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Review Article

Quantum-Inspired Nano Biotechnology: Wave–Particle Duality in *In Vitro* and *In Vivo* Bioassays

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Abstract

Quantum-inspired nanobiotechnology re-conceptualizes conventional bioassays by utilizing the waveparticle duality in quantum physics. Rather than considering photons, electrons or excitations strictly as wave or particle, the aim is to develop assays that exploit both aspects of their duality for ultra-sensitive, specific and informative bioassay designs. Wave-oriented assays utilize interference and coherence to amplify signals from a single molecule, particle-centric assays quantitatively count discrete events, such as an electron tunnelling through a nanopore, or photons emitted from a quantum dot; and correlation-centric assays exploit entanglement and quantum correlations to surpass classical noise thresholds. In total, these forms of bioassays provide powerful designs for *In Vitro* diagnostics, live-cell imaging and translational medicine. In this narrative review, we provide an overview of wave-centric, particle-centric, and correlation-centric bioassays, clarify their advantages and disadvantages, and point out the potential to merge and expand with artificial intelligence (AI), hybrid nanodevices that incorporate nanobiotechnologies, and nanotheranostics. We also cover health and safety, biocompatibility, ethical, and regulatory considerations that need to be considered in order to transition quantum-inspired bioassays from the lab to the clinic. Ultimately, we will suggest a roadmap for the next decade of this rapidly developing field.

Keywords: Quantum-inspired nanobiotechnology, wave-particle duality, bioassays, nanotheranostics, artificial intelligence (AI).

Introduction

Modern diagnostics demand trace-level detection, real-time cellular readouts, and multiplexed profiling with minimal perturbation. Classical optical/electrochemical methods often hit sensitivity and stability ceilings; quantum-inspired designs borrow selected quantum principles without requiring fully coherent processors. The central idea is wave–particle duality: interference and coherence (wave) can amplify tiny signals and cancel noise, while quantization (particle) yields digital events resilient to analogue drift; non-classical correlations can suppress shot noise and improve limits of detection (e.g., squeezing/entanglement) [1]. Practically, this spans interferometric scattering microscopy for label-free single-particle tracking (including viruses)[2, 3], nanoplasmonic sensors for rapid, multiplexed, point-of-care-ready assays, nanopore platforms for portable long-read sequencing, digital ELISA for attomolar proteins, and quantum-enhanced imaging that beats classical noise floors. Throughout, we treat "quantum-inspired" as performance-oriented engineering: using interference, confinement, tunnelling, and correlation effects within robust, mostly classical devices to improve SNR, specificity, and quantitation. We also emphasize translation: microfluidic integration to shrink workflows; AI/ML to denoise, classify, and control instruments in real time; and biocompatible materials to bridge *In Vitro* chips and *In Vivo* imaging. The remainder of this review maps the three regimes (wave, particle, correlation), examines hybrid intersections, and consolidates challenges stability, fabrication uniformity, safety/biocompatibility, and regulatory/ethical considerations before outlining a near-term roadmap to clinical adoption.

Scope of This Review

This narrative review focuses on three regimes of quantum-inspired nanobiotechnology: [1] wave-dominated assays that use interference, coherence and plasmonics, [2] particle-dominated assays that exploit quantization, tunnelling and discrete detection, and [3] correlation-enabled assays that harness entanglement or squeezing. For each regime we discuss theoretical foundations, key technologies, *In Vitro* and *In Vivo* applications, limitations, and integration with AI and hybrid nanodevices. We highlight emerging nanotheranostics that combine diagnosis and therapy in a single platform, and we address technical, ethical and regulatory challenges. Tables and figures summarize assay classes, workflows and translational pathways, although actual figures are not reproduced here. Figure 1 synthesizes the three operating regimes discussed in this review wave-dominated, particle-dominated, and correlation-enabled together with hybrid designs that sit at their intersections.

