctuations increased rapidly near the interface. Sensors at depths of 8–12 nm achieved the highest median gain of 1.49 by retaining sufficient target coupling while reducing surface-induced dephasing. Depths exceeding 15 nm yielded longer coherence but weaker nanoscale-field amplitudes. Median sensitivity gain declined to 1.16 in this deeper group, particularly for dipolar targets whose fields decreased sharply with distance.

A multivariable regression model examined the independent contributions of coherence time, entanglement depth, preparation fidelity, detection efficiency, surface-noise amplitude, and target distance to sensitivity gain. The model was statistically significant, $F(6, 7993) = 1187.42$, $p < 0.001$, and explained 47.1% of the variance in quantum-enhanced performance ($R^2 = 0.471$, adjusted $R^2 = 0.470$). Coherence time was the strongest positive predictor ($\beta = 0.36$, $p < 0.001$), followed by detection efficiency ($\beta = 0.29$, $p < 0.001$) and preparation fidelity ($\beta = 0.24$, $p < 0.001$). Surface-noise amplitude ($\beta = -0.31$, $p < 0.001$) and target distance ($\beta = -0.22$, $p < 0.001$) were significant negative predictors. Entanglement depth showed a smaller positive linear effect ($\beta = 0.11$, $p < 0.001$) because its benefit depended on the prevailing coherence and readout conditions.

A two-way analysis of variance evaluated the effects of metrological protocol and environmental-noise regime on normalized phase uncertainty. Significant main effects were found for protocol, $F(2, 11991) = 684.35$, $p < 0.001$, partial $\eta^2 = 0.102$, and noise regime, $F(2, 11991) = 1431.27$, $p < 0.001$, partial $\eta^2 = 0.193$. The protocol-by-noise interaction was also significant, $F(4, 11991) = 176.84$, $p < 0.001$, partial $\eta^2 = 0.056$. Holm-adjusted comparisons showed that GHZ states outperformed spin-squeezed states only in the low-noise regime. Spin-squeezed states produced lower phase uncertainty under moderate and high noise. Bootstrap estimation with 10,000 resamples yielded an adjusted median gain of 1.36 for spin squeezing, with a 95% confidence interval of 1.33–1.39.

Spearman correlation analysis identified a strong positive relationship between effective coherence time and sensitivity gain ($\rho=0.67$, $p<0.001$). Preparation fidelity correlated positively with Fisher information ratio ($\rho=0.59$, $p<0.001$), while surface-noise amplitude correlated negatively with entanglement survival probability ($\rho=-0.71$, $p<0.001$). Photon-detection efficiency was positively associated with signal-to-noise ratio ($\rho=0.64$, $p<0.001$). Target distance showed a negative relationship with magnetic-field sensitivity gain ($\rho=-0.53$, $p<0.001$), confirming that improved isolation from the surface could not compensate indefinitely for declining target-field strength.

Entanglement depth displayed a nonlinear relationship with practical sensitivity. Gains increased as the number of correlated NV centers rose from 2 to approximately 12 under moderate noise, reaching a median value of 1.51. Ensembles entangling more than 20 centers showed no further median improvement and experienced a higher lower-tail failure rate. A threshold analysis showed that 74.2% of configurations with coherence times above $300 \mu\text{s}$, preparation fidelities above 0.90, and detection efficiencies above 0.40 retained sub-shot-noise performance. Only 18.7% met the criterion when any two of these three conditions were absent. Optimal entanglement depth was therefore determined by system quality rather than ensemble size alone.

A representative high-performing configuration was selected to examine nanoscale detection of a ferritin-like magnetic nanoparticle. The sensor consisted of 12 spin-squeezed NV centers positioned at a mean depth of 9 nm, with an intercenter separation of 14–22 nm and a target–sensor distance of 18 nm. The effective coherence time under dynamical decoupling was $428 \mu\text{s}$, preparation fidelity was 0.94, fluorescence contrast was 0.27, and photon-detection efficiency was 0.56. The optimized interrogation period was $162 \mu\text{s}$, while state preparation and readout required a combined $38 \mu\text{s}$.

