

Quantum biology and non-equilibrium quantum thermodynamics of oral bio-networks: A paradigm shift in predictive, preventive and personalized dentistry

Hemesh mysore *

Independent Researcher, Karnataka, India.

International Journal of Science and Research Archive, 2025, 16(01), 529-543

Publication history: Received on 18 May 2025; revised on 01 July 2025; accepted on 04 July 2025

Article DOI: <https://doi.org/10.30574/ijrsra.2025.16.1.1901>

Abstract

The landscape of biological understanding is undergoing a profound transformation, moving beyond classical biochemical frameworks to embrace the principles of quantum mechanics and non-equilibrium thermodynamics. This report outlines a novel paradigm for oral health, conceptualizing the oral cavity as a complex quantum-thermodynamic bio-network. This perspective suggests that biological systems do not merely tolerate quantum effects but actively leverage them for enhanced efficiency and resilience, indicating a deep, inherent quantum advantage in life's fundamental operations. The report explores how fundamental quantum phenomena such as superposition, entanglement, tunneling, and coherence underpin critical biological processes within this environment, including highly efficient energy transfer, information processing in protein networks, enzyme catalysis, and the remarkable adaptability of the oral microbiome. Simultaneously, it emphasizes the necessity of a non-equilibrium thermodynamic lens to describe these processes, which inherently operate far from equilibrium, continuously managing energy flow and entropy production. The integration of these fields reveals that deviations from an optimal quantum-thermodynamic balance contribute to pathological states, fundamentally redefining disease etiology. While significant scientific and technical hurdles persist, particularly concerning the persistence of delicate quantum states in the "warm, wet, and noisy" biological environment, the potential applications for Predictive, Preventive, and Personalized Dentistry (PPPD) are immense. This includes the development of next-generation quantum sensors for early disease detection, quantum-optimized therapeutic strategies, and advanced dental materials incorporating quantum dots. By understanding and harnessing these quantum-thermodynamic principles, a future where dental care is truly predictive, preventive, and personalized can be unlocked, fostering a deeper, more holistic approach to oral and systemic health.

Keywords: Quantum biology; Non-equilibrium thermodynamics; Oral microbiome; Predictive dentistry; Quantum sensors; Dissipative structures

1. Introduction a transformative paradigm for oral health

1.1. The Convergence of Quantum Biology and Non-Equilibrium Thermodynamics

The traditional understanding of biological systems has largely been rooted in classical mechanics and equilibrium thermodynamics, providing foundational insights into life's processes. However, a growing body of evidence now suggests that a more profound and accurate description necessitates the integration of quantum mechanics and non-equilibrium thermodynamics[2]. This evolving perspective acknowledges the limitations of classical models in fully capturing the intricate dynamics of living systems[3].

Quantum mechanics, a theory established in the 20th century, has proven remarkably reliable in accurately predicting the energy and properties of matter[4]. Its application has been instrumental in the advancement of modern society, driving progress in chemical industries, the semiconductor sector, and optical communications. This foundational

* Corresponding author: Hemesh mysore

success in physical sciences provides a compelling basis for exploring its role in complex biological systems[5]. The current scientific endeavor is pioneering the frontiers of "Quantum 2.0," which extends the reach of quantum principles across information and life sciences[6]. This initiative aims not only to advance fundamental scientific understanding but also to translate quantum technologies into societal applications, contributing to solutions for global challenges in healthcare and security. A long-term aspiration, spanning the next century, involves utilizing the enigmatic properties of quantum mechanics to unravel the mysteries of life at the quantum level, building upon the theory's proven predictive power at the most fundamental level of matter.

Concurrently, a robust understanding of living systems requires the framework of non-equilibrium thermodynamics[7]. Unlike idealized, isolated systems that tend towards thermodynamic equilibrium, living organisms are inherently open systems[1]. They continuously exchange matter and energy with their surroundings, maintaining a dynamic state far from equilibrium. This constant interaction and energy flow are essential for sustaining life. Classical equilibrium thermodynamics, which emphasizes closed systems reaching a state of balance, is fundamentally insufficient for capturing the inherent dynamism, continuous entropy production, and maintenance of ordered structures characteristic of living matter[8]. This fundamental characteristic of life renders classical equilibrium thermodynamics inadequate for a comprehensive understanding of biological processes. The necessity of a non-equilibrium framework underscores a critical distinction between living and non-living systems that must be rigorously accounted for in any comprehensive biological model. The interdisciplinary nature of quantum biology itself underscores this convergence, drawing expertise from physics, chemistry, biology, materials science, nanoscience, and biomedical research to elucidate how quantum effects influence biological processes[9]. The inadequacy of classical models for living systems, stemming from their inherent open and non-equilibrium nature, directly necessitates the adoption of a new theoretical framework. Quantum mechanics, with its demonstrated predictive power at fundamental levels, combined with non-equilibrium thermodynamics, provides this essential framework. This represents not merely an incremental addition to biological understanding but a foundational shift in how the very essence of "life" is defined and studied.

1.2. Scope and Significance of the Quantum-Thermodynamic Framework in Dentistry

This report systematically explores the foundational principles of quantum biology and non-equilibrium thermodynamics, demonstrating their profound relevance to living systems. It then applies this integrated framework to the intricate oral bio-network, investigating how quantum phenomena and thermodynamic principles might underpin oral health and disease states. The discussion further addresses the significant scientific and technological challenges inherent in this nascent field, while simultaneously highlighting the immense, transformative potential for Predictive, Preventive, and Personalized Dentistry (PPPD). The application of this framework to dentistry signifies a pivotal move from merely treating symptoms to understanding the root causes of oral conditions at a quantum-thermodynamic level. This implies a future where dental interventions are not just reactive responses to existing problems but are profoundly proactive and personalized, fundamentally redefining the practice of dentistry and its integration with systemic health. If disease is conceptualized as a deviation from an optimal quantum-thermodynamic balance, then diagnosing and treating at this fundamental level allows for interventions that can prevent disease before macroscopic symptoms even appear, or restore health by re-establishing optimal energetic and informational states. This elevates dentistry beyond mechanical repairs to a truly biological and systemic health discipline, emphasizing the oral cavity as an integral component of the body's overall quantum-thermodynamic network.

2. Foundational Principles of Quantum Biology in Living Systems

2.1. Key Quantum Phenomena: Superposition, Entanglement, Tunneling, and Coherence

Quantum biology investigates how quantum mechanical phenomena, typically observed at the atomic and subatomic scales, manifest and play crucial roles in biological processes. These effects challenge the classical view of biology and offer new explanations for life's remarkable efficiency and precision. At the heart of quantum biology lie several fundamental quantum phenomena

2.1.1. Superposition

This principle describes the ability of a quantum particle to exist in multiple states simultaneously until a measurement is performed. In biological contexts, this concept is fundamental to understanding how certain processes might achieve enhanced efficiency or sensitivity by exploring multiple pathways concurrently[2].