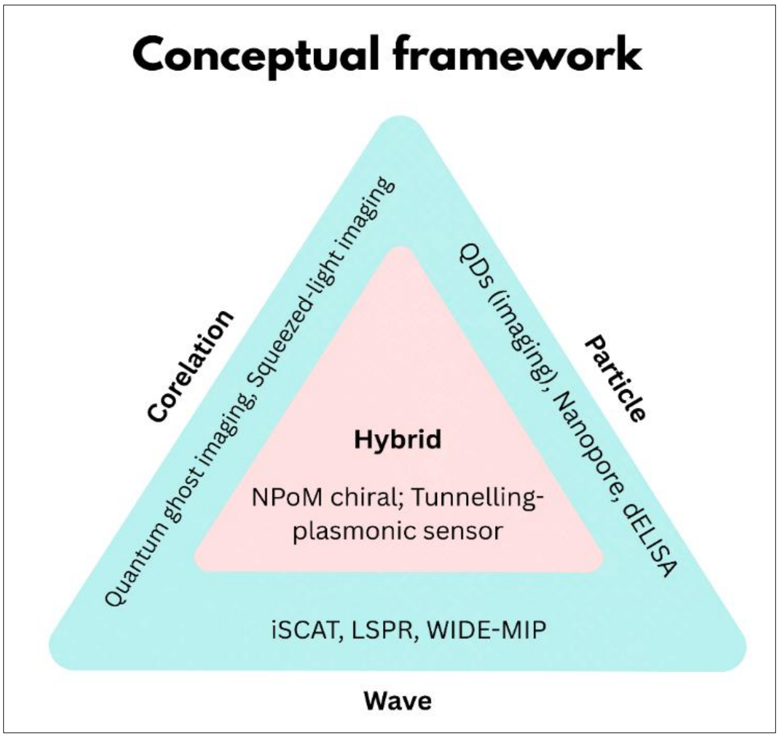

Figure 1: Conceptual framework for quantum-inspired bioassays. An equilateral map locates three regimes Wave, Particle, Correlation with a smaller inner triangle denoting Hybrid approaches. Exemplars are placed near their regimes: Wave: iSCAT, LSPR, WIDE-MIP; Particle: QDs (imaging), Nanopore, dELISA; Correlation: Quantum ghost imaging, Squeezed-light imaging (4) Hybrid: NPoM chiral sensor, tunnelling-plasmonic sensor

Conceptual Foundation: Wave–Particle Duality in Nanobiotechnology

At the nanoscale, light and matter exhibit wave phenomena interference, diffraction, and coherence that can amplify weak biosignals and encode spatial detail. Plasmonic nanostructures sustain coherent electron oscillations that create intense near fields, boosting scattering/absorption from nearby biomolecules; this underpins fast, label-free nano-plasmonic sensing [5]. Interferometric scattering microscopy (iSCAT) combines scattered and reference fields to reveal unlabeled nanoscale objects with high spatial–temporal fidelity [2]. These wave-dominated approaches excel when signal amplification, background suppression, and label-free operation are paramount, while remaining sensitive to phase stability and optical noise.

In the particle-dominated picture, energy and charge appear as discrete quanta enabling tunnelling, single-photon emission, and digital counting. Nanopores read single DNA/RNA molecules as transient, base-specific current modulations, delivering portable, long-read sequencing; biological pores (e.g., α-hemolysin, MspA) and enzymes such as phi29 polymerase regulate translocation for improved SNR, exemplified by Oxford Nanopore's MinION deployments in infectious-disease surveillance. Quantum dots (QDs) provide size-tunable, photostable emission for multiplexed imaging; surface functionalization enables targeting, while ZnS shells or cadmium-free cores (e.g., InP) address biocompatibility[6].

Correlation-enabled regimes exploit quantum correlations to surpass classical noise floors. Entanglement and squeezing redistribute uncertainty to achieve sub-shot-noise performance, and ghost imaging reconstructs objects by correlating detections from photon pairs even when only one beam interacts with the sample useful for low-light, low-photodamage bioimaging [7]. Hybrids (e.g., nanoparticle-on-mirror gaps operating near the tunnelling limit) straddle wave and particle behaviors, enabling single-molecule chiral sensing while demanding reproducible nanofabrication.

Historically, de Broglie's matter waves and Einstein's photoelectric effect established duality; Bohr's complementarity then framed wave and particle descriptions as mutually exclusive yet jointly necessary. In assays, complementarity is practical interference-based amplification and discrete counting are complementary strategies rather than competitors. Table 1 aligns representative platforms across principle, labels, sensitivity/throughput, samples, advantages/limitations, and translational status, revealing three patterns: wave methods favor label-free amplification; particle methods deliver digital quantitation and multiplexing; correlation methods beat classical noise but require sophisticated sources/detectors. Figure 2 summarizes a unifying design-to-decision workflow that recurs across platforms.