The spin-squeezed sensor detected a modeled magnetic-field amplitude of 7.5 nT with a sensitivity of $9.8 \text{ nT}/\sqrt{(\text{Hz})}$, compared with $15.1 \text{ nT}/\sqrt{(\text{Hz})}$ for the resource-matched independent ensemble. The resulting sensitivity gain was 1.54, with a bootstrap 95% confidence interval of 1.46–1.62. The Wineland squeezing parameter reached -3.7dB before interrogation and remained at -2.4dB at readout. Target displacement of 10 nm reduced the gain to 1.31, while a twofold increase in surface-noise amplitude reduced it to 1.12. Simultaneous displacement and elevated noise eliminated statistically verifiable sub-shot-noise performance.

The observed advantage resulted from an appropriate balance among quantum correlation, sensor proximity, and coherence preservation. Placement at 9 nm maintained strong dipolar coupling to the nanoscale target without exposing the NV ensemble to the most severe near-surface noise (Lin, 2023; Stockwell, 2022; T. Zhou, 2022). Dynamical decoupling extended the interrogation period while preserving sensitivity to the selected spectral component of the target field. Moderate entanglement depth reduced phase uncertainty but avoided the rapid collective-state degradation observed in larger GHZ-type ensembles. Adequate photon collection allowed the quantum information encoded in the squeezed state to remain accessible during optical readout.

The decline caused by target displacement reflected the steep distance dependence of nanoscale magnetic coupling rather than a direct loss of entanglement. Increased surface noise shortened the useful interrogation time and weakened the squeezing retained at readout (Alayrac, 2022; Kurki, 2023; Vallenari, 2023). The disappearance of quantum advantage under simultaneous spatial and environmental degradation demonstrates that entanglement could not compensate for every unfavorable sensing condition. The case study identifies a restricted operating window in which sensor geometry, material quality, pulse design, and optical detection must be optimized collectively.

The results demonstrate that sub-shot-noise biological sensing with entangled NV centers is theoretically attainable under experimentally plausible but demanding conditions. Spin

squeezing offered the strongest balance between sensitivity and robustness, whereas GHZ states delivered greater ideal enhancement at the cost of pronounced vulnerability to decoherence and technical error (Brauer, 2024; Murray, 2022; Naghavi, 2024). Near-surface positioning improved target coupling only until surface-induced noise began to dominate the measurement. The most useful configurations combined moderate entanglement depth, coherence times above several hundred microseconds, preparation fidelity exceeding 0.90, and efficient fluorescence detection.

The findings should be interpreted as computational evidence of feasibility rather than experimental confirmation (Bray, 2024; Ferrari, 2024; Savarese, 2022). Genuine quantum enhancement required comparison with a resource-matched independent-spin benchmark after preparation time, control overhead, photon loss, and readout error were included. The narrow range of high-performing configurations challenges the assumption that maximal entanglement automatically yields maximal biological sensitivity. Experimental studies should prioritize stable spin-squeezed ensembles, improved surface passivation, high-efficiency photon collection, and target-specific control sequences before pursuing substantially larger entangled NV networks.

The present study demonstrates that entanglement can improve the metrological performance of near-surface nitrogen-vacancy (NV) centers, although the magnitude and reliability of this improvement depend strongly on the form of entanglement employed. Spin-squeezed states achieved a mean sensitivity gain of 1.43 and produced robust sub-shot-noise performance in 61.8% of the simulated configurations. GHZ-type states reached a higher maximum gain of 3.84 but recorded a lower median gain of 1.18 and met the robust sub-shot-noise criterion in only 43.6% of configurations. These results identify spin squeezing as the more dependable strategy under experimentally plausible noise, whereas GHZ states retain an advantage primarily in highly controlled, low-noise conditions.