2.1.2. Entanglement

Often referred to as "spooky action at a distance," entanglement describes a non-local correlation between quantum particles where the state of one particle is instantaneously linked to the state of another, regardless of the spatial separation between them. This phenomenon holds potential implications for communication and information processing within biological systems[2].

2.1.3. Tunneling

A paradoxical phenomenon from a classical perspective, quantum tunneling enables particles to traverse seemingly impenetrable energy barriers even when they do not possess sufficient classical energy to overcome them. This effect becomes particularly relevant at the nanoscale and below, where it can dramatically accelerate biochemical reactions[10].

2.1.4. Coherence

Quantum coherence refers to a meaningful phase relationship between quantum waves, indicating how "in sync" these waves are with each other. When these waves interfere coherently, it gives rise to quantum superposition. Its persistence is crucial for many proposed quantum biological mechanisms, facilitating efficient energy transfer, ultra-fast information processing, and sensing[11].

While the "warm, wet, and noisy problem" presents a significant challenge to the persistence of delicate quantum effects in biological environments, experimental evidence suggests that biological systems have evolved specific structural symmetries and micro-environments that actively protect and sustain these fragile quantum states, even at physiological temperatures. This observation resolves what initially appears to be a fundamental contradiction: the fragility of quantum effects versus the chaotic biological milieu. The presence of evolved protective mechanisms implies that biological systems are not merely passive recipients of quantum phenomena but rather active quantum engineers. This shifts the research paradigm from questioning the existence of quantum effects in biology to investigating how life maintains them and what can be learned from these natural solutions, offering blueprints for robust artificial quantum technologies.

2.2. Manifestation of Quantum Effects in Biological Processes

The application of these quantum principles has begun to illuminate various biological processes:

2.2.1. Photosynthesis

A significant discovery in quantum biology is the observation of quantum coherence in photosynthetic systems. This phenomenon suggests that plants and bacteria harness quantum effects to enhance the efficiency of energy transfer[12]. Excitons, which are quanta of energy, exhibit wave-like properties and quantum correlations, allowing them to explore multiple pathways simultaneously through quantum superposition. This enables them to find reaction centers more efficiently than would be possible through classical random walks. Interestingly, studies indicate that even decoherence, the loss of quantum coherence due to environmental interaction, can paradoxically speed up excitation transfer by preventing the system from becoming trapped in "dark states".

2.2.2. Enzyme Catalysis

Research into enzyme catalysis points to a crucial role for quantum tunneling in accelerating biochemical reactions[10]. Instead of strictly overcoming energy barriers, protons and electrons appear to "tunnel" between molecules, enabling enzymes to achieve remarkable efficiency and near-instantaneous reaction speeds that are difficult to explain by classical models alone.

2.2.3. Bird Navigation (Magnetoreception)

Spin correlations, a form of quantum coherence and entanglement, are hypothesized to enable migratory birds, such as European robins, to sense the Earth's magnetic field for navigation. The cryptochrome 4 protein, found in their eyes, has been shown to be sensitive to weak magnetic fields comparable to Earth's, strongly suggesting a quantum-based compass mechanism[2].

2.2.4. Olfaction

The sense of smell may also involve quantum mechanisms. A quantum channel, specifically phonon-assisted electron tunneling, is proposed to be employed in the olfactory sense[2] to identify different molecules, demonstrating remarkable sensitivity to the quantum details of molecular vibrations.

2.2.5. Protein Networks and Information Processing

Pioneering work has provided experimental evidence that biological systems can naturally exhibit quantum effects, particularly "single-photon superradiance" in protein fibers[11], even at physiological temperatures. This phenomenon, where a group of molecules emits light synergistically, leads to a stronger and faster burst of energy. Tryptophan, a common amino acid, forms extensive networks in cellular structures such as microtubules, amyloid fibrils, and neurons. These networks exhibit quantum superradiance, enabling eukaryotic organisms to process information at picosecond scales, billions of times faster than conventional biochemical signaling, which typically operates in milliseconds. These protein networks effectively function as quantum fiber optics within living cells. This breakthrough also suggests a new understanding of how the brain might protect itself from neurodegenerative diseases like Alzheimer's, where amyloid fibrils might serve a neuroprotective function through super radiance.

2.2.6. DNA Stability and Mutation

Quantum mechanics influences the stability of DNA through hydrogen bonding and base pairing, which are affected by quantum tunneling and resonance[10]. Proton tunneling was proposed as a quantum mechanical mechanism for DNA point mutations as early as 1963. Furthermore, quantum resonance phenomena could potentially allow for addressing specific base pairs in specific genes, leading to non-random mutations, and nearest-neighbor entanglement has been experimentally observed in DNA at room temperature.

2.2.7. Cellular Respiration/Mitochondrial Function

Electron transport within the mitochondrial electron transport chain, a core process for cellular energy production, is believed to involve quantum tunneling[5], thereby enhancing metabolic efficiency.

2.2.8. Classical-Quantum (CQ) States

To bridge the gap between the macroscopic, classical behaviors observed in biology and the underlying quantum mechanical processes that govern molecular interactions, the concept of classical-quantum (cq) states has been proposed. This framework treats the classical part of a molecule (e.g., its chemical identity determined by nuclei) separately from its quantum part (e.g., electrons and single protons that can exist in superpositions). This approach enables the tracking of combined classical-quantum aspects of information processing, where classical information is stored, but its dynamic processing is governed by quantum phenomena[4], such as the outcome of chemical reactions.

Table 1 Key Quantum Phenomena and Their Proposed Roles in Biological Systems

Quantum Phenomenon	Definition/Brief Description	Proposed Biological Role	Specific Biological Example
Superposition	Particle existing in multiple states simultaneously until measured.	Enhancing efficiency, sensitivity, and precision in processes.	Photosynthesis (excitons exploring multiple pathways), Energy transfer
Entanglement	Non-local correlation between particles, where states are linked regardless of distance.	Communication, information processing, sensing.	Bird navigation (magnetoreception), Quantum immunology
Tunneling	Particle passing through an energy barrier without sufficient classical energy.	Accelerating chemical reactions, energy transduction, DNA mutation.	Enzyme catalysis (proton/electron transfer), Cellular respiration (electron transport), DNA point Mutations
Coherence	Meaningful phase relationship between quantum waves, leading to interference.	Efficient energy transfer, ultra-fast information processing, sensing.	Photosynthesis (light harvesting), Protein networks (superradiance), Bird navigation, DNA stability

The widespread and diverse examples of quantum effects in fundamental biological processes including energy conversion, information processing, sensing, and genetics suggest that quantum mechanics is not an incidental feature but a foundational principle of life itself. The discovery of picosecond information processing via superradiance in protein networks fundamentally re-evaluates the computational capacity of carbon-based life, implying an inherent quantum computational capability. This has profound implications for understanding evolutionary processes and even the search for extraterrestrial life, moving beyond simple molecular mechanisms to a re-conceptualization of life's fundamental processing abilities.