Table 1: Comparative landscape of quantum-inspired assay classes

Regime	Principle (one line)	Representative platform	Label?	Sensitivity (qual.)	Speed / Throughput (qual.)	Typical sample	Key advantages	Core limitations	Translational status
Wave-dominated	Interference of scattered and reference light to amplify weak signals	Interferometric scattering microscopy (iSCAT)	Label-free	Single-particle / single-molecule	Video-rate; moderate FOV	Live cells, viruses on coverslips	Label-free, nanometre precision, tracks dynamics	Phase stability, background from heterogeneous samples	Research; moving to advanced lab workflows
Wave-dominated	Localized surface plasmon resonance shifts with refractive index	Nanoplasmonic LSPR biosensors (Au/Ag)	Label-free	pM–fM (platform-dependent; qualitative here)	High-throughput microarrays possible	Serum, saliva, buffer; microfluidics-ready	Rapid, multiplexable, portable	Nanofabrication uniformity; surface fouling	POC prototypes; research & early translational use
Wave-dominated	Mid-IR absorption → photothermal change read by interferometric visible probe	WIDE-MIP photothermal microscopy	Label-free	Single-virus fingerprinting (qual.)	Widefield; high-throughput hyperspectral imaging	Virions, nanoparticles, thin films	Chemical fingerprints + morphology; low photodamage	Instrumentation complexity; IR source alignment	Research stage
Particle-dominated	Size-tuned quantum confinement → discrete photon emission	Quantum dots (QDs) for bioimaging	Labeled	Very bright; multiplex imaging	Fast imaging (video-rate)	Cells, small animals (NIR QDs)	High photostability, tunable emission, multiplexing	Heavy-metal toxicity (Cd-based), blinking	Preclinical common; clinical use limited
Particle-dominated	Ionic current modulation by single-molecule translocation	Nanopore sequencing (protein pores / solid-state)	Label-free	Single-nucleotide events	Real-time; portable devices	DNA/RNA in buffer	Long reads, portability, digital output	Sample prep quality; basecalling accuracy	Widely used in research & surveillance
Particle-dominated	Sample partitioning → count positive single-molecule reactions	Digital ELISA (droplet/well partitioning)	Labeled (reporter chemistry)	Reported down to ~aM and beyond (qual.)	Parallel partitions; moderate-to-high throughput	Proteins, nucleic acids, biomarkers	Absolute quantification; ultra-sensitive	Chip/reader complexity; cost	Research; emerging clinical applications

Hybrid (wave+particle)	Hybrid (wave+particle)	Correlation-enabled	Correlation-enabled
Quantum tunnelling current excites plasmonic modes for refractometric sensing	Plasmonic nanogap on mirror; tunnelling modifies chiral interactions	Squeezed/correlated light suppresses measurement noise	Entangled pairs: correlate detections to reconstruct image
Resonant quantum tunnelling plasmonic sensor	Nanoparticle-on-mirror (NPoM) single-molecule chiral sensor	Sub-shot-noise imaging / quantum-enhanced OCT	Quantum ghost imaging (QGI)
Label-free	Label-free	Label-free	Label-free
Ultra-sensitive refractive index (qual.)	Single-molecule chiral sensing (qual.)	Below shot-noise (qual.)	Sub-shot-noise regime (qual.)
Imaging metasurfaces possible	Spot measurements; arrayable	Modest throughput; setup-dependent	Low-flux; scanning or widefield variants
Thin films, biomolecular coatings	Chiral small molecules, peptides	Cells, tissues (optical)	Delicate biological samples
Built-in light source; compact metasurface design	Extreme field enhancement; quantum–classical synergy	Improved SNR and sensitivity	Low-light imaging; wavelength-flexible illumination/detection
Device complexity; fabrication yield	Nanogap fabrication; reproducibility	Sophisticated optics; stability	Complex sources/detectors; low brightness
Early research	Research stage	Laboratory demonstrations	Laboratory demonstrations

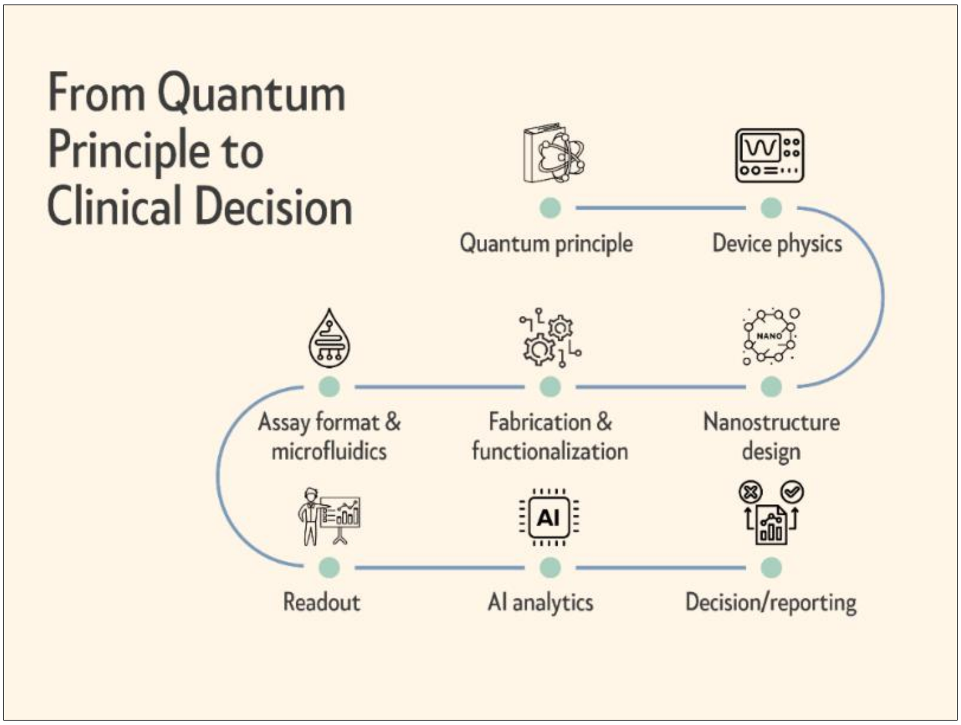

Figure 2: End-to-end workflow from quantum principle to clinical decision

Wave-Dominated Bioassays

Wave-dominated assays exploit interference, coherence, and field confinement to amplify weak biological signals while preserving native context. Among these, interferometric scattering microscopy (iSCAT) and localized surface plasmon resonance (LSPR) sensing are archetypes: iSCAT enhances tiny scattering amplitudes by interfering the object-scattered field with a reference wave, and LSPR concentrates electromagnetic fields in metallic nanostructures so that minute refractive-index changes from biomolecular binding become measurably spectral. Together, they enable rapid, label-free detection across single particles, viruses, and live-cell dynamics with high spatial–temporal fidelity.