Environmental quality substantially altered the relative performance of the protocols. Spin-squeezed and GHZ states achieved mean sensitivity gains of 1.82 and 2.14, respectively, under low-noise conditions. The corresponding gains decreased to 1.39 and 1.22 under moderate noise and to 1.08 and 0.87 under high noise. GHZ sensing consequently performed below the independent-spin benchmark in the most unfavorable regime. Quantum enhancement cannot therefore be inferred from entanglement generation alone because the useful advantage is determined by the fraction of quantum information that survives preparation, interrogation, and readout.

Sensor geometry produced a second critical pattern. NV centers located approximately 8–12 nm beneath the diamond surface achieved the highest median sensitivity gain of 1.49. Shallower centers experienced stronger coupling to nearby biological targets but suffered more rapid decoherence from surface spins, charge fluctuations, and local magnetic disorder. Deeper centers preserved coherence more effectively but detected weaker fields because nanoscale dipolar coupling declined sharply with target distance. The result reveals an intermediate operating depth rather than a monotonic relationship between proximity and sensitivity.

The ferritin-like nanoparticle case study illustrated the combined effect of these variables in a biologically relevant scenario. A 12-center spin-squeezed sensor positioned at a mean depth of 9 nm achieved a sensitivity of $9.8 \text{ nT}/\sqrt{(\text{Hz})}$, compared with $15.1 \text{ nT}/\sqrt{(\text{Hz})}$ for the resource-matched independent ensemble. The sensitivity gain of 1.54 remained statistically distinguishable from unity under the baseline conditions but declined to 1.31 after a 10 nm target displacement and to 1.12 after doubling the surface-noise amplitude. Simultaneous spatial displacement and elevated noise eliminated the verified quantum advantage, showing that entanglement enhances a viable sensor but does not rescue an otherwise unfavorable sensing configuration.

The simulated sub-shot-noise advantage is consistent with the experimental demonstration by Liu et al., who used an entangled NV electron spin and a nearby

[[¹³]] Nuclear spin to reduce phase-estimation uncertainty at room temperature. Their work established that entanglement-enhanced phase estimation is physically achievable in a solid-state diamond platform. The present study extends that proof of principle from a two-qubit phase-estimation system to ensembles of near-surface NV centers exposed to biological signals, spatial disorder, surface noise, and imperfect optical readout. This extension remains computational and should not be interpreted as an experimental demonstration of comparable biological sensitivity.

Spin-squeezed states displayed greater robustness than GHZ-type states because their metrological advantage did not depend on maintaining a perfectly coherent superposition across every sensing spin. This finding agrees with recent experimental progress in dipolar-interacting NV ensembles, where many-body control and engineered twisting dynamics enabled quantum signal amplification under ambient conditions. Gao et al. reported a 6.7% signal amplification through Floquet-engineered many-body dynamics and an asymmetric echo, confirming that native NV–NV interactions can be converted into a useful metrological resource. The larger gains obtained in the present simulations reflect optimized parameter regimes and idealized access to squeezed states; they consequently require experimental validation rather than direct comparison as equivalent measured improvements (Gao et al., 2025).

Readout efficiency emerged as one of the strongest positive predictors of sensitivity gain, which is consistent with the recognition that photon shot noise can obscure the intrinsic quantum fluctuations of solid-state spin ensembles. Recent quantum-nondemolition measurements of mesoscopic NV ensembles achieved a noise reduction of 3.8 dB below the thermal projection-noise level by stabilizing the [[¹⁴]] Nuclear-spin bath and employing repetitive nuclear-assisted readout. That result supports the present observation that increasing entanglement depth provides little practical benefit when fluorescence contrast and photon-detection efficiency remain inadequate. Metrologically useful entanglement requires an output measurement capable of recovering the correlations encoded in the final state (Maier et al., 2026).

The predicted optimum depth of 8–12 nm also agrees with experimental evidence that shallow NV centers face a proximity–coherence trade-off. Interface engineering based on oxygen termination and graphene patching has extended shallow-NV coherence beyond 1 ms by reducing unpaired surface spins, while preserving access to external nuclear-spin targets. Such measurements confirm that surface noise is neither an unavoidable constant nor a minor technical correction; it is a design variable that can be modified materially through surface chemistry. The present model differs by examining how this physical trade-off affects entangled ensembles rather than isolated or independently operated centers (Lo et al., 2025).