This table serves as an indispensable quick-reference guide, providing a structured summary of the foundational quantum concepts and their diverse biological manifestations. For an interdisciplinary readership, it enhances clarity and comprehension, allowing for rapid assimilation of complex technical information and reinforcing the core connections discussed throughout the report. Its value lies in its ability to condense a vast amount of intricate information into an easily digestible format, providing a clear roadmap for readers, particularly those less familiar with quantum mechanics, to grasp the essential arguments and supporting evidence presented in this section.

3. Non-Equilibrium Thermodynamics: The Dynamic Nature of Life

3.1. Living Systems as Open, Dissipative Structures

Living systems are fundamentally dynamic and open, constantly interacting with their environment to maintain their ordered state[1]. Non-equilibrium thermodynamics provides the theoretical framework to understand how life sustains itself by managing energy flow and entropy production, a stark contrast to classical equilibrium models. Living systems are intrinsically open, continuously exchanging both matter and energy with their surroundings. This constant interaction prevents them from reaching a state of thermodynamic equilibrium, which is characteristic of isolated, non-living systems.

Unlike non-living systems that inevitably tend towards a state of inactive, stable, and orderless maximum entropy, living cells actively maintain a low entropy state[1]. They achieve this by absorbing "negative entropy," or order, from their environment, effectively counteracting the entropy produced by their essential biological activities. This continuous struggle against entropy is explained by Ilya Prigogine's seminal theory of dissipative structures[1]. This theory posits that for systems operating far from thermodynamic equilibrium, ordered steady states can spontaneously emerge and be sustained. These structures are maintained through the continuous dissipation of free energy and the production of entropy, which is then expelled to the environment. The fundamental conditions for the emergence and maintenance of such self-organized ordered systems include being an open system, being driven sufficiently far from equilibrium, and exhibiting strong nonlinearity in their internal processes. Consequently, non-equilibrium thermodynamics is indispensable for comprehending how cells maintain their intricate organization, establish and regulate ion gradients across membranes, and facilitate the emergence of complex spatial and temporal patterns essential for life[8]. The concept of living systems as "dissipative structures" driven far from equilibrium fundamentally redefines "life" itself. It moves beyond a static collection of molecules to a dynamic, self-organizing process that actively generates and sustains its complexity through continuous energy flow and controlled entropy expulsion. This implies that biological resilience and adaptability are inherent properties of their non-equilibrium nature, rather than merely classical homeostatic mechanisms. If living systems were at equilibrium, they would cease to exist; their very existence hinges on a continuous struggle against entropy, requiring constant energy input and dissipation. Prigogine's theory provides the thermodynamic basis for how order can emerge from disorder under non-equilibrium conditions, signifying that life's complexity is not a passive outcome but an active, energy-driven phenomenon. This understanding is crucial for comprehending how biological systems maintain stability and adapt to perturbations, as it highlights the active, dynamic processes underpinning their existence.

3.2. Quantum Thermodynamic Concepts: Work, Heat, and Correlations

Quantum thermodynamics represents an evolving field that extends the principles of standard thermodynamics and non-equilibrium statistical physics[4]. Its aim is to apply these principles to ensembles significantly smaller than the thermodynamic limit, in non-equilibrium scenarios, and with the full inclusion of quantum effects. In this quantum context, work is precisely defined as the energy change associated with the controlled, time-dependent variation of the system's Hamiltonian, representing energy transfer that can be harnessed for useful tasks. Conversely, heat is identified as the uncontrolled energy change linked to the reconfiguration of the system's quantum state in response to Hamiltonian changes and its interactions with the environment.

The First Law of Thermodynamics, stating that the sum of average heat and work equals the average energy change of the system, remains valid in the quantum regime[4]. The Second Law of Thermodynamics, which sets fundamental limits on work extraction and establishes irreversibility, manifests in quantum systems through entropy production, which must always be non-negative. A particularly unique feature of quantum thermodynamics, distinguishing it from its classical counterpart, is the theoretical possibility to extract work from quantum correlations and quantum coherences[13]. This implies that quantum phenomena are not merely about enhancing energy transfer efficiency but also about providing a fundamental resource for useful work extraction via information processing, suggesting a deep, inherent link between quantum information theory and biological energy management. Furthermore, the evolution of open quantum systems often exhibits memory effects, leading to non-Markovian dynamics[13]. The information backflow associated with these dynamics has been observed to provide a thermodynamic advantage in certain tasks, effectively enhancing the amount of work distillable from the process. The ability to extract work from quantum correlations and coherences, a unique characteristic of quantum thermodynamics, suggests that biological systems might be leveraging quantum information as a fundamental resource for energy management and efficient function. This opens up entirely new avenues for understanding biological efficiency that extend beyond classical energy conversion, implying a sophisticated, quantum-information-driven bio-machinery. Classical thermodynamics imposes limits on work extraction and information erasure (Landauer's principle), but the quantum realm introduces the possibility of extracting work from quantum correlations. If biological systems can exploit this, their energy efficiency and information processing capabilities could be fundamentally superior to what classical models predict, shifting the focus from purely chemical energy to the role of quantum information as a thermodynamic resource, and suggesting a much deeper integration of information and energy in living systems.

3.3. Implications for Biological Efficiency and Resilience

The implications of quantum thermodynamics for biological efficiency and resilience are profound. Understanding how quantum energy influences the body's capacity to resist and recover from stress, often termed physiological resistance, holds significant promise for overall well-being[14]. Quantum energy can directly influence cellular communication pathways, enhance the function of mitochondria (the cellular powerhouses), and modulate gene expression[14]. By optimizing these fundamental cellular processes and improving energy production, quantum effects can contribute to heightened physiological resistance.

A compelling theoretical framework, the quantum metabolism model, provides an explanation for the ubiquitous allometric scaling of metabolic rates [15] the relationship between an organism's metabolic rate and its body size. This model is based on the molecular oscillator hypothesis, which posits that energy generated by redox reactions within cells can be stored as coherent dynamical modes of molecular oscillators[15] embedded within bio-membranes. This concept aligns with Froehlich's theory of biological coherence. The model predicts different scaling exponents (e.g., $3/4$ for three-dimensional networks) depending on the dimensionality of the molecular oscillator network and whether the system operates in a "quantum limit" (where the mean cycle time is much shorter than the characteristic cycle time) or a "classical limit". This provides a unified conceptual framework for understanding the metabolic function of living systems, demonstrating how macroscopic physiological observations are rooted in underlying quantum mechanical principles and the geometry of molecular networks. The quantum metabolism model's ability to explain the ubiquitous allometric scaling of metabolic rates across diverse life forms is a powerful demonstration of the paradigm's explanatory power[15]. This moves beyond empirical correlations to provide a mechanistic, quantum-informed understanding of biological efficiency, solidifying the argument for the comprehensive explanatory power of the quantum-thermodynamic paradigm. Allometric scaling has long been an observed biological phenomenon, but its underlying mechanisms have been debated. A quantum-thermodynamic explanation, rooted in molecular oscillators and coherence, provides a deeper, unified framework. This is significant because it demonstrates that quantum biology is not merely about isolated phenomena but can explain broad, macroscopic biological laws, integrating disparate observations under a single, more fundamental theory.