iSCAT**.** Recent variants including wide-field and confocal iSCAT deliver label-free 3-D imaging of living cells, quantifying nanoscale topography and tracking organelles and protein complexes in real time. iSCAT has been used to follow clathrin-coated pits, microtubules, and the dynamics of the nuclear envelope, and to track individual viruses (e.g., SARS-CoV-2) with nanometre precision [2]. Closely related interferometric methods (phase-shift/common-path schemes, digital holography) extend this capability to quantitative phase imaging of cells and thin films, offering non-invasive readouts of thickness and refractive-index changes.

LSPR plasmonic sensing

Plasmonic nanostructures (e.g., gold/silver nanoparticles, nanogaps, and metasurfaces) sustain coherent electron oscillations that create intense near fields. LSPR biosensors transduce binding events into resonance shifts or spectral-line-shape changes, enabling rapid, label-free, and multiplexed detection of proteins, nucleic acids, and viral antigens/antibodies. Their advantages simple optics, short assay times, high surface sensitivity, and compatibility with microfluidics make them attractive for point-of-care formats; data-driven analysis (e.g., machine learning on spectra) further improves limit-of-detection and selectivity [5]. At the wave–particle boundary, resonant quantum-tunnelling plasmonic sensors embed tunnel junctions as on-chip emitters and use metasurface nanoantennas to boost spectral and refractometric responses, illustrating how tunnelling currents can directly excite plasmonic modes for ultrasensitive refractive-index sensing [8].

Nanogap hot spots and SERS integration

Sub-nanometre nanogaps (e.g., bowtie antennas, nanoparticle-on-mirror, and DNA-templated dimers) confine light to extreme volumes, creating “hot spots” that dramatically enhance scattering and Raman cross-sections. Coupling these structures to iSCAT readouts or to surface-enhanced Raman scattering (SERS) enables detection of proteins and nucleic acids at very low concentrations, with molecular-fingerprint specificity when SERS is used. While reproducible fabrication of uniform gaps remains challenging, advances in electron-beam lithography, colloidal self-assembly, and DNA-origami templating are steadily improving array-level uniformity [9].

Mid-IR photothermal (WIDE-MIP)

Pushing wave assays into the mid-infrared (3–10 µm) leverages intrinsic vibrational fingerprints of biomolecules. In mid-IR photothermal microscopy, an IR pump excites molecular vibrations; non-radiative relaxation produces a nanoscale temperature rise that a visible probe senses as changes in refractive index/scattering. A widefield, interferometric defocus-enhanced implementation WIDE-MIP deliberately offsets the objective focus to tune the phase between particle-scattered and substrate-reflected photons, maximizing photothermal contrast. This architecture boosts throughput by orders of magnitude compared with scanning approaches and fingerprints single viruses, differentiating DNA vs RNA viruses via thymine/uracil vibrations and even reporting β-sheet enrichment in viral proteins [10]. By tuning the IR wavenumber, hyperspectral cubes yield label-free molecular signatures at the single-particle level, complementing nucleic-acid amplification and antigen tests.

Limitations and practical challenges

Despite their strengths, wave-dominated assays are phase-sensitive: environmental vibration, thermal drift, and speckle/stray-light backgrounds can degrade contrast. Biological heterogeneity (scattering and refractive-index variability) complicates background subtraction and can bias quantitation. On the manufacturing side, achieving array-scale uniformity in plasmonic features especially sub-nanometre gaps and stable surface chemistries—remains non-trivial and can impact reproducibility [9]. *In Vivo* deployment faces penetration limits and potential phototoxicity; progress hinges on near-infrared operation, adaptive optics, minimally perturbative probes, and real-time computational correction. Even so, the trajectory is clear: as stability engineering, fabrication control, and data-driven correction mature, iSCAT/LSPR platforms and mid-IR photothermal imaging are poised to deliver portable, quantitative, label-free readouts across research and translational settings[2, 5, 10].

Particle-Dominated Bioassays

Particle-dominated readouts treat signals as discrete events electrons, ions, photons, or single molecules so measurements become counts rather than analogue amplitudes. This digitalization confers drift resistance and enables absolute quantitation at ultralow copy numbers. Core exemplars include quantum dots (QDs) for bright, multiplexed labeling; nanopores for single-molecule sequencing; and digital ELISA (dELISA) for attomolar protein detection, with additional families (digital PCR/CRISPR, single-electron/tunnelling devices) extending the same counting logic.