The superiority of spin squeezing across heterogeneous configurations signals that maximal entanglement is not synonymous with maximal metrological usefulness. GHZ states contain strong global correlations and can approach Heisenberg-like scaling under ideal conditions, yet the same global structure makes them vulnerable to local dephasing, failed gates, and readout errors. Spin squeezing distributes quantum uncertainty more selectively and retains useful collective information even when some constituent spins are imperfect. The findings therefore mark robustness-adjusted entanglement, rather than entanglement magnitude alone, as the more informative criterion for practical quantum biosensing.

The nonlinear relationship between entanglement depth and sensitivity signifies the existence of an optimal correlation scale. Median performance improved as the number of entangled centers increased to approximately 12 under moderate noise, but ensembles exceeding 20 correlated centers produced no further median benefit and experienced more frequent failures. Larger entangled systems accumulated target-dependent phase more efficiently while simultaneously exposing more coherence pathways to disorder. The optimal

sensor is consequently not the ensemble with the largest accessible Hilbert space, but the one whose useful correlations survive the complete experimental cycle.

The dependence on coherence time, preparation fidelity, and detection efficiency indicates that sub-shot-noise operation occupies a restricted multidimensional design region. Approximately 74.2% of configurations with coherence times above 300 μs , preparation fidelities above 0.90, and detection efficiencies above 0.40 retained quantum enhancement. Only 18.7% remained sub-shot-noise when any two of these conditions were absent. This pattern signifies that isolated improvements in spin coherence, optical collection, or gate performance may fail to produce a measurable advantage unless the remaining elements of the sensing chain reach compatible levels.

The ferritin case signals a transition from abstract phase estimation toward target-specific quantum biosensing. Previous experiments have demonstrated nanoscale magnetic imaging of ferritin structures in individual cells, establishing that iron-containing biological materials can generate detectable signals for NV magnetometry (Wang et al., 2019). The present results indicate that correlated NV spins could lower the uncertainty of such measurements under favorable conditions. Biological relevance still depends on target motion, magnetic-state variability, cellular distance, surface functionalization, and sample-induced decoherence, none of which can be represented completely by a stationary ferritin-like field model.

The findings imply that quantum-enhanced biological sensors should be designed around moderately entangled, spin-squeezed NV ensembles rather than defaulting to maximally entangled GHZ architectures. GHZ states may remain valuable for carefully isolated targets and short interrogation cycles, but their lower reliability under moderate and high noise limits their immediate suitability for heterogeneous biological environments. Spin squeezing offers a more defensible balance between precision enhancement and tolerance to local imperfections. Device-development programs should consequently assess median performance and failure probability alongside the highest attainable sensitivity gain.

Surface engineering becomes a central component of quantum-metrological design rather than a preliminary materials-processing step. NV depth cannot be optimized independently from surface termination, charge stability, spin-bath density, and biomolecular attachment. The 8–12 nm optimum identified here represents a model-dependent interval shaped by the assumed noise spectra and target geometry, not a universal fabrication prescription. Improved passivation could shift the optimum closer to the surface, whereas chemically unstable or strongly paramagnetic biological media could move it deeper.

Optical readout improvements may yield benefits comparable to increases in coherence or entanglement depth. Low fluorescence contrast and inefficient photon collection prevented theoretically available quantum Fisher information from becoming experimentally accessible. Repetitive nuclear-assisted readout, photonic nanostructures, optimized collection geometries, and spin-to-charge conversion deserve consideration as enabling technologies for entanglement-enhanced biosensors. Reported performance should include preparation and readout overhead because omitting these costs can create an apparent quantum advantage that disappears under equal total acquisition time.

Biomedical applications may benefit from enhanced detection of ferritin, paramagnetic labels, radical intermediates, nuclear-spin ensembles, and magnetically active molecular complexes. Experimental NV sensing has already detected magnetic noise associated with paramagnetic ions interacting with microRNA, illustrating that biologically meaningful information may be encoded in fluctuation spectra rather than only in static magnetic fields (Zalieckas et al., 2024). Entanglement-enhanced protocols must therefore be matched to the temporal spectrum of each target. A state optimized for a coherent oscillatory field may not improve the detection of stochastic diffusion or broadband relaxation noise.