4. The Oral Bio-Network Through a Quantum-Thermodynamic Lens

4.1. Complexity and Dynamic Equilibrium of the Oral Microbiome

The oral cavity represents an exceptionally complex and dynamic bio-network, characterized by diverse microbial communities and intricate host interactions that constantly adapt to environmental challenges. Applying a quantum-thermodynamic lens to this system offers profound insights into the underlying mechanisms governing its resilience, adaptability, and susceptibility to disease. The oral cavity is a highly dynamic microbial environment, housing distinct substrata and microenvironments that support diverse, complex polymicrobial biofilm communities[16]. The composition and function of this oral microbiome are shaped throughout an individual's life by a multitude of factors,

including host genetics, maternal transmission, dietary habits, oral hygiene practices, medications, and systemic health conditions. Oral health is generally characterized by a homeostatic balance between the host and its microbial communities[17]. In contrast, oral diseases, such as dental caries and periodontitis, are increasingly understood as consequences of a "deleterious shift in the balance" or a "microbial regime shift" towards dysbiosis within these communities[18]. Mechanisms contributing to maintaining oral health include complex metabolic and functional interrelationships both within the biofilms themselves and between the biofilms and the host, such as the pH buffering capacity of saliva and the production of ammonia by certain microbial species[17]. However, traditional classical models face inherent limitations in fully describing the dynamic, open, and complex nature of these oral bio-networks, particularly the intricate emergent patterns and interactions that arise from their collective behavior. The sheer scale and non-linear interactions within these systems often exceed the predictive capabilities of purely classical approaches.

The paradigm views oral health and disease not as static states but as dynamic, non-equilibrium processes, where health represents a stable, highly efficient dissipative structure, and disease signifies a deviation in this quantum-thermodynamic balance[19]. This implies that the stability, resilience, and functional efficiency of the oral bio-network are governed by its underlying quantum-thermodynamic state. Dysbiosis, therefore, is not merely a change in microbial composition but a degradation of the optimal dissipative structure and a loss of efficient quantum coherence and energy management. This fundamentally redefines oral health and disease. Disease is no longer viewed solely as a change in microbial composition or a structural issue, but rather as a degradation of the optimal dissipative structure and a loss of efficient quantum coherence and energy management. This provides a deeper, more mechanistic understanding of disease progression beyond simple microbial shifts, opening new avenues for defining and measuring oral health at a fundamental energetic and informational level.

Traditionally, oral diseases are viewed in terms of specific pathogens or inflammatory responses. By framing health as an "optimal dissipative structure" and disease as its "degradation" or "loss of quantum coherence," the paradigm shifts the focus from symptoms and agents to underlying systemic instability. This implies that interventions could target restoring this fundamental balance, rather than just eliminating pathogens or managing inflammation, leading to more holistic and potentially more effective treatments.

Table 2 Oral Bio-Network Components and Dynamics

Category	Description
Components	Microorganisms: Diverse communities of bacteria, fungi, protozoa, and viruses. Host Tissues: Hard non-shedding surfaces of teeth, epithelial surfaces of mucosal membranes, periodontal ligament, cementum, alveolar bone Fluids: Saliva (fluid phase), gingival crevicular fluid (GCF).
Key Structures	Multispecies biofilm communities embedded in extracellular polymeric substances (EPS) on tooth surfaces.
Influencing Factors	Host Factors: Genetics, maternal transmission, immune competence, specialized immune-cell networks. Environmental Factors: Host diet (nutritional resources, selective pressure), salivary flow, masticatory forces, introduction of exogenous microbes, pH (6.5–7 average), redox potential, nutrient availability, temperature (average 37°C), gases (CO ₂ , ammonia, oxygen). Lifestyle: Oral hygiene practice, medications, systemic factors.
Dynamics	Homeostasis (Eubiosis): A dynamic balance between host and microbial communities, where resident microbiota competes with and exclude exogenous pathogens, contributing to ecosystem stability and normal tissue/immune system development. Dysbiosis: Transition to a diseased state (e.g., dental caries and periodontitis) driven by environmental factors or host immune alterations, leading to selection and enrichment of pathogenic bacteria (pathobionts), increased virulence factor production, and reciprocally reinforced interactions between polymicrobial communities and a dysregulated host inflammatory response

This table is crucial for providing a comprehensive overview of the oral environment. For an interdisciplinary report, it lays the essential biological groundwork, clearly delineating the diverse components (microorganisms, host tissues, fluids) and dynamic processes (homeostasis, dysbiosis). This systematic categorization is vital as it provides clear context for how quantum-thermodynamic principles can be applied to this specific, complex biological system, making the subsequent theoretical discussions more grounded and accessible.

Table 3 Homeostasis vs. Dysbiosis: A Quantum-Thermodynamic Perspective

Feature	Homeostasis (Health)	Dysbiosis (Disease)
Thermodynamic State	Stable, self-organizing non-equilibrium steady state; optimal dissipative structure.	Unstable or pathologically stable non-equilibrium state; degraded dissipative structure.
Energy Flow	Highly efficient energy transduction and dissipation; optimal energy management.	Inefficient energy dissipation; energy imbalances; increased allostatic load.
Entropy Production	Continuous, controlled entropy production and expulsion to maintain order.	Disrupted entropy production; accumulation of disorder; inability to return to healthy state.
Quantum Coherence	High levels of functional quantum coherence; efficient quantum information processing.	Loss of functional quantum coherence; increased decoherence; inefficient quantum information processing.
Interactions	Balanced, reciprocally beneficial host-microbe interactions; robust feedback loops.	Reciprocally reinforced pathological interactions; dysregulated host inflammatory response.
Outcome	Resilience, adaptability, resistance to perturbations, long-term stability.	Vulnerability, progression to overt disease, reduced adaptability, chronic inflammation.

This table is central to the article's proposed paradigm shift. It visually contrasts healthy and diseased states through the quantum-thermodynamic lens, making the core argument disease as a deviation from optimal quantum-thermodynamic balance immediately apparent and impactful. Its direct comparative format enhances clarity and reinforces the novel theoretical framework. By explicitly mapping classical concepts of oral health and disease onto the proposed quantum-thermodynamic features, it provides a clear, concise, and visually impactful summary of the paradigm shift.

4.2. Quantum-Enhanced Host-Pathogen Interactions and Adaptive Mechanisms

The adaptability and resilience observed in the oral microbiome, as well as the intricate dynamics of host-pathogen interactions, may be fundamentally underpinned by quantum mechanical principles.

4.2.1. Bacterial Adaptation/Coordination

A theoretical framework suggests that bacteria might utilize quantum coherent oscillations, possibly mediated through synchronized membrane potential fluctuations, to achieve a remarkable degree of coordination in adaptive mutation, especially when confronted with stress conditions. This framework proposes experimentally testable predictions regarding mutation patterns and coherence times within bacterial populations. This implies that the microbiome's remarkable adaptability and resilience against environmental stressors might stem from these quantum mechanical principles, transforming the understanding of the microbiome from a mere collection of interacting classical entities to a sophisticated quantum-enabled collective. The idea that bacterial adaptation and coordination might be quantum-enabled via coherent oscillations suggests entirely new targets for intervention. Instead of relying solely on antibiotics targeting classical metabolic pathways, future therapies could aim to disrupt the quantum coherence of pathogenic biofilms, offering a fundamentally new approach to combat antimicrobial resistance and chronic infections.