Quantum dots (QDs)

Semiconductor QDs exhibit size-tunable, narrow emission and exceptional photostability, often outperforming organic dyes in brightness and resistance to bleaching [6]. Their surfaces are readily functionalized (peptides, antibodies, nucleic acids), enabling targeted imaging and single-excitation multiplexing because differently sized QDs emit at distinct wavelengths. Near-infrared (NIR) emitters support deeper tissue penetration and fast *In Vivo* imaging. (Toxicological and biocompatibility considerations are treated in the Safety section [6].

Nanopore sequencing

In nanopore platforms, an electric field drives single DNA/RNA strands through a nanoscale pore; each base modulates ionic current, producing a discrete event stream. Biological pores such as α-hemolysin and MspA are common, and enzymes like phi29 polymerase regulate translocation to improve SNR [11]. Oxford Nanopore's MinION exemplifies portability and long-read capability for pathogen surveillance and human genomics, with base-level digital outputs that facilitate absolute counting, variant detection, and adaptive sampling.

Digital ELISA (dELISA)

dELISA partitions samples into femtolitre-scale compartments so that each reactor contains zero or one target molecule; fluorogenic turnover flags positives, which are counted to yield absolute concentrations. Confinement (e.g., ~50 fL vs ~100 µL in conventional ELISA) boosts effective local concentration and reaction kinetics, enabling single-molecule sensitivity from femto- down to attomolar levels. Reported applications span tumor markers, viral antigens, nucleic acids, inflammatory proteins, and prognostic panels [9].

Other digital/counting platforms

The same partition-and-count principle underpins digital PCR (dPCR) and digital CRISPR assays: thousands to millions of droplets or nanowells isolate zero/one target copy, amplification or nuclease-triggered reporters create binary readouts, and the fraction of positives gives absolute copy number without standard curves. In parallel, single-electron/tunnelling devices exploit Coulomb blockade to turn biomolecular interactions near a nanometre-scale junction into quantized conductance changes, suggesting routes to label-free digital protein/nucleic-acid detection when coupled to microfluidics. At the wave–particle boundary, nanogap tunnelling plasmonic sensors inject electrons through tunnel junctions to excite nanoantenna modes, with refractive-index-sensitive emission providing compact, on-chip readouts [8].

Limitations and practical considerations

Translating particle-dominated assays requires attention to materials and device robustness, sample preparation, and workflow complexity. Nanopore systems depend on membrane/pore stability and carefully controlled buffer conditions; high-purity nucleic acids and downstream analytics remain non-trivial. dELISA typically needs microfluidic partitioning and custom optics, which may challenge cost and maintenance outside specialized labs. QDs, while bright and multiplexable, bring materials-safety questions (addressed in the Safety section) and can show blinking that complicates quantitation without appropriate core–shell engineering [6]. Tunnelling and single-electron sensors are sensitive to atomic-scale fabrication tolerances and drift, and many implementations are still pre-commercial. Across platforms, the advantages absolute quantitation, ultrahigh sensitivity, multiplexing, and robustness to analogue drift are compelling; continued progress in standardized cartridges, integrated microfluidics, and on-device computation will be key to routine deployment [12].

Correlation-Enabled Quantum Bioassays

Quantum ghost imaging (QGI)

QGI employs entangled photon pairs from spontaneous parametric down-conversion: one (idler) interrogates the specimen and is collected by a bucket detector; its partner (signal), which never meets the specimen, is recorded with spatial resolution. Image reconstruction arises from non-classical correlations between detections, enabling high-visibility images at ultra-low photon flux. For delicate biological targets, QGI reduces photodamage and permits wavelength transduction illumination at one band (e.g., mid-IR vibrational resonances) with detection at another (visible) facilitating chemical-fingerprint imaging without exposing samples to harmful radiation [7].

Sub-shot-noise (squeezed/correlated-beam) imaging

Squeezed states redistribute quantum uncertainty so that noise in a chosen quadrature falls below the shot-noise limit. In interferometers or wide-field microscopes, correlated beams and squeezed light lower measurement noise, improving sensitivity and contrast for weak signals in scattering tissues. Demonstrations show quantum noise suppression with scattering elements and squeezed illumination, yielding higher SNR and effective resolution than classical counterparts [2, 13]. For biosensing, this means detecting subtle refractive-index or absorption changes at reduced dose and with enhanced robustness to classical fluctuations.

Other correlation-enabled modalitie

Extensions of entanglement/time-correlation underpin quantum-enhanced OCT (narrower effective fringes for better axial precision) and quantum super-resolution strategies that beat classical limits under appropriate photon-statistics constraints. Squeezed-light concepts have also been explored for stimulated Raman scattering microscopy (noise-reduced vibrational readouts), optical tweezers stability, and microresonator sensing. Likewise, "quantum correlation spectroscopy" generalizes arrival-time/energy correlations to probe molecular dynamics at lower concentrations than classical FCS. While these sub-modalities are at varying maturity, they share a unifying theme: leveraging photon-number or field-quadrature correlations to elevate sensitivity or resolution without proportionally increasing sample dose.

Barriers and prospects

Practical deployment remains constrained by source, system, and detector complexity. Bright, stable, and tunable quantum light sources (nonlinear crystals, waveguides) must be paired with ultra-low-noise single-photon detectors, phase-stable interferometry, and careful mode matching all of which are sensitive to environmental drift. Many benches operate at modest photon flux, limiting throughput; some detectors require cryogenic operation, raising cost and form-factor hurdles. Interfacing fragile quantum states with microfluidics, live cells, or turbid tissues risks correlation loss through scattering and absorption, and hybrid quantum–classical instrument control is still maturing. Pathways to translation include integrated photonics (on-chip SPDC/squeezers, waveguide interferometers, and SNSPD arrays), multiplexed sources/detectors for higher brightness, and algorithmic gains (model-based reconstruction and real-time denoising) that preserve quantum advantage under realistic noise. With these advances, correlation-enabled bioassays can complement wave- and particle-dominated platforms by delivering dose-efficient, noise-suppressed measurements aligned with biological constraints [7, 13].

In Vitro vs. *In Vivo* Applications

In Vitro Bioassays

Quantum-inspired methods already enable sensitive, label-free *In Vitro* measurements across proteins, nucleic acids, and whole particles. Wave-dominated interferometry and plasmonics provide multiplexed readouts on microarrays and chips e.g., nanoplasmonic LSPR surfaces that quantify antigen/antibody or oligonucleotide binding with short assay times and simple optics [5], while iSCAT/digital holography track single proteins, viruses, and membrane dynamics in living cells [14]. A major vector for translation is microfluidics/lab-on-a-chip: integrated cartridges that execute sample prep, separation, and detection [15], couple nanoplasmonic sensors for refractometric binding, embed nanopores for direct pathogen sequencing, and partition femtolitre reactors for digital ELISA/dPCR to achieve absolute quantitation with minimal reagents [16]. Digital microfluidics (electrowetting) further automates droplet generation/merging for on-chip dilution series and multiplex panels. Spectroscopic integrations add chemical specificity: mid-IR/Raman on-chip fingerprinting and WIDE-MIP-style interferometric photothermal readouts can, in principle, identify intact virions and monitor kinetics without labels [10]. Across these platforms, AI supports real-time denoising, anomaly detection, and flow control, closing the loop between sensor response and actuation. Remaining engineering priorities include anti-fouling surfaces, robust laminar control at small scales, and user-friendly, disposable cartridges; nonetheless, microfluidic and lab-on-a-chip formats are central to moving quantum-inspired assays into portable diagnostics and high-throughput discovery [17].

In Vivo Applications

Translation *In Vivo* emphasizes contrast, penetration, and minimal perturbation. Near-infrared quantum dots (QDs) functionalized with targeting ligands visualize tumors, vasculature, and neural circuits with fast, multiplexed readouts and deeper tissue reach than visible fluorophores; NIR emitters have enabled high-speed blood-flow imaging in brain tumor models, with materials-safety considerations addressed in the Safety section [18]. For therapy/theranostics, plasmonic nanoparticles (e.g., gold nanorods/nanoshells) convert NIR light into heat for photothermal therapy (PTT) and can be co-designed with sensing readouts to monitor response in situ. Additional *In Vivo* contrast routes such as up conversion nanoparticles for IR-to-visible conversion offer low-dose imaging and could interface with correlation-enabled illumination in future systems. Practical hurdles remain: scattering/absorption in tissue, immune clearance, and maintaining optical stability under motion. Even so, the combination of NIR-addressable emitters/absorbers, minimally perturbative illumination, and compact readouts positions quantum-inspired platforms to support image-guided intervention and longitudinal disease monitoring as device engineering and clinical workflows mature [19].

Emerging Integrations and Cross-Disciplinary Advances

AI-Enhanced Quantum Bioassay Data

The data streams of quantum-inspired assays interference movies, LSPR spectra, nanopore current traces, droplet-level positives require analytics that are fast, robust, and explainable. AI/ML now functions as the analysis-and-control layer: in practice, models turn raw physical signals into decisions, while feedback loops stabilize instruments and microfluidics in real time [20]. In Table 2, the mapping is: interferometric/photothermal images to vision models for denoising/segmentation; LSPR spectra to regression/classification; nanopore event streams to sequence models for base-calling and event typing; digital assays to detector models for droplet calling and artifact rejection. Maturity is highest for image/spectral tasks; temporal models for nanopores and single-photon arrivals are advancing quickly.

High-value AI tasks (near-term impact)

1. Physics-aware denoising/segmentation for interferometry/photothermal imaging to recover weak contrasts and automate ROI discovery(20).
2. Event classification and base-calling for nanopores to improve SNR, detect modifications, and enable adaptive sampling on device (12).
3. Positive-well/droplet calling with outlier rejection for dELISA/dPCR to push LoD and reduce false positives(21).
4. Active stabilization and flow control learning controllers that hold phase, tune laser power, or

adjust microfluidic valves to maintain optimal SNR under drift.

Deployment is split between edge inference (time-critical control, privacy) and cloud pipelines (training, curation, QA). Regardless of venue, models need calibration standards, drift monitoring, and dataset versioning for reproducibility. Compact additions such as PINNs (physics-informed networks) and reinforcement learning can encode wave/transport constraints and optimize instrument set-points with minimal data [22]. Classical AI remains the workhorse; putative quantum-ML benefits are longer-term[23].

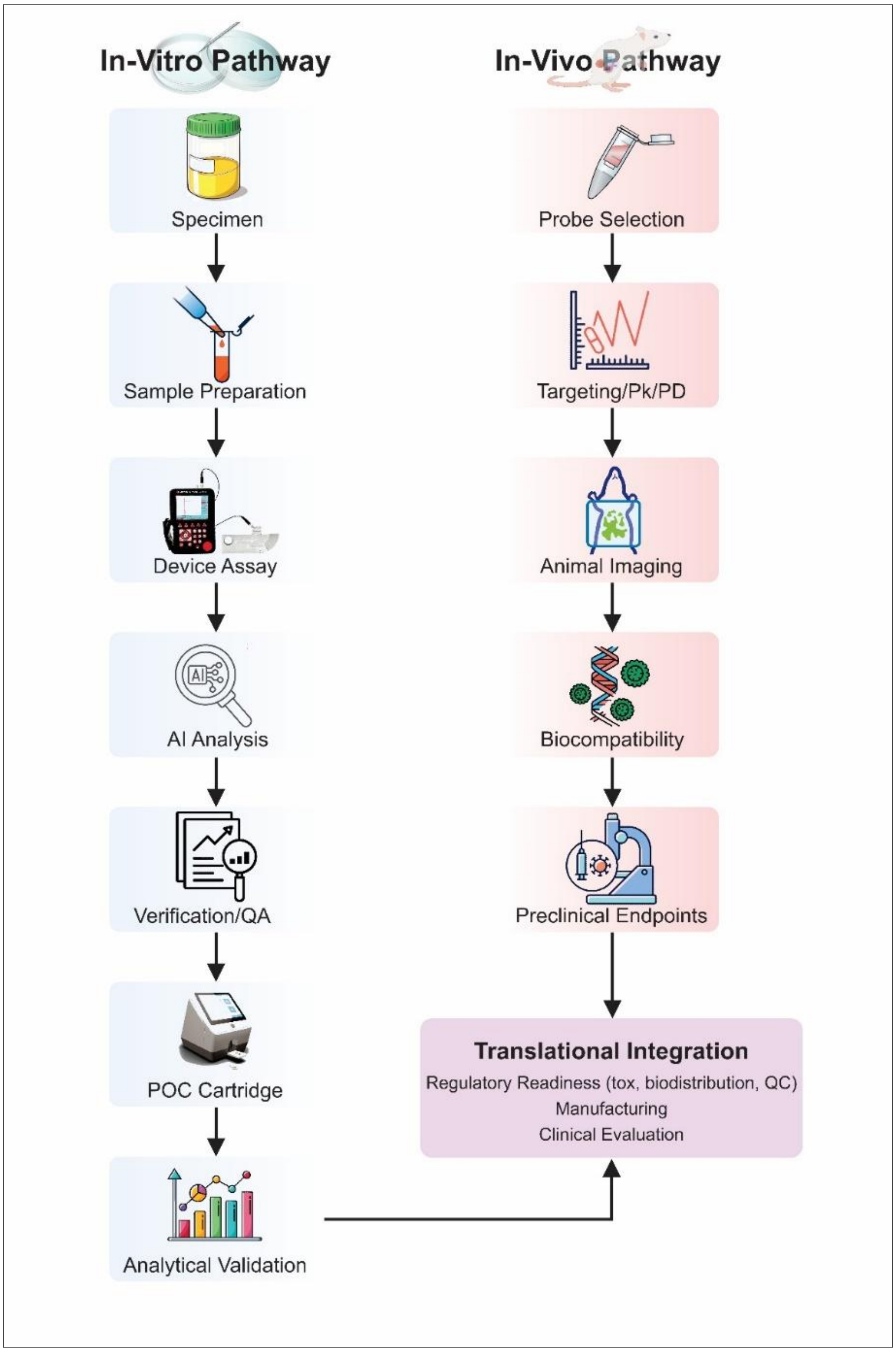

Figure 3: Translational pathways from bench to bedside

Hybrid nanodevices

Platforms that co-locate wave and particle effects are emerging. The nanoparticle-on-mirror (NPoM) chiral sensor places a gold nanoparticle above a metal film with a nanometer gap, plasmonic fields (wave) amplify signals while tunnelling (particle) modulates chiral interactions, reaching detection of ~4 molecules per particle [21]. Plasmonic nanopores focus light into a translocation channel so optical and tunnelling/electrical readouts report on the same molecule, and QD–antenna hybrids enhance emission via the Purcell effect while enabling electrical control of brightness. These hybrids illustrate how engineered field confinement and quantized transport yield multimodal sensitivity in compact, integrable formats.

Challenges and Ethical Considerations

Technical barriers and data interpretation

Quantum-inspired assays must operate amid biological noise while preserving phase stability, coherence, or correlations. Environmental vibration/thermal drift readily degrade interferometric contrast; on the device side, nanometer-scale tolerances (e.g., nanogap dimensions, pore geometry, QD uniformity) limit reproducibility and lot-to-lot consistency. Throughput is constrained by modest photon flux and complex optical alignments, motivating brighter sources, multiplexed detection, and integrated photonics. Integration with existing microscopes, microfluidics, and clinical analyzers adds packaging/alignment burdens, especially when pairing single-photon detectors or entangled sources with live-sample workflows. Interpreting outputs interference movies, spectral shifts, tunnelling traces, and correlation functions require substantial computation; while AI/ML can automate denoising, classification, and control, models demand curated training data, independent validation, calibration standards, and drift monitoring to ensure generalization across instruments and matrices.

Safety and biocompatibility

Inorganic nanomaterials (metals/metal oxides) offer exceptional optical/electrical performance but can provoke inflammation, immune activation, and long-term accumulation. Surface modification and polymer or organic–inorganic composite shells improve dispersion, biocompatibility, and clearance profiles [19]. For quantum dots, heavy-metal risks motivate cadmium-free cores and protective shells; rigorous studies of biodistribution and clearance remain essential for any *In Vivo* use [18].Noble-metal plasmonic structures are often described as biocompatible, yet their long-term fate and tissue interactions still warrant systematic evaluation.

Ethical and regulatory issues

Sensitive nanoscale diagnostics raise concerns around informed consent, privacy of AI-derived results, dual-use/misuse, environmental persistence, and equitable access. Ethical deployment should address sustainable sourcing, manufacturing footprints, and end-of-life recycling. Regulators (e.g., FDA, EMA) increasingly require rigorous evidence of safety, efficacy, quality, and post-market surveillance for nanomaterial-containing devices; early engagement with regulators, standardized characterization, and transparent reporting can streamline translation[19, 24].

Future Perspectives

Move quantum light generation/detection on-chip (SPDC/squeezers, single-photon sources, waveguide interferometers, integrated SNSPDs) and co-package with microfluidics and edge AI. This enables compact, phase-stable, low-noise biosensors that run real-time control/denoising locally while syncing heavier training/QA to the cloud. Clinical translation benefits from cartridge-based optics, lowered alignment burden, and standardized electrical/optical I/O for plug-and-play use in microscopes and analyzers.

Co-locate field confinement (plasmonics, nanogaps) with quantized transport (tunnelling, nanopores) and bright emitters (QDs, up-conversion) to yield multimodal readouts simultaneous optical and electrical signals from the same molecule or cell. Examples include plasmonic nanopores (optical focusing and ionic/current signatures) and QD–nanogap antennas (Purcell-enhanced emission with electrical modulation). Near-term targets are portable, label-free analytics; mid-term, theranostics that pair sensing with photothermal/photodynamic actuation for image-guided intervention.

Establish common metrology (LoD, NEQ, quantum efficiency, coherence stability), biocompatibility/toxicity protocols, and reporting checklists for AI-assisted instruments (dataset versioning, drift tests). Engage early with regulators on combination products (device, nanomaterial and software) and design for GMP-ready manufacturing. To democratize impact: prioritize low-cost fabrication and resilient supply chains, adopt open data/models where feasible, and invest in training for clinicians and laboratorians so deployments in resource-limited settings are safe, interpretable, and sustainable.

CONCLUSION

Quantum-inspired nanobiotechnology reframes bioassays through three complementary regimes of wave–particle duality. Wave-dominated platforms (e.g., iSCAT, LSPR) amplify faint, label-free signals; particle-dominated formats (e.g., nanopores, dELISA) convert biology into discrete counts for absolute quantitation; and correlation-enabled approaches (e.g., ghost or sub-shot-noise imaging) suppress classical noise to reveal weak effects. Hybrids that co-locate field confinement with quantized transport, together with AI, microfluidics, and theranostic design, point to portable, multiplexed, and clinically actionable tools. Translation will hinge on phase/throughput engineering, reproducible nanofabrication, and rigorous biocompatibility, alongside clear regulatory pathways and attention to ethics, privacy, sustainability, and equitable access. More than a philosophical motif, wave–particle duality is a pragmatic engineering framework poised to reshape diagnostics, imaging, and therapy into ultra-sensitive, minimally invasive, personalized care.

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