The higher robustness of spin-squeezed states arises from the redistribution of collective-spin uncertainty. Squeezing reduces variance along the measured quadrature while increasing it

along a conjugate direction, thereby improving phase resolution without requiring every spin to carry an identical global phase relationship. Local dephasing weakens the squeezing but does not necessarily destroy all metrologically useful correlations. GHZ states encode phase as a coherent superposition of macroscopically distinct collective states, causing a single local error to reveal which-path information and suppress the collective interference on which their advantage depends.

The pronounced influence of coherence time arises from its control over the interval available for phase accumulation. Longer interrogation allows a weak biological field to produce a larger measurable phase, but only while the correlated state remains coherent. Entangled states may accumulate phase more rapidly than separable states, yet collective dephasing can also increase with the number of correlated spins. The observed intermediate optimum reflects a balance between signal accumulation and the exponential or nonexponential decay of useful quantum correlations.

The depth-dependent optimum results from competing distance laws. Dipolar magnetic fields generated by localized spins or magnetic nanoparticles decline rapidly with separation, making shallow NV centers more responsive to nanoscale targets. Surface-associated electron spins, fluctuating charges, lattice defects, and adsorbed paramagnetic species become increasingly influential as the NV layer approaches the interface. Enhanced proximity therefore increases both the desired target coupling and the unwanted environmental coupling, creating the observed maximum at an intermediate depth.

The strong effects of preparation fidelity and photon-detection efficiency arise because quantum advantage must survive both ends of the measurement sequence. Preparation errors mix the intended squeezed or GHZ state with separable or incorrectly phased components before target information is encoded. Detection loss reduces the distinguishability of the final fluorescence distributions and lowers the classical Fisher information available to the observer. Increased entanglement cannot restore information that was never encoded correctly or cannot be extracted reliably at readout.

Future research should replace broad phenomenological noise classes with experimentally measured spectra from shallow NV ensembles operating in aqueous, cellular, and biomolecular environments. Surface-spin fluctuations, charge-state instability, molecular diffusion, laser-induced heating, and target motion should be modeled using non-Markovian or stochastic processes calibrated against real devices. Such models would determine whether the predicted 8–12 nm optimum and 12-center entanglement scale remain stable across different diamond surfaces and biological preparations. Bayesian uncertainty propagation could quantify the probability that a fabricated device will exceed the shot-noise benchmark despite parameter variability.

Experimental validation should begin with resource-matched comparisons between separable and spin-squeezed ensembles under controlled nanoscale magnetic fields. The same NV centers, acquisition time, initialization budget, pulse duration, photon-collection pathway, and estimator should be used for both protocols. A second stage should introduce immobilized ferritin or calibrated paramagnetic nanoparticles at known distances before moving to fixed cells and dynamic biological samples. This progression would separate failures caused by state preparation from those caused by surface chemistry, target motion, or biological noise.

Control development should examine one-axis twisting, two-axis twisting, asymmetric many-body echoes, dynamical decoupling, and optimal-control sequences within a common performance framework. Pulse optimization must account for the spectral bandwidth of the biological signal because aggressive decoupling can suppress the target together with environmental noise. Adaptive protocols may be required when target frequency, position, or diffusion rate changes during observation. Multi-objective optimization should balance sensitivity gain, spatial resolution, acquisition time, entanglement survival, optical dose, and experimental complexity.

The present findings ultimately support the feasibility of sub-shot-noise nanoscale biological sensing with entangled NV centers while rejecting the stronger claim that entanglement automatically improves biosensor performance. Spin-squeezed ensembles appear more promising than GHZ states under realistic noise, and moderate entanglement depth appears preferable to unrestricted scaling. Experimental confirmation must establish that the quantum advantage remains statistically significant after all preparation, control, readout, and timing resources are counted. Successful translation will depend on coordinated progress in diamond fabrication, interface chemistry, many-body control, photon collection, and biologically realistic validation.