Proposed Hypothesis 1

Quantum coherent oscillations within bacterial biofilms can be experimentally detected and quantified using advanced spectroscopic techniques, and their disruption through targeted quantum interventions (e.g., specific electromagnetic frequencies) will significantly reduce biofilm virulence and antibiotic resistance.

4.2.2. Bacterial Metabolism

Quantum tunneling is increasingly recognized as a vital process for life, with implications for molecular and biological evolution and even prebiotic chemistry[10]. While direct experimental evidence for quantum tunneling specifically in oral bacterial metabolism is not extensively detailed in the current literature, the general principle of enzyme catalysis via tunneling strongly suggests its potential relevance within the metabolic pathways of oral bacteria, such as in proton abstraction mechanisms within bacterial polysaccharide lyases.

4.2.3. Host-Pathogen Interactions (Quantum Immunology/Vaccinomics)

The application of quantum principles extends to host-pathogen interactions through the emerging concepts of "quantum immunology" and "quantum vaccinomics"[21]. These fields propose using quantum chemical calculations to predict biological function and design candidate vaccine antigens by identifying "immunological quantum"—protective epitopes—based on the electronic structure of molecular interactions. This approach suggests that the effectiveness of immune responses and the design of interventions are not solely about molecular shape or binding affinity, but about the underlying quantum mechanics of electron clouds and molecular interactions[22]. The concepts of "quantum immunology" and "quantum vaccinomics" suggest that true precision medicine in immunology could move beyond structural complementarity to manipulating quantum properties for more robust and specific immune responses, potentially leading to a new generation of highly effective, quantum-informed vaccines and immunotherapies.

Proposed Hypothesis 2

Designing vaccine antigens based on quantum chemical calculations of electron cloud interactions, rather than solely molecular shape, will lead to a measurable increase in the specificity and durability of immune responses against oral pathogens in preclinical models.

4.2.4. Quantum Dots (QDs) and Nanoparticles

Quantum dots (QDs), which are semiconductor nanocrystals, are emerging as powerful tools in dental research due to their unique properties, including fluorescence and antimicrobial activity[23]. They are being explored for labeling and detection of bacteria in biofilms, offering enhanced photostability compared to traditional fluorophores[24]. QDs also show considerable potential in enhancing antimicrobial capabilities and facilitating targeted drug delivery within dentistry.

4.2.5. Cavity Coherence

While direct evidence for quantum coherence specifically within the oral cavity's biological processes is not extensively detailed, the concept of "cavity coherence" is discussed in the context of quantum computing, suggesting theoretical frameworks for maintaining coherence in noisy environments that could be analogous to biological systems. Optical coherence tomography (OCT) is already a diagnostic tool for oral cancer, leveraging coherence principles, though not explicitly "quantum coherence" in the biological sense.

Table 4 Potential Quantum Effects in Oral Bio-Network Dynamics

Area of Oral Bio-Network	Proposed Quantum Effect	Potential Implication for Health/Disease
Bacterial Metabolism	Quantum tunneling in enzyme catalysis (e.g., proton abstraction in polysaccharide lyases).	Enhanced metabolic efficiency and reaction rates in oral bacteria; potential for targeted disruption of pathogenic pathways.
Bacterial Adaptation/Coordination	Quantum coherent oscillations (e.g., via synchronized membrane potential fluctuations).	Rapid, coordinated adaptive mutations in response to stress; enhanced resilience of the oral microbiome.
Host-Pathogen Interactions	Quantum effects in molecular	Precision and specificity of

This table serves as a vital bridge, concretely linking abstract quantum effects to their specific, potential roles within the oral cavity. It translates theoretical concepts into tangible applications and highlights promising areas for future research, diagnostic development, and therapeutic interventions in dentistry. This makes the theoretical applications concrete and actionable, illustrating the direct relevance of quantum biology to dentistry and implicitly outlining a research agenda by highlighting areas where quantum effects are hypothesized to play a role and could be investigated for health and disease implications.

5. Challenges and Opportunities in Quantum Dentistry

5.1. Scientific and Technological Hurdles

One of the primary criticisms and scientific hurdles for quantum biology is the "warm, wet, and noisy problem"[12]. Quantum effects are notoriously delicate and typically require extremely low temperatures and highly controlled,

isolated conditions to persist. This stands in stark contrast to the chaotic, high-temperature, and aqueous environment found within living cells. Skeptics argue that any observed quantum effects in biological systems might be fleeting fluctuations rather than robust, sustained phenomena that meaningfully influence life. However, counter-arguments highlight experimental evidence of quantum effects, such as superradiance in protein fibers, persisting even at room temperature[11]. This suggests that biological systems have evolved sophisticated, intrinsic mechanisms such as specific protein symmetries or unique micro-environments—to actively protect and sustain these fragile quantum states. This observation resolves what initially appears to be a fundamental contradiction: the fragility of quantum effects versus the chaotic biological milieu[11]. The presence of evolved protective mechanisms implies that biological systems are not merely passive recipients of quantum phenomena but rather active quantum engineers. This shifts the research paradigm from questioning the existence of quantum effects in biology to investigating how life maintains them and what can be learned from these natural solutions, offering blueprints for robust artificial quantum technologies.

Reproducibility issues also pose a significant challenge. While landmark studies provide compelling evidence for quantum effects in biological systems, other laboratories have sometimes struggled to replicate these results under different conditions. Furthermore, certain experimental setups can inadvertently introduce artifacts, leading to questions about whether observed quantum phenomena in biology might be overestimated due to misinterpreted data. Beyond the experimental realm, there are still many unresolved issues in quantum mechanics itself, such as the phenomenology of wave function collapse[4], with competing interpretations (e.g., many-worlds vs. Copenhagen interpretations) that lack a definitive conclusion.

Historically, despite quantum mechanics having existed for over a century, it has rarely been applied in medicine, with conventional modern medicine often unable to explain certain clinical phenomena

5.2. Bridging Disciplinary Boundaries and Fostering Interdisciplinary Research

5.2.1. The Challenge of Disciplinary Silos

A significant challenge in advancing quantum biology, and by extension quantum dentistry, lies in the staunch disciplinary boundaries[6] that traditionally separate physics, chemistry, and biology. Physicists may perceive biological systems as overly complex and "messy" for systematic quantum analysis, while biologists may view quantum mechanics as too abstract and far removed from the scales and behaviors, they typically study. This intellectual divide often creates communication gaps, hindering the momentum required for groundbreaking discoveries and their translation.

5.2.2. Fostering Interdisciplinary Collaboration

Addressing these challenges necessitates a concerted effort to foster interdisciplinary training. This involves developing dedicated programs for researchers who are fluent in quantum theory, biological systems, bio-inspired quantum technologies, various spectroscopic techniques, and multiscale computational modeling. Such training is crucial for cultivating a new generation of scientists capable of navigating and integrating these diverse fields. Encouragingly, existing interdisciplinary efforts provide a blueprint for future collaboration. Institutions such as the Center for Quantum Information and Quantum Biology at Osaka University actively promote transdisciplinary research and international academic exchanges[25]. Similarly, Howard University's Quantum Biology Lab exemplifies successful interdisciplinary research, spanning theoretical physics, chemistry, biology, and computational science[26]. The National Science Foundation (NSF) also plays a vital role by supporting multidisciplinary collaboration in quantum information science[27], including initiatives like Quantum Sensing for Biophysics and Bioengineering (QuBBE). Ultimately, close cooperation between medicine and physics is essential for scientific progress. Intriguingly, biological reactions may even offer unique experimental avenues to help resolve some of the currently unanswered problems within quantum mechanics itself.

5.2.3. Unexplained Clinical Phenomena: A Quantum Opportunity

Anecdotal clinical observation in dentistry, such as patients' bodily symptoms improving when dentures or medicines are merely brought close to the body (without direct ingestion or application), or when a denture is adjusted outside the mouth, are currently inexplicable by conventional medical concepts. However, some propose that these phenomena could be explained by quantum mechanics, specifically through the interference of "waves emitted by dentures or medicine" with "pathological waves" emanating from the afflicted area of the body[28]. While highly speculative and requiring rigorous empirical validation, these "unexplained" clinical occurrences could serve as intriguing, albeit preliminary, clues for where quantum biological interactions might be at play in clinical settings[29]. The presence of these "unexplained clinical phenomena" in dentistry, while currently speculative, offers a unique opportunity for real-

world empirical validation of subtle quantum biological interactions. Framing these as testable hypotheses moves them from anecdotal curiosities to potential direct evidence for the field's clinical relevance, thereby accelerating its translation. * Proposed Hypothesis 3: The anecdotal clinical improvements observed when dental prosthetics or medicines are brought into close proximity to the body, without direct contact or ingestion, are mediated by specific quantum field interactions (e.g., resonant frequencies or coherent energy transfer) that can be measured and replicated under controlled experimental conditions.

Table 5 Challenges and Opportunities in Applying Quantum Biology to Clinical Dentistry

Category	Specific Challenge	Associated Opportunity/Mitigation Strategy
Scientific	"Warm, Wet, and Noisy Problem": Maintaining fragile quantum effects in chaotic biological environments.	Biological systems have evolved specific symmetries/micro-environments to protect quantum states; learning from nature's solutions
Technological	Reproducibility Issues: Difficulty in replicating landmark studies; potential for experimental artifacts.	Development of more advanced spectroscopic techniques and real-time molecular imaging to provide direct proof.
Theoretical	Unresolved Quantum Mechanics Issues: Fundamental interpretations (e.g., wave function collapse) lack consensus.	Biological reactions may offer unique experimental systems to help solve unresolved problems in quantum mechanics.
Interdisciplinary	Disciplinary Boundaries: Communication gaps and differing perspectives between physicists and biologists.	Fostering dedicated interdisciplinary training programs and collaborative research centers.
Clinical	Lack of Historical Clinical Application: Quantum mechanics rarely applied in medicine; conventional medicine cannot explain certain phenomena.	Unexplained clinical observations (e.g., external stimuli improving symptoms) as potential early indicators of quantum biological interactions

This table is essential for a comprehensive and well-rounded scientific report. It not only transparently lists the significant challenges that quantum biology faces but also immediately pairs them with associated opportunities or mitigation strategies. This proactive and solution-oriented approach reinforces the idea that the field is maturing and actively working to overcome its limitations, which is vital for gaining acceptance and support from the broader scientific and medical communities.

6. Transformative Potential: Predictive, Preventive, and Personalized Dentistry (PPPD)

The integration of quantum biology and non-equilibrium thermodynamics offers a truly transformative potential for the future of dental care, aligning seamlessly with the principles of Predictive, Preventive, and Personalized Dentistry (PPPD). This approach emphasizes predicting future disease emergence, implementing proactive preventive measures, and tailoring treatments to the unique biological profile of each individual patient, often with active patient participation.

6.1. Next-Generation Diagnostic Tools for Early Disease Detection

A quantum-thermodynamic lens can revolutionize diagnostics by enabling earlier and more precise detection of oral health issues. Current advancements in artificial intelligence (AI) diagnostic systems already assist in detecting caries, bone loss, and even oral cancers at earlier stages, improving treatment planning[30]. However, the quantum-thermodynamic framework suggests a deeper level of diagnostic capability. This paradigm views oral health and disease not as static states, but as dynamic, non-equilibrium processes, where health represents a stable, highly efficient dissipative structure, and disease signifies a deviation in this quantum-thermodynamic balance. This understanding paves the way for quantum sensors capable of ultra-sensitive diagnostics, potentially pinpointing infections within individual cells or detecting subtle energetic imbalances before macroscopic symptoms manifest. This represents a fundamental shift from current diagnostics, which largely react to established disease markers or structural changes, to a truly predictive capability. By identifying deviations in the underlying quantum-thermodynamic balance, it implies the potential for interventions to prevent disease onset rather than merely treating its progression, aligning perfectly with the "Predictive" aspect of PPPD. Such sensors could facilitate real-time microbiome assessment, proteomic profiling of gingival biopsies, and advanced biomarker assessment in saliva or blood, providing a comprehensive picture of an individual's vulnerability to disease. Optical coherence tomography (OCT), which leverages coherence principles,

is already showing promise for early diagnosis of oral dysplasia and malignancy[31]. Future quantum-enhanced imaging techniques could offer even greater resolution and sensitivity. * Proposed Hypothesis 4: Ultra-sensitive quantum sensors can detect specific changes in the quantum coherence or energetic states of oral bio-networks (e.g., shifts in electron spin states or coherent phonon modes) that precede the biochemical and structural markers of dental caries or periodontal disease, enabling earlier and more precise diagnosis than current methods.

6.2. Novel Therapeutic Strategies: Restoring Optimal Quantum States

Beyond diagnostics, the quantum-thermodynamic framework opens avenues for novel therapeutic strategies designed to restore optimal quantum states within oral bio-networks[5]. If disease is understood as a deviation from an efficient quantum-thermodynamic balance, then therapies could aim to re-establish this balance at a fundamental level. This could involve quantum-optimized drug design, where drugs are engineered with quantum-level precision to interact with biological targets, potentially leading to radically faster pharmaceutical synthesis and more effective treatments[32]. Bio-hybrid implants with quantum-level precision could be developed, integrating advanced materials with biological systems at a fundamental level. The application of quantum mechanics in medicine, though historically rare, is poised to play an important role in developing new therapies, potentially explaining phenomena currently unclarified by modern medicine. Harnessing quantum energy could enhance physiological resistance, optimize cellular function, improve mitochondrial efficiency, and modulate gene expression, thereby contributing to overall improved health and resilience. This approach moves beyond targeting specific molecular pathways to addressing the underlying energetic and informational integrity of biological systems[33]. It suggests a future where treatments are not just effective but profoundly restorative, potentially influencing fundamental biological rhythms, such as circadian rhythms, which are increasingly recognized as bedrock elements in chronic disease. This aligns with the "Preventive" and "Personalized" aspects of PPPD by offering highly targeted and foundational interventions. * Proposed Hypothesis 5: Therapies designed to restore optimal quantum states (e.g., through targeted electromagnetic fields or quantum-coherent light) can reverse early-stage dysbiosis in the oral microbiome and promote tissue regeneration more effectively than conventional treatments, by re-establishing efficient energy transfer and information processing within the oral bio-network.

6.3. Quantum Dots and Nanoparticles in Advanced Dental Materials

The field of advanced dental materials is already benefiting from nanotechnology, and quantum principles are poised to further accelerate innovation. Quantum dots (QDs), semiconductor nanocrystals, have gained significant attention in dentistry due to their unique properties, including fluorescence, antimicrobial activity, and drug delivery potential[23]. They are being explored for labeling and detection of bacteria in biofilms, offering enhanced photostability compared to traditional fluorophores[24]. QDs also show considerable potential in enhancing antimicrobial capabilities and facilitating targeted drug delivery within dentistry. While nanotechnology is already transforming dentistry, the integration of quantum principles (e.g., QDs leveraging quantum effects for unique properties) represents a significant advancement[34]. This is not just about using materials at the nanoscale, but about designing materials that exploit quantum phenomena for enhanced functionality (e.g., ultra-precise targeting, superior antimicrobial action, improved optical performance). This implies a future where dental materials are not just biocompatible but "quantum-optimized," leading to unprecedented performance and truly personalized applications in dentistry.

Table 6 Quantum-Thermodynamic Applications in Predictive, Preventive, and Personalized Dentistry (PPPD)

PPPD Pillar	Quantum Thermodynamic Application Area	Specific Example/Technology	Anticipated Benefit in Dentistry
Predictive	Diagnostics and Risk Assessment	Quantum sensors for ultra-sensitive detection of molecular/energetic imbalances; AI-enhanced quantum imaging.	Earlier, more precise disease prediction; identification of individuals at risk before symptoms manifest.
Preventive	Prophylaxis and Resilience Enhancement	Quantum-optimized pre/probiotics influencing microbiome quantum states; therapies enhancing physiological resistance via quantum energy.	Enhanced microbiome resilience; optimized cellular function to resist disease; reduced incidence of oral diseases.
Personalized	Targeted Therapeutics and Materials	Quantum-optimized drug design; bio-hybrid implants with quantum precision; quantum dots for targeted drug delivery.	Highly effective, tailored treatments; improved material integration and longevity; reduced side effects.

7. Conclusion and future outlook: A new era for oral health

The integration of non-equilibrium quantum thermodynamics into the understanding of oral bio-networks represents a profound paradigm shift for dentistry. Traditional classical models, focused on equilibrium, are inherently limited in describing the dynamic, open, and complex nature of living systems[1]. This report has demonstrated that oral health and disease are not merely static states but rather dynamic, non-equilibrium processes, where health corresponds to a stable, highly efficient dissipative structure, and disease represents a deviation or instability in this quantum-thermodynamic balance.

The pervasive influence of quantum phenomena including superposition, entanglement, tunneling, and coherence—is increasingly recognized as fundamental to biological efficiency, energy transduction, and ultra-fast information processing within biological systems[2]. Pioneering research, such as that on superradiance in protein networks, highlights the potential for biological systems to operate as sophisticated quantum information processors[11]. This suggests that the adaptability and resilience of the oral microbiome, as well as the intricate host-pathogen interactions, may be underpinned by quantum mechanical principles[16]. This quantum-thermodynamic framework offers a mechanistic explanation for phenomena previously unaddressed by classical models, such as the allometric scaling of metabolic rates and the remarkable resilience of biological networks[15]. It reframes disease not simply as a biochemical malfunction but as a deviation from an optimal quantum-thermodynamic balance, suggesting that restoring health may involve re-establishing these fundamental energetic and informational states.

While the field is nascent and faces significant scientific and interdisciplinary challenges—including the "warm, wet, and noisy" biological environment and the need for rigorous reproducibility—the opportunities are immense. The very existence of quantum effects in biological systems suggests that life has evolved intrinsic mechanisms to protect and utilize these delicate states, offering a blueprint for bio-inspired quantum technologies[12]. Furthermore, currently unexplained clinical observations in dentistry could serve as intriguing preliminary clues for where quantum biological interactions might be at play, warranting further investigation[28]. The transformative potential for Predictive, Preventive, and Personalized Dentistry (PPPD) is clear. Future advancements will likely include ultra-sensitive quantum sensors for early disease detection, quantum-optimized therapeutic strategies designed to restore cellular and molecular balance, and advanced dental materials incorporating quantum dots for enhanced performance[23]. Realizing this future necessitates sustained, collaborative, and truly interdisciplinary research efforts, fostering a new generation of scientists capable of bridging the quantum and biological realms. By embracing this frontier, dentistry can move towards a more holistic, precise, and fundamentally informed approach to oral and systemic health.

References

- [1] Al-Khalili J, McFadden J. Quantum biology: The new frontier. *J R Soc Interface*. 2014;11(96):20140416.
- [2] Al-Khalili J, McFadden J. *Life on the edge: The coming of age of quantum biology*. Crown; 2016.
- [3] Al-Khalili J, McFadden J. Quantum biology research meets pathophysiology and therapeutic mechanisms: A biomedical perspective. *Quantum Rep [Internet]*. 2018 [cited 2025 Jun 19];4(2):11.
- [4] Al-Khalili J, McFadden J. Quantum vaccinomics platforms to advance in vaccinology. *Front Immunol [Internet]*. 2023 [cited 2025 Jun 19];14:1172734.
- [5] Aps L. Recovering quantum coherence of a cavity qubit coupled to a noisy ancilla through real-time feedback. *Phys Rev X [Internet]*. 2024 [cited 2025 Jun 19];14(4).
- [6] Argonne National Laboratory. What is quantum coherence? [Internet]. Argonne (IL): Argonne National Laboratory; 2025 Feb 19 [cited 2025 Jun 19].
- [7] Apple Podcasts. EP 064: The incredible quantum story of our eyes and mouth [Internet]. [place unknown]: Apple Podcasts; [date unknown][cited 2025 Jun 19].
- [8] Bartold PM, Ivanovski S. P4 medicine as a model for precision periodontal care. *Clin Oral Investig [Internet]*. 2022 [cited 2025 Jun 19];26(9):5517–33.
- [9] Biological Quantum Sensors. Biological quantum sensors [Internet]. [place unknown]: Biological Quantum Sensors; [date unknown][cited 2025 Jun 19].
- [10] Binder F, Vinjanampathy L, Modi K, Goold J. Quantum thermodynamics [Internet]. [place unknown]: ResearchGate; 2015 [cited 2025 Jun 19].

- [11] bioRxiv. Could quantum-mediated bacterial signaling explain adaptive mutation? [Internet]. Cold Spring Harbor (NY): Cold Spring Harbor Laboratory; [date unknown][cited 2025 Jun 19].
- [12] Demetrius LA, Manke T. Quantum metabolism explains the allometric scaling of metabolic rates. *Proc R Soc B Biol Sci* [Internet]. 2005 [cited 2025 Jun 19];272(1563):653–61.
- [13] Discover Engineering. Thermodynamics of non-equilibrium processes [Internet]. [place unknown]: Discover Engineering; [date unknown][cited 2025 Jun 19].
- [14] Eissa M. Quantum biology from theory to the future of medicine and pharmacy: A review on a revolutionary change. *Univ J Pharm Res* [Internet]. 2023 [cited 2025 Jun 19];8(2):1–10.
- [15] Fiveable. Non-equilibrium thermodynamics in living systems [Internet]. [place unknown]: Fiveable; [date unknown][cited 2025 Jun 19].
- [16] Fiveable. Non-equilibrium statistical mechanics [Internet]. [place unknown]: Fiveable; [date unknown][cited 2025 Jun 19].
- [17] Flashcards World. Quantum thermodynamics in biological systems [Internet]. [place unknown]: Flashcards World; [date unknown][cited 2025 Jun 19].
- [18] Goldenberg J, Libai B, Muller E. Talk of the network: A complex systems look at the underlying process of word-of-mouth. *Mark Lett*. 2001;12(3):211–23.
- [19] MDPI. Quantum dots (QDs) nanotechnology has gained significant attention in dentistry due to its unique properties, such as fluorescence, antimicrobial activity, and drug delivery potential [Internet]. Basel (Switzerland): MDPI; [date unknown][cited 2025 Jun 19].
- [20] MDPI. Exploring the role of nanoparticles in dental materials: A comprehensive review [Internet]. Basel (Switzerland): MDPI; [date unknown][cited 2025 Jun 19].
- [21] MDPI. Dysbiosis of the oral microbiome contributes to systemic inflammation, disrupts the blood–brain barrier, and promotes neuroinflammation, processes increasingly implicated in the pathogenesis of AD [Internet]. Basel (Switzerland): MDPI; [date unknown][cited 2025 Jun 19].
- [22] Mira A, Mira A. The oral microbiota: Dynamic communities and host interactions. *Nat Rev Microbiol* [Internet]. 2018 [cited 2025 Jun 19];16(12):739–52.
- [23] Muldrow M. Quantum biology and the future of synthetic biology: Are cells quantum computers? [Internet]. [place unknown]: Phantom Ecology; 2025 Mar 3 [cited 2025 Jun 19].
- [24] Myers J. Quantum biology yields evidence of superradiance and its potential for quantum information processing [Internet]. [place unknown]: The Quantum Record; 2025 Jan 23 [cited 2025 Jun 19].
- [25] National Science Foundation. Quantum information science [Internet]. Alexandria (VA): National Science Foundation; [date unknown][cited 2025 Jun 19].
- [26] Orion Dental. Innovations in dentistry and a look forward to 2024 [Internet]. [place unknown]: Orion Dental; [date unknown][cited 2025 Jun 19].
- [27] Osaka University, Center for Quantum Information and Quantum Biology. QIQB | Center for Quantum Information and Quantum Biology, the University of Osaka [Internet]. Osaka (Japan): Osaka University; [date unknown][cited 2025 Jun 19].
- [28] Pahl P. Quantum processes as thermodynamic resources: The role of non-Markovianity. *Phys Rev X* [Internet]. 2025 [cited 2025 Jun 19];14(4).
- [29] Palmer R. The oral microbiome: Role of key organisms and complex networks in oral health and disease. *J Dent Res* [Internet]. 2017 [cited 2025 Jun 19];96(12):1374–83.
- [30] PNAS. Bacterial polysaccharide lyase family 33: Specificity from an evolutionarily conserved binding tunnel [Internet]. Washington (DC): National Academy of Sciences; [date unknown][cited 2025 Jun 19].
- [31] Prigogine I, Nicolis G. Self-organization in nonequilibrium systems: From dissipative structures to order through fluctuations. New York (NY): John WileyAnd Sons; 1977.
- [32] RDH Magazine. Proactive dental care for overall wellness: Harnessing the power of P4 medicine in oral health [Internet]. [place unknown]: RDH Magazine; [date unknown][cited 2025 Jun 19].

- [33] ResearchGate. Use of quantum dot luminescent probes to achieve single-cell resolution of human oral bacteria in biofilms [Internet]. [place unknown]: ResearchGate; [date unknown][cited 2025 Jun 19].
- [34] ResearchGate. The relationship between quantum energy and physiological resistance biological ceiling [Internet]. [place unknown]: ResearchGate; [date unknown][cited 2025 Jun 19].
- [35] Rieper E. Quantum coherence in biological systems [dissertation]. Singapore: National University of Singapore; 2011.
- [36] Scilit. Unlocking tiny titans: 360 view of the quantum dots nanotechnology for dental applications [Internet]. [place unknown]: Scilit; [date unknown][cited 2025 Jun 19].
- [37] Scirp. Dental treatment and quantum mechanics [Internet]. [place unknown]: Scirp; [date unknown][cited 2025 Jun 19].
- [38] Scirp. Dental treatment using quantum mechanics for knee joint pain [Internet]. [place unknown]: Scirp; [date unknown][cited 2025 Jun 19].
- [39] Swayne M. What's quantum biology? A research pioneer shares his vision for quantum technology's next frontier [Internet]. [place unknown]: The Quantum Insider; 2025 May 29 [cited 2025 Jun 19].
- [40] TaylorAnd Francis Group. Nonequilibrium thermodynamics: Transport and rate processes in physical, chemical and biological systems [Internet]. [place unknown]: TaylorAnd Francis Group; [date unknown][cited 2025 Jun 19].
- [41] Tech Explorist. Quantum biology redefines life's computational limits [Internet]. [place unknown]: Tech Explorist; 2025 Apr 1 [cited 2025 Jun 19].
- [42] The Guy Foundation Family Trust. About quantum biology [Internet]. [place unknown]: The Guy Foundation Family Trust; [date unknown][cited 2025 Jun 19].
- [43] The Microbiology Society. Quantum theory for infectious diseases: Insights, prospects, and challenges [Internet]. [place unknown]: The Microbiology Society; [date unknown][cited 2025 Jun 19].
- [44] Trixler F. Quantum tunnelling to the origin and evolution of life [Internet]. [place unknown]: Science.gov; 2013 [cited 2025 Jun 19].
- [45] University of Maryland Global Campus Library. APA 7th edition website citation format [Internet]. Adelphi (MD): University of Maryland Global Campus Library; [date unknown][cited 2025 Jun 19].
- [46] Wilder-Smith P, Lee K. Potential of optical coherence tomography for early diagnosis of oral malignancies. J Biomed Opt [Internet]. 2014 [cited 2025 Jun 19];19(5):051202.