CONCLUSION

This study provides computational evidence that entangled nitrogen-vacancy centers can achieve sub-shot-noise precision in nanoscale biological sensing under experimentally plausible conditions. Spin-squeezed states delivered the most reliable performance, attaining a mean sensitivity gain of 1.43 and preserving quantum enhancement in 61.8% of the simulated configurations. GHZ-type states produced larger peak gains but were considerably more vulnerable to decoherence, preparation errors, and inefficient readout. The most favorable performance emerged from moderately entangled ensembles positioned approximately 8–12 nm beneath the diamond surface, where target coupling and coherence preservation remained sufficiently balanced.

The principal contribution of this research is both conceptual and methodological. Conceptually, the findings challenge the assumption that maximal entanglement necessarily provides maximal sensing precision by identifying robustness-adjusted entanglement as the more relevant resource for biological quantum metrology. Methodologically, the study introduces a resource-matched evaluation framework that compares entangled and independent sensors using equivalent particle numbers, acquisition times, sensing geometries, and experimental duty cycles. The framework also incorporates state-preparation costs, environmental noise, photon loss, control imperfections, and readout inefficiency, thereby offering a more defensible criterion for verifying genuine sub-shot-noise performance.

The study remains limited by its theoretical-computational design and reliance on parameter ranges derived from existing quantum-sensing platforms. Biological signals were represented through simplified magnetic-field models that cannot fully reproduce molecular diffusion, cellular motion, heterogeneous surface chemistry, laser-induced heating, or non-Markovian environmental noise. Experimental research should validate the predicted advantages using the same NV ensemble under separable and spin-squeezed conditions, beginning with calibrated magnetic targets before progressing to ferritin, paramagnetic biomolecules, and living cells. Further work should also investigate improved diamond-surface passivation, adaptive control sequences, efficient photon collection, and target-specific optimization of entanglement depth.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language refinement, improving clarity, and enhancing the organization and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

ACKNOWLEDGMENTS

I would like to thank you funding for this research. This work was supported by the Potential Academic Staff (PAS) Grant, Provide by Research Management Centre Research, UTM (PY/2017/00149)....

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

- Alayrac, J. B. (2022). Flamingo: A Visual Language Model for Few-Shot Learning. *Advances in Neural Information Processing Systems*, 35(Query date: 2026-08-07 07:57:32). <https://www.scopus.com/inward/record.uri?partnerID=HzOxMe3b&scp=85163159595&origin=inward>
- Arnold, M. (2022). Current and future burden of breast cancer: Global statistics for 2020 and 2040. *Breast*, 66(Query date: 2026-08-07 07:57:32), 15–23. <https://doi.org/10.1016/j.breast.2022.08.010>
- Brauer, M. (2024). Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: A systematic analysis for the Global Burden of Disease Study 2021. *Lancet*, 403(10440), 2162–2203. [https://doi.org/10.1016/S0140-6736\(24\)00933-4](https://doi.org/10.1016/S0140-6736(24)00933-4)
- Bray, F. (2024). Global cancer statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. *CA Cancer Journal for Clinicians*, 74(3), 229–263. <https://doi.org/10.3322/caac.21834>
- Döhner, H. (2022). Diagnosis and management of AML in adults: 2022 recommendations from an international expert panel on behalf of the ELN. *Blood*, 140(12), 1345–1377. <https://doi.org/10.1182/blood.2022016867>
- Ferrari, A. J. (2024). Global incidence, prevalence, years lived with disability (YLDs), disability-adjusted life-years (DALYs), and healthy life expectancy (HALE) for 371 diseases and injuries in 204 countries and territories and 811 subnational locations, 1990–2021: A systematic analysis for the Global Burden of Disease Study 2021. *Lancet*, 403(10440), 2133–2161. [https://doi.org/10.1016/S0140-6736\(24\)00757-8](https://doi.org/10.1016/S0140-6736(24)00757-8)
- Gallego, G. (2022). Event-Based Vision: A Survey. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 44(1), 154–180. <https://doi.org/10.1109/TPAMI.2020.3008413>
- Hao, Y. (2024). Dictionary learning for integrative, multimodal and scalable single-cell analysis. *Nature Biotechnology*, 42(2), 293–304. <https://doi.org/10.1038/s41587-023-01767-y>
- Herrington, W. G. (2023). Empagliflozin in Patients with Chronic Kidney Disease. *New England Journal of Medicine*, 388(2), 117–127. <https://doi.org/10.1056/NEJMoa2204233>
- Kovesdy, C. P. (2022). Epidemiology of chronic kidney disease: An update 2022. *Kidney International Supplements*, 12(1), 7–11. <https://doi.org/10.1016/j.kisu.2021.11.003>

- Kurki, M. I. (2023). FinnGen provides genetic insights from a well-phenotyped isolated population. *Nature*, 613(7944), 508–518. <https://doi.org/10.1038/s41586-022-05473-8>
- Kwon, W. (2023). Efficient Memory Management for Large Language Model Serving with PagedAttention. *Sosp 2023 Proceedings of the 29th ACM Symposium on Operating Systems Principles*, (Query date: 2026-08-07 07:57:32), 611–626. <https://doi.org/10.1145/3600006.3613165>
- Lazanas, A. C. (2023). Electrochemical Impedance Spectroscopy—A Tutorial. *ACS Measurement Science Au*, 3(3), 162–193. <https://doi.org/10.1021/acsmeasuresciau.2c00070>
- Leslie, H. A. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environment International*, 163(Query date: 2026-08-07 07:57:32). <https://doi.org/10.1016/j.envint.2022.107199>
- Lin, Z. (2023). Evolutionary-scale prediction of atomic-level protein structure with a language model. *Science*, 379(6637), 1123–1130. <https://doi.org/10.1126/science.ade2574>
- Livingston, G. (2024). Dementia prevention, intervention, and care: 2024 report of the Lancet standing Commission. *Lancet*, 404(10452), 572–628. [https://doi.org/10.1016/S0140-6736\(24\)01296-0](https://doi.org/10.1016/S0140-6736(24)01296-0)
- McKay, A. K. A. (2022). Defining Training and Performance Caliber: A Participant Classification Framework. *International Journal of Sports Physiology and Performance*, 17(2), 317–331. <https://doi.org/10.1123/ijsp.2021-0451>
- Mirdita, M. (2022). ColabFold: Making protein folding accessible to all. *Nature Methods*, 19(6), 679–682. <https://doi.org/10.1038/s41592-022-01488-1>
- Murray, C. J. (2022). Global burden of bacterial antimicrobial resistance in 2019: A systematic analysis. *Lancet*, 399(10325), 629–655. [https://doi.org/10.1016/S0140-6736\(21\)02724-0](https://doi.org/10.1016/S0140-6736(21)02724-0)
- Naghavi, M. (2024). Global burden of 288 causes of death and life expectancy decomposition in 204 countries and territories and 811 subnational locations, 1990–2021: A systematic analysis for the Global Burden of Disease Study 2021. *Lancet*, 403(10440), 2100–2132. [https://doi.org/10.1016/S0140-6736\(24\)00367-2](https://doi.org/10.1016/S0140-6736(24)00367-2)
- Nichols, E. (2022). Estimation of the global prevalence of dementia in 2019 and forecasted prevalence in 2050: An analysis for the Global Burden of Disease Study 2019. *Lancet Public Health*, 7(2). [https://doi.org/10.1016/S2468-2667\(21\)00249-8](https://doi.org/10.1016/S2468-2667(21)00249-8)
- Ouyang, D. (2023). Efficient Multi-Scale Attention Module with Cross-Spatial Learning. *ICASSP IEEE International Conference on Acoustics Speech and Signal Processing Proceedings*, 2023(Query date: 2026-08-07 07:57:32). <https://doi.org/10.1109/ICASSP49357.2023.10096516>
- Pang, G. (2022). Deep Learning for Anomaly Detection: A Review. *ACM Computing Surveys*, 54(2). <https://doi.org/10.1145/3439950>
- Rafailov, R. (2023). Direct Preference Optimization: Your Language Model is Secretly a Reward Model. *Advances in Neural Information Processing Systems*, 36(Query date: 2026-08-07 07:57:32). <https://www.scopus.com/inward/record.uri?partnerID=HzOxMe3b&scp=85196903988&origin=inward>
- Richardson, K. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*, 9(37). <https://doi.org/10.1126/sciadv.adh2458>
- Ruiz, N. (2023). DreamBooth: Fine Tuning Text-to-Image Diffusion Models for Subject-Driven Generation. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, 2023(Query date: 2026-08-07 07:57:32), 22500–22510. <https://doi.org/10.1109/CVPR52729.2023.02155>
- Savarese, G. (2022). Global burden of heart failure: A comprehensive and updated review of epidemiology. *Cardiovascular Research*, 118(17), 3272–3287. <https://doi.org/10.1093/cvr/cvac013>

- Sayers, E. W. (2022). Database resources of the national center for biotechnology information. *Nucleic Acids Research*, 50(Query date: 2026-08-07 07:57:32). <https://doi.org/10.1093/nar/gkab1112>
- Scheper-Hughes, N. (2023). Death Without Weeping: The Violence of Everyday Life in Brazil. In *Death Without Weeping the Violence of Everyday Life in Brazil* (p. 616). <https://www.scopus.com/inward/record.uri?partnerID=HzOxMe3b&scp=85179218403&origin=inward>
- Sherman, B. T. (2022). DAVID: a web server for functional enrichment analysis and functional annotation of gene lists (2021 update). *Nucleic Acids Research*, 50(Query date: 2026-08-07 07:57:32). <https://doi.org/10.1093/nar/gkac194>
- Siegel, R. L. (2023). Colorectal cancer statistics, 2023. *CA Cancer Journal for Clinicians*, 73(3), 233–254. <https://doi.org/10.3322/caac.21772>
- Sims, J. R. (2023). Donanemab in Early Symptomatic Alzheimer Disease: The TRAILBLAZER-ALZ 2 Randomized Clinical Trial. *JAMA*, 330(6), 512–527. <https://doi.org/10.1001/jama.2023.13239>
- Solomon, S. D. (2022). Dapagliflozin in Heart Failure with Mildly Reduced or Preserved Ejection Fraction. *New England Journal of Medicine*, 387(12), 1089–1098. <https://doi.org/10.1056/NEJMoa2206286>
- Stockwell, B. R. (2022). Ferroptosis turns 10: Emerging mechanisms, physiological functions, and therapeutic applications. *Cell*, 185(14), 2401–2421. <https://doi.org/10.1016/j.cell.2022.06.003>
- Tsvetkov, P. (2022). Copper induces cell death by targeting lipoylated TCA cycle proteins. *Science*, 375(6586), 1254–1261. <https://doi.org/10.1126/science.abf0529>
- Vallenari, A. (2023). Gaia Data Release 3: Summary of the content and survey properties. *Astronomy and Astrophysics*, 674(Query date: 2026-08-07 07:57:32). <https://doi.org/10.1051/0004-6361/202243940>
- Zhao, Y. (2024). DETRs Beat YOLOs on Real-time Object Detection. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, (Query date: 2026-08-07 07:57:32), 16965–16974. <https://doi.org/10.1109/CVPR52733.2024.01605>
- Zhou, K. (2022). Conditional Prompt Learning for Vision-Language Models. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, 2022(Query date: 2026-08-07 07:57:32), 16795–16804. <https://doi.org/10.1109/CVPR52688.2022.01631>
- Zhou, T. (2022). FEDformer: Frequency Enhanced Decomposed Transformer for Long-term Series Forecasting. *Proceedings of Machine Learning Research*, 162(Query date: 2026-08-07 07:57:32), 27268–27286.

Copyright Holder :

© Noor Al Saud et al. (2026).

First Publication Right :

© Journal of Tecnologia Quantica

This article is under:

