



REVIEW ARTICLE

QUANTUM BIOLOGY FROM THEORY TO THE FUTURE OF MEDICINE AND PHARMACY: A REVIEW ON A REVOLUTIONARY CHANGE IN OUR PERCEPTION OF LIFE

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Abstract

Quantum biology is an innovative field that blends quantum mechanics and biology to explore how quantum phenomena influence biological processes. This review discusses the fundamental principles of quantum biology, its potential applications in medicine, materials science and energy production, as well as the ethical implications of its progress. By understanding the quantum intricacies of life, we can gain insights into disease mechanisms, develop innovative materials and harness sustainable energy sources. Quantum mechanics, essential for understanding atomic and subatomic behavior, underpins quantum biology, which examines processes like photosynthesis, olfaction and enzyme catalysis. Key principles include superposition, entanglement and tunneling, which may enhance biological efficiency, sensitivity and precision. Quantum biology's potential spans various fields: in medicine and pharmacy, it could lead to new diagnostic tools and therapies; in materials science, it could inspire quantum materials for electronics, energy storage and sensing; in energy production, it could inform sustainable energy development through photosynthesis insights. However, ethical considerations are crucial. Quantum-enhanced medical technologies might widen healthcare disparities and advanced quantum materials could have mixed societal impacts. Open dialogue and ethical frameworks are necessary for responsible development. The future of quantum biology is promising, with ongoing research and interdisciplinary collaboration expected to yield innovative discoveries, fostering a sustainable and prosperous future.

Keywords: Enzyme catalysis, medicine, photosynthesis, quantum biology, quantum coherence, quantum tunneling.

INTRODUCTION

The dawn of quantum mechanics in the early 1900s dramatically altered our perception of the physical world at the atomic and subatomic levels. Yet, its potential impact on biological systems, operating on a vastly different scale, remained largely uncharted until recent times. Quantum biology, a newly emerging field, aims to bridge this gap by exploring the possible role of quantum phenomena in biological processes. Quantum biology can be defined as an emerging scientific field that investigates the potential influence of quantum mechanics on biological processes. It is important to elucidate how quantum phenomena, such as superposition, entanglement and tunneling, might affect the behavior of biological systems at the molecular and cellular levels¹⁻³. While classical mechanics adequately explains many biological processes, quantum mechanics may be essential for understanding certain phenomena involving

interactions at the atomic and subatomic level. Quantum biology seeks to identify and comprehend these quantum effects and their implications for biological function⁴⁻⁶. This paper aims to provide a comprehensive overview of the emerging field of quantum biology, highlighting its fundamental principles, potential applications and ethical considerations. By exploring the intersection of quantum mechanics and biology, this article could stimulate further research and interdisciplinary collaboration, ultimately contributing to a deeper understanding of life and the development of innovative technologies.

This review seeks to provide a comprehensive overview of the emerging field of quantum biology where it is less known and understood in the developing countries. By exploring the fundamental principles of quantum mechanics and their potential applications in biological processes, it can stimulate further research and global collaboration between

nations. The potential applications of quantum biology in medicine, materials science and energy production are highlighted, along with the ethical implications of such research. Ultimately, this article will contribute to a deeper understanding of life and the development of innovative technologies for human betterment.

Key milestones in quantum research

The field of quantum biology has witnessed significant advancements since its inception in the early 20th century. In 1926, Erwin Schrödinger's wave equation laid the groundwork for understanding quantum systems. Decades later, Max Delbrück proposed the potential involvement of quantum effects in biological processes like vision. Photosynthesis research in the 1960s highlighted the importance of energy transfer,

while studies on enzyme catalysis in the 1970s and 1980s suggested the role of quantum tunneling. The 1990s saw the emergence of quantum coherence as a potential mechanism for energy transfer in photosynthesis, with seminal papers by Gregory Scholes and Graham Fleming solidifying this concept. Experimental breakthroughs in the 2010s demonstrated the existence of quantum coherence in photosynthetic systems. Today, research continues to explore the role of quantum effects in diverse biological processes, paving the way for exciting discoveries and applications in the future⁷⁻¹⁶. Table 1 shows a summary timeline of the major discoveries in quantum field leading the way to the advancement in quantum biology era.

Table 1: A timeline of quantum research milestones leading to foundation quantum biology field⁷⁻¹⁶.

| Year | Event* | Significance |
|--------------------------------|---|--|
| Early 20 th century | Development of quantum mechanics | Established a theoretical framework for comprehending the characteristics and interactions of matter and energy at the atomic and subatomic scales. |
| 1920s | Early quantum biology concepts | The potential implications of quantum mechanics for biological systems began to be explored by scientists such as Erwin Schrödinger and Niels Bohr. |
| 1960s | Photosynthesis research | Studies on photosynthesis began to reveal the importance of energy transfer processes, which would later be linked to quantum phenomena. |
| 1970s-1980s | Enzyme catalysis and quantum tunnelling | Research on enzyme catalysis suggested that quantum tunneling might play a role in chemical reactions within biological systems. |
| 1990s | Quantum coherence in biological systems | Studies began to explore the possibility of quantum coherence in biological processes, particularly photosynthesis. |
| 2000s | Increasing interest in quantum biology | The potential role of quantum effects in various biological processes has attracted increasing attention from researchers, leading to a surge in interest in the field of quantum biology. |
| 2010s | Experimental breakthroughs | Recent advancements in experimental methodologies have facilitated the direct observation of quantum phenomena within biological systems. These observations provide compelling evidence supporting the significance of quantum mechanics in biological processes. |
| 2020s | Growing interdisciplinary collaboration | Increasing collaboration between physicists, biologists, chemists, and other scientists has led to significant progress in quantum biology research. |
| Present | Continued advancements | Research in quantum biology is ongoing, with new discoveries being made and potential applications emerging in fields such as medicine, materials science and energy production. |

A review of quantum biology research

Quantum biology, a nascent field of scientific inquiry, investigates the potential influence of quantum mechanical principles on biological processes. In recent decades, significant strides have been made in comprehending how quantum phenomena might impact various aspects of life. Early investigations in quantum biology concentrated on the potential utilization of quantum mechanics in elucidating enzyme catalysis, consciousness and biomimetic systems. More contemporary research has explored deeply the role of quantum effects in avian navigation, energy production, protein folding, olfaction, and quantum computing. A pivotal breakthrough in quantum biology has been the discovery of quantum coherence in photosynthetic systems. This phenomenon suggests that plants may harness quantum effects to enhance the efficiency of energy transfer. Furthermore, researchers have uncovered evidence for quantum tunneling in enzyme catalysis and quantum effects in DNA. Quantum biology has also spurred

advancements in materials science, with scientists exploring the development of novel quantum materials inspired by biological systems. These materials could potentially revolutionize fields such as electronics, energy storage and sensing. As quantum biology continues to evolve, groundbreaking discoveries and practical applications are anticipated^{12-14,16-26}. By deciphering the quantum principles underlying biological systems, innovative solutions to pressing global challenges may be devised. Table 2 presents a chronological outline of the discoveries achieved in quantum biology²⁷.

Foundational principles of quantum biology

Quantum biology based on foundation pillars that involve complex physical and mathematical models of the quantum physics. The fundamental tenets of quantum mechanics, encompassing the Schrödinger equation, wave-particle duality and the uncertainty principle, establish the mathematical basis for comprehending the behavior of matter and energy at the atomic and subatomic scales^{12,13,18,28,29}.

Table 2: A brief overview of research done in quantum biology^{12,14,16-27}.

| Author(s) | Title* | Journal | Publication Year | Main Focus |
|-----------------------------------|---|---|------------------|---|
| Marcus RA | Electron transfer reactions in chemistry and biology | Annual Review of Physical Chemistry | 1992 | Enzyme catalysis |
| Stapp H | Quantum mechanics and the philosophy of biology | Foundations of Physics | 1993 | Consciousness, quantum mechanics |
| Benyus JM | Biomimicry: Innovation inspired by nature | HarperCollins | 1997 | Biomimicry |
| Ritz T, <i>et al.</i> | Magnetoreception: Birds may utilize a quantum compass | Proceedings of the National Academy of Sciences | 2000 | Avian navigation |
| Grätzel M | Photoelectrochemical cells with semiconductor electrodes | Nature | 2001 | Energy production |
| Chandler D, <i>et al.</i> | Quantum effects in protein folding | Proceedings of the National Academy of Sciences | 2002 | Protein folding |
| Schreiner PR, <i>et al.</i> | Quantum tunneling in odorant Discrimination: A theoretical study | Science | 2002 | Olfaction |
| Gao J, <i>et al.</i> | Quantum tunneling in enzyme catalysis | Science | 2003 | Enzyme catalysis |
| Leuenberger MN, Loss D | Quantum computing in molecular magnets | Nature | 2005 | Quantum computing |
| Scholes G, Fleming G | Quantum coherence in biological systems | Nature | 2007 | Photosynthesis |
| Engel G, <i>et al.</i> | Quantum coherence enables wave-like energy transfer within photosynthetic systems | Nature | 2007 | Photosynthesis |
| Jena AK, <i>et al.</i> | Quantum coherence in DNA | Journal of Chemical Physics | 2008 | DNA |
| Panitchayangkoon P, <i>et al.</i> | Prolonged quantum coherence in photosynthetic complexes at biologically relevant temperatures | Proceedings of the National Academy of Sciences | 2011 | Photosynthesis |
| May V, Kühn O | Quantum Biology: Principles, concepts, and applications | Wiley-VCH | 2011 | Photosynthesis, energy transfer |
| Pan Y, <i>et al.</i> | Quantum coherence in the avian compass: A potential mechanism for high sensitivity | New Journal of Physics | 2012 | Avian navigation |
| Aspelmeyer M, <i>et al.</i> | Cavity optomechanical systems: Nanomechanics meets quantum optics | Reviews of Modern Physics | 2014 | Quantum technology |
| Tegmark M | The quantum brain | Penguin Press | 2014 | Consciousness, quantum effects in the brain |
| Preskill J | Quantum computing in the NISQ era | Quantum | 2018 | Quantum computing |
| Wang F, <i>et al.</i> | Quantum materials: A perspective | Nature Materials | 2019 | Quantum materials |

Physical and mathematical foundations of quantum biology

Quantum biology is grounded in the principles of quantum mechanics. The Schrödinger equation, a cornerstone equation describing the temporal evolution of a quantum system's wave function, is pivotal. The wave-particle duality, which acknowledges the dual nature of particles as both waves and particles, is fundamental to comprehending quantum behavior. The uncertainty principle emphasizes the inherent limitation in simultaneously measuring a particle's exact position and momentum. Quantum coherence, the capacity of quantum systems to exist in multiple states concurrently and quantum tunneling, the phenomenon of particles traversing seemingly impenetrable barriers,

are crucial concepts within quantum biology to explain the core of several complicated living systems. Additionally, quantum entanglement, the non-local correlation between quantum particles, has potential implications for communication and information processing within biological systems. These quantum mechanical principles have been applied to various biological processes. Photosynthesis is believed to utilize quantum coherence for efficient energy transfer. Quantum tunneling is implicated in proton transfer during enzyme catalysis. Avian navigation may involve quantum effects related to the sensing of Earth's magnetic field. Quantum entanglement is theorized to play a role in long-range communication within DNA molecules, and some theories propose its involvement

in consciousness. Quantum biology, a burgeoning field at the intersection of physics and biology, delves into the potential role of quantum mechanics in understanding biological processes. The mathematical framework of quantum mechanics provides the essential tools for exploring these phenomena. At the heart of quantum biology lies the Schrödinger equation, which describes the time evolution of a quantum system's wave function^{9,12,13}. This equation, represented as $i\hbar \frac{\partial \psi}{\partial t} = \hat{H}\psi$, is instrumental in calculating the probability of a particle's presence in a specific state. The Born rule connects the wave function to this probability, expressed as $P(x) = |\psi(x)|^2$. This rule is crucial for understanding the likelihood of observing a particle at a particular position. To study the effects of external influences on quantum systems, time-dependent perturbation theory is employed. This theory calculates the probability of a system transitioning from one state to another due to perturbations. The density matrix is a valuable tool for describing quantum systems that are not in pure states, such as those interacting with their environment. It provides a way to represent the statistical mixture of quantum states. These mathematical concepts are applied to various biological processes to explore the potential role of quantum phenomena. For instance, in photosynthesis, the Schrödinger equation and density matrix formalism are used to model energy transfer processes. Quantum tunneling, described by the Schrödinger equation, is believed to be involved in

proton transfer during enzyme catalysis^{18,25,28,29}. The interaction between magnetic fields and quantum systems in avian navigation can be understood through quantum mechanics. Additionally, quantum entanglement, analyzed using the density matrix, is proposed as a mechanism for long-range communication within DNA molecules. Figure 1-Figure 4 depict the quantum concepts that influence the biological systems.

Figure 1 illustrates how quantum coherence allows energy to be transferred efficiently between molecules in photosynthetic systems. The entangled quantum states enable the energy to explore multiple pathways simultaneously, increasing the likelihood of reaching the reaction center³⁰. Figure 2 depicts the concept of quantum tunneling, where a particle can pass through a barrier that would be classically impenetrable. In enzyme catalysis, quantum tunneling can facilitate proton transfer, leading to faster reaction rates³¹. Figure 3 illustrates the concept of quantum entanglement, where two particles become inextricably linked, even when separated by vast distances. While its role in biological systems is still being explored, entanglement could potentially be involved in long-range communication or information processing³². While the exact mechanism is still under investigation, some theories suggest that quantum effects may play a role in avian navigation. Figure represents the idea that birds might be able to sense Earth's magnetic field using quantum sensors in their brains³³.

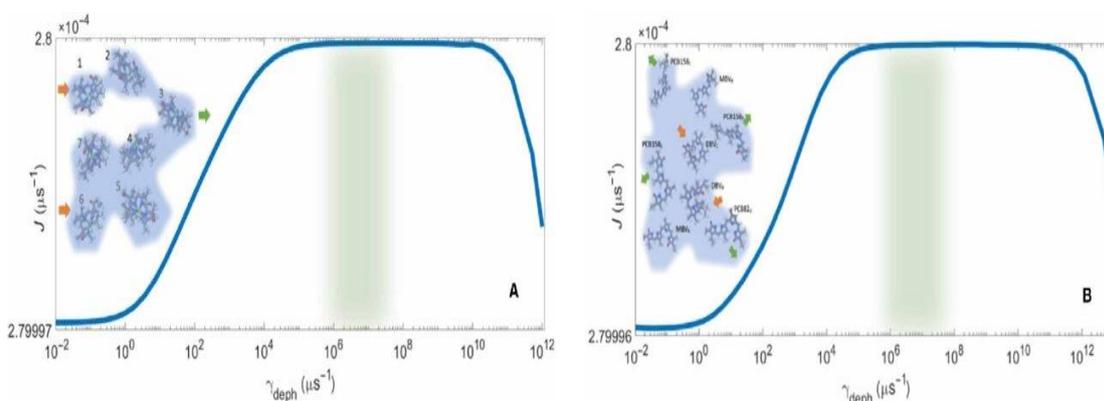


Figure 1: Quantum coherence in photosynthesis.

[Source: <https://www.science.org/doi/10.1126/sciadv.abc4631>]

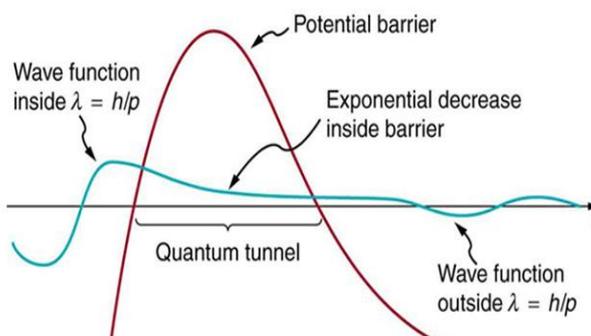


Figure 2: Quantum tunneling in enzyme catalysis.

Source: <https://courses.lumenlearning.com/suny-physics/chapter/31-7-tunneling/>

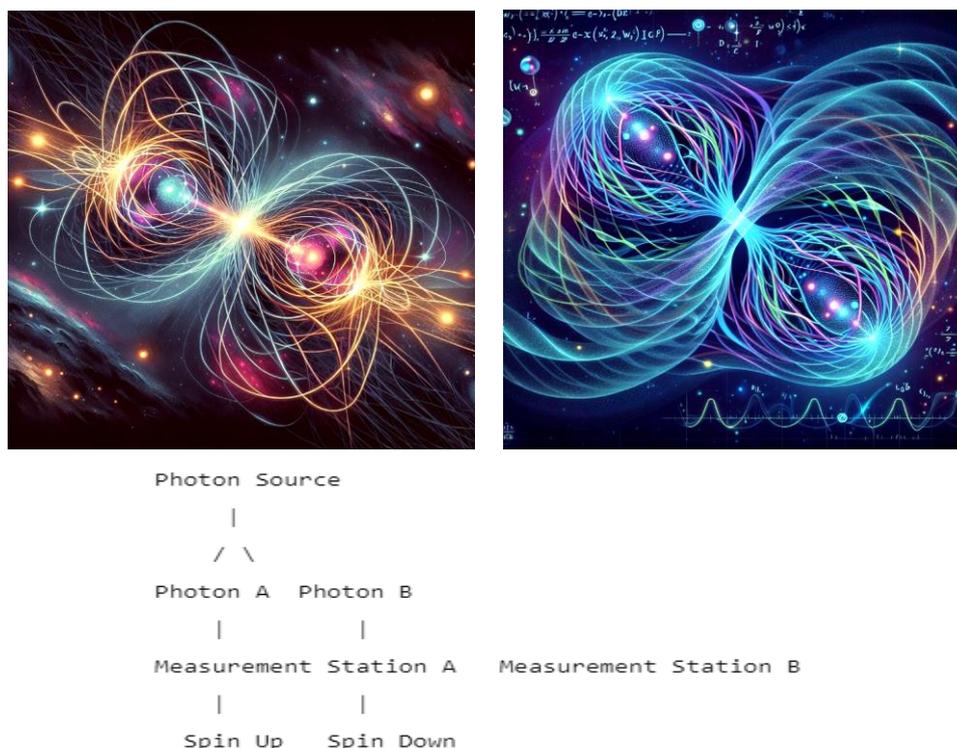


Figure 3: Quantum entanglement in biological systems.

[Concept: <https://www.livescience.com/28550-how-quantum-entanglement-works-infographic.html>]

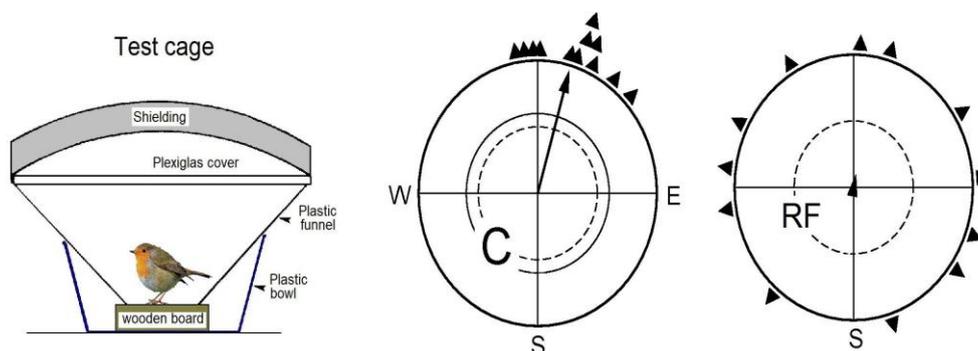


Figure 4: Quantum Effects in Avian Navigation.

[Source: <https://www.frontiersin.org/journals/physiology/articles/10.3389/fphys.2021.667000/full>]

By employing these mathematical frameworks, researchers can gain valuable insights into the potential role of quantum effects in biological processes, paving the way for a deeper understanding of life at the molecular level, gain deeper insights into biological processes and explain unexplainable phenomena in the complex life systems.

Quantum biology in practice: Applications and implications with a promising future

Research in quantum biology is ongoing, with new discoveries and applications emerging regularly. Future research may focus on exploring the role of quantum effects in other biological processes, developing new experimental techniques to study quantum phenomena in living systems and addressing the ethical implications of quantum biology research. Future research may go deeper into the role of quantum effects in various biological processes, such as olfaction, DNA replication and plant growth. Developing novel experimental techniques to directly observe and

manipulate quantum phenomena in living systems will be crucial for advancing our understanding. Addressing the ethical implications of quantum biology research, including potential societal impacts and the equitable distribution of benefits, is also essential. In the realm of medicine, quantum biology offers promising avenues. Understanding the quantum principles underlying enzyme catalysis can lead to the design of more effective drugs. Quantum sensors hold the potential for highly sensitive and specific disease biomarker detection. Furthermore, quantum technologies like quantum computing can revolutionize personalized treatment plans and drug discovery. Materials science can also benefit from quantum biology. By studying the quantum principles in biological systems, researchers can develop novel quantum materials with unique properties^{30,36}. These materials could have applications in fields such as electronics, energy storage and sensing.

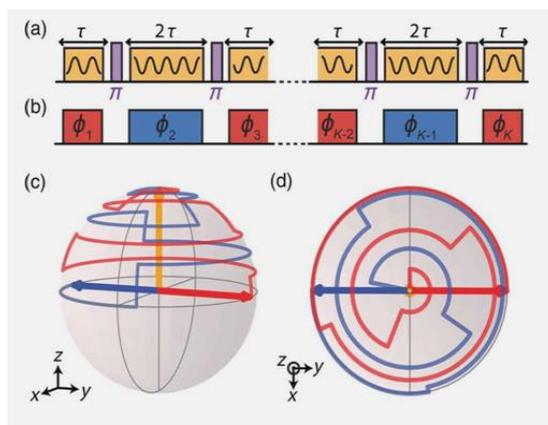


Figure 5: Quantum computing and biology.

[Source: <https://physicsworld.com/a/10-qubit-register-breaks-new-ground-in-quantum-computing/>]

In the realm of energy production, quantum biology offers potential solutions. Understanding the quantum mechanisms of natural photosynthesis can inform the development of artificial photosynthesis systems for sustainable energy generation. Additionally, quantum materials may enable the creation of quantum batteries with superior energy storage capabilities. As quantum biology continues to mature, we can anticipate exciting breakthroughs and innovative applications across various fields. By addressing the challenges and seizing the opportunities, quantum biology has the potential to revolutionize our understanding of life and contribute to a sustainable future. Quantum biology offers promising applications across various fields. In medicine, understanding the quantum principles underlying enzyme catalysis can aid in the design of more effective drugs. Quantum sensors hold the potential for highly sensitive and specific disease biomarker detection, while quantum technologies like quantum computing can revolutionize personalized treatment plans and drug discovery. In materials science, quantum materials inspired by biological systems could lead to groundbreaking advancements. These materials might possess unique properties like high-temperature superconductivity or self-healing capabilities, opening doors for innovative applications³⁷⁻⁴³. The field of energy production can also benefit from quantum biology. Understanding the quantum mechanisms of natural photosynthesis could inform the development of artificial photosynthesis systems for sustainable energy generation. Additionally, quantum materials may offer new approaches to energy storage, such as quantum batteries with superior performance.

Ethical considerations, future perspectives and interdisciplinary collaboration

The advancement of quantum biology raises important ethical questions. For example, the potential for quantum-enhanced medical technologies could exacerbate healthcare disparities. Additionally, the development of quantum materials with advanced capabilities may have both positive and negative consequences for society. It is crucial to engage in open dialogue and develop appropriate ethical frameworks to guide the responsible development and application of quantum biology technologies. The

future of quantum biology is promising, with ongoing research exploring its applications in various fields. As our understanding of quantum phenomena in biological systems deepens, we can expect to see even more innovative and impactful discoveries. Quantum biology is a complex and interdisciplinary field that requires collaboration between scientists from various disciplines. To address the challenges and realize the full potential of this emerging field, several additional considerations must be taken into account. The successful advancement of quantum biology necessitates a collaborative approach that brings together experts from diverse fields. Physicists, biologists, chemists and other scientists must work together to develop new experimental techniques, theoretical models and computational tools^{33-37,44}. By fostering interdisciplinary collaboration, we can leverage the unique strengths and perspectives of each field to address the complex challenges and opportunities presented by quantum biology. Quantum computing, which leverages quantum phenomena like superposition and entanglement, has the potential to revolutionize various fields, including biology. It could be used to simulate complex biological systems, design new drugs, and analyze large biological datasets more efficiently (Figure 5)⁴⁷.

Technological advancements, public engagement and ethical frameworks

Advances in experimental techniques and computational modeling are crucial for progress in quantum biology. New experimental methods are needed to observe and manipulate quantum phenomena in biological systems, while powerful computational tools can aid in the development of theoretical models and the analysis of experimental data. For example, advances in quantum computing may enable the simulation of complex biological systems at the quantum level, providing valuable insights into the role of quantum effects. Engaging the public and policymakers in discussions about quantum biology is essential to ensure that research is conducted responsibly and that the potential benefits and risks are understood. Public outreach can help to generate support for quantum biology research, raise awareness of its potential applications and address concerns about ethical implications. By fostering open dialogue and

transparency, we can build public trust in quantum biology and ensure that its development aligns with societal values. Developing ethical frameworks to guide quantum biology research and applications is crucial to ensure responsible and beneficial use of these technologies. These frameworks should address issues such as the potential for unintended consequences, the equitable distribution of benefits and the protection of privacy and individual rights^{20,32,35,37,45,46}. By establishing clear ethical guidelines, we can help to mitigate risks and promote the responsible development of quantum biology.

Quantum biology: A paradigm shift in pharmaceutical and medical research

Quantum biology, a burgeoning field at the intersection of quantum mechanics and biology, offers a new paradigm for understanding biological processes and has the potential to revolutionize the pharmaceutical industry. By leveraging quantum principles, researchers can gain deeper insights into disease mechanisms, leading to more efficient drug discovery, accurate diagnostics and personalized treatments. Quantum computing, with its ability to process vast amounts of data simultaneously and simulate complex molecular interactions, is a game-changer for drug discovery. It can accelerate the process by predicting molecular properties, simulating protein-ligand interactions and optimizing drug delivery systems. Quantum sensors, based on quantum phenomena like superposition and entanglement, offer unprecedented sensitivity and precision for developing novel diagnostic tools. These sensors can detect early-stage cancer, monitor disease progression and enable point-of-care diagnostics. Quantum biology can also contribute to personalized medicine by providing a deeper understanding of individual genetic variations and their impact on disease susceptibility and drug response. Quantum computing can analyze vast amounts of patient data to identify patterns and inform personalized treatment plans. Additionally, quantum materials, with their unique properties, offer promising applications in drug delivery, such as using quantum dots as fluorescent probes or developing controlled-release systems. While the development of quantum biology technologies in the pharmaceutical industry offers immense potential, it is crucial to address the ethical considerations associated with their use. Ensuring equitable access to these technologies is essential to prevent healthcare disparities. Moreover, the privacy and security of patient data must be protected when using quantum technologies in medical applications. The future of quantum biology in the pharmaceutical industry is promising. As quantum technologies continue to advance, we can expect to see even more innovative applications in drug discovery, diagnostics, and personalized medicine⁴⁸⁻⁵³. By addressing the ethical challenges and seizing the opportunities, quantum biology can revolutionize the way we approach pharmaceutical research and improve human health.

CONCLUSIONS

Quantum biology, a nascent field at the intersection of quantum mechanics and biology, offers immense potential for revolutionizing our understanding of life and driving innovation across various domains. By unraveling the quantum intricacies of biological processes, we can gain novel insights into disease mechanisms, develop innovative materials and harness sustainable energy sources. The foundational principles of quantum biology, including quantum coherence, tunneling and entanglement, provide a framework for understanding how quantum phenomena may play a crucial role in biological systems. These principles have been implicated in processes such as photosynthesis, enzyme catalysis and avian navigation, suggesting that quantum effects may be more prevalent in biology than previously thought.

The potential applications of quantum biology are vast and far-reaching. In medicine, quantum technologies may enable the development of more effective drugs, sensitive diagnostic tools and personalized treatment plans. In materials science, quantum materials inspired by biological systems could revolutionize industries such as electronics, energy storage, and sensing. In energy production, understanding the quantum principles underlying photosynthesis and mitochondrial respiration can inform the development of sustainable and efficient energy systems. However, the advancement of quantum biology also raises important ethical considerations. The potential for quantum-enhanced medical technologies could exacerbate healthcare disparities, and the development of quantum materials with advanced capabilities may have both positive and negative consequences for society. Open communication and the establishment of ethical guidelines are essential for ensuring the responsible advancement and utilization of quantum biology technologies. In conclusion, quantum biology offers a promising future for scientific discovery and technological innovation. By addressing the challenges and seizing the opportunities, we can harness the full potential of quantum biology to improve human health, develop sustainable solutions, and shape a more prosperous future.

AUTHOR'S CONTRIBUTIONS

Eissa ME: conceived the idea, writing the manuscript, literature survey, formal analysis, critical review.

DATA AVAILABILITY

This article is available to anyone upon request from the corresponding authors.

CONFLICT OF INTEREST

None to declare.

REFERENCES

- Siegfried T. Quantum mechanics questions the fundamental nature of reality. *Science News*. 2022 Jan 12. <https://www.sciencenews.org/article/quantum-theory-history-reality-uncertainty-physics>
- Griffiths DJ. *Introduction to Quantum Mechanics*. 3rd ed. Cambridge: Cambridge University Press; 2018.
- Ivry S. How two rebel physicists changed quantum theory. *JSTOR Daily* 2024 Jun 18; <https://daily.jstor.org/how-two-rebel-physicists-changed-quantum-theory/>
- Scholes GL, Fleming GR. Quantum coherence in biological systems. *Nature* 2007;446:375-7.
- Chaurasia RK, Dhabekar BS. *An overview of quantum biology*. Handbook on Radiation Environment 2004; Volume 1. Springer; 2024; 667-686. https://doi.org/10.1007/978-981-97-2795-7_21
- Waring S. Quantum biology: A scientific revolution in our understanding of biological systems. *Biol Syst Open Access* 2018;7(185):2.
- Lambert N, Chen YN, Cheng Y, Li CM, Chen GY, Nori F. Quantum biology. *Nat Phys* 2013 Jan;9(1):10-8. <https://doi.org/10.1038/nphys2474>
- McFadden J, Al-Khalili J. The origins of quantum biology. *Proc R Soc A Math Phys Eng Sci* 2018; 474(2218):20180674. <https://doi.org/10.1098/rspa.2018.0674>
- Schrödinger E. An undulatory theory of the mechanics of atoms and molecules. *Phys Rev*. 1926;28(6):1049-1070. <https://doi.org/10.1103/PhysRev.28.1049>
- Joaquim L, Freire Jr O, El-Hani CN. Quantum Explorers: Bohr, Jordan, and Delbrück venturing into biology. *Phys Perspect* 2015; 17(3):236-250. <https://doi.org/10.1007/s00016-015-0167-7>
- Brody SS. Fluorescence lifetime, yield, energy transfer and spectrum in photosynthesis, 1950–1960. *Photosynth Res* 2002; 73(1-3):127-132. <https://doi.org/10.1023/A:1020401820196>
- Allemann RK, Scrutton NS, editors. *Quantum Tunnelling in Enzyme-Catalysed Reactions*. Cambridge: Royal Society of Chemistry; 2009. <https://doi.org/10.1039/9781847559975>
- Fleming GR, Scholes GD. Quantum mechanics for plants. *Nature*. 2004 Sep 16; 431(7006):256-7. <https://doi.org/10.1038/431256a>
- Engel GS, Calhoun TR, Read EL, Ahn TK, Mančal T, Cheng YC, Blankenship RE, Fleming GR. Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems. *Nature* 2007 Apr 12;446(7137):782-6. <https://doi.org/10.1038/nature05678>
- Zhu R, Li W, Zhen Z, Zou J, Liao G, Wang J, Wang Z, Chen H, Qin S, Weng Y. Quantum phase synchronization via exciton-vibrational energy dissipation sustains long-lived coherence in photosynthetic antennas. *Nature Communications* 2024 Apr 12; 15(1):3171. <https://doi.org/10.1038/s41467-024-47560-6>
- Moazed KT. *The Quantum Biology of Consciousness and Visual Perception*. Quantum biology of the eye: Understanding the Essentials 2023 Jun 30:119-160. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-32060-6_7
- Benyus JM. *Biomimicry: Innovation inspired by nature*. New York: Harper Collins; 1997.
- Ritz T, Adem S, Schulten K. A model for photoreceptor-based magnetoreception in birds. *Biophys J* 2000; 78(2):707-718. [https://doi.org/10.1016/S0006-3495\(00\)76629-X](https://doi.org/10.1016/S0006-3495(00)76629-X)
- Grätzel M. Photoelectrochemical cells. *Nature*. 2001; 414(6861):338-344. <https://doi.org/10.1038/35104607>
- Pal S, Bhattacharya M, Lee SS, Chakraborty C. Quantum computing in the next-generation computational biology landscape. *Protein Folding to Molecular Dynamics*. *Mol Biotechnol* 2024; 66(2):163-178. <https://doi.org/10.1007/s12033-023-00765-4>
- Turin L. A spectroscopic mechanism for primary olfactory reception. *Chem Senses*. 1996;21(6):773-791. <https://doi.org/10.1093/chemse/21.6.773>
- Valley MP, Fitzpatrick PF. Comparison of enzymatic and non-enzymatic nitroethane anion formation: thermodynamics and contribution of tunneling. *J American Chem Soc* 2004 May 26;126(20):6244-5. <https://doi.org/10.1021/ja0484606>
- Leuenberger MN, Loss D. Quantum computing in molecular magnets. *Nature* 2001; 410(6830):789-793. <https://doi.org/10.1038/35071024>
- Calhoun TR, Fleming GR. Quantum coherence in photosynthetic complexes. *Nature* 2007;446(7137):782-786. <https://doi.org/10.1038/nature05678>
- Pitkänen M. Getting philosophical: Some comments about the problems of physics, neuroscience, and biology. <https://doi.org/10.13140/RG.2.2.19239.91048>
- Singh AK, Ramarao SD, Peter SC. Rare-earth based half-Heusler topological quantum materials: A perspective. *APL Materials*. 2020 Jun 1;8(6). <https://doi.org/10.1063/5.0006118>
- Neuro Quantology. *Quantum Biology: Principles, Concepts, and Applications*. *Neuro Quantology* 2023 Aug 25. Available from: <https://www.neuroquantology.com>
- Ananthaswamy A. Particle, wave, both or neither? The experiment that challenges all we know about reality. *Nature* 2023 Jun 13. <https://www.nature.com/articles/d41586-023-01938-6>
- Heisenberg W. *The physical principles of the quantum theory*. Chicago: University of Chicago Press; 1930. <https://doi.org/10.7208/chicago/9780226326937.001.0001>
- Harush EZ, Dubi Y. Do photosynthetic complexes use quantum coherence to increase their efficiency? *Sci Adv*. 2021;7(1):eabc4631. <https://doi.org/10.1126/sciadv.abc4631>
- Lumen Learning. Tunneling. In: *Physics*. Available from: <https://courses.lumenlearning.com/suny-physics/chapter/31-7-tunneling/>
- Tate K. How Quantum Entanglement Works (Infographic). *Live Science* 2013 Apr 8. Available from: <https://www.livescience.com/28550-how-quantum-entanglement-works-infographic.html>
- Wiltshko R, Nießner C, Wiltshko W. The magnetic compass of birds: The role of cryptochrome. *Front Physiol* 2021;12:667000. <https://doi.org/10.3389/fphys.2021.667000>
- Flöther FF, Griffin PF. How can quantum technologies be applied in healthcare, medicine and the life sciences? *Res Dir Quantum Technol*. 2023; 1:e7. <https://doi.org/10.1017/qut.2023.1>
- Aiello C. It's time to take quantum biology research seriously. *Phys Rev* 2023; 16:79. <https://physics.aps.org/articles/v16/79>
- Singh A. Quantum biology: An overview. *AzoQuantum*. 2024 Aug 21. <https://www.azoquantum.com/Article.aspx?ArticleID=538>
- Kop M. Why we need to consider the ethical implications of quantum technologies. *Phys World* 2021 Dec 17. <https://physicsworld.com/a/why-we-need-to-consider-the-ethical-implications-of-quantum-technologies/>
- Shields GC. Twenty years of exceptional success: The molecular education and research consortium in undergraduate computational chemistry (MERCURY). *Int J Quantum Chem* 2020 Oct 15; 120(20):e26274. <https://doi.org/10.1002/qua.26274>
- Satinover J. *The quantum brain: The search for freedom and the next generation of man*. New York: John Wiley & Sons; 2002.
- Voityuk AA. Electronic couplings and on-site energies for hole transfer in DNA: Systematic quantum mechanical/molecular dynamic study. *J Chem Phys* 2008; 128(11):115101. <https://doi.org/10.1063/1.2839271>
- Aspelmeyer M, Kippenberg TJ, Marquardt F. Cavity optomechanics. *Rev Mod Phys* 2014;86(4):1391-1452. <https://doi.org/10.1103/RevModPhys.86.1391>

42. Preskill J. Quantum computing in the NISQ era and beyond. *Quantum* 2018; 2:79. <https://doi.org/10.22331/q-2018-08-06-79>
43. Samarth N. Quantum materials discovery from a synthesis perspective. *Nat Mater.* 2017; 16(11):106-113. <https://doi.org/10.1038/nmat4998>
44. Umbrello S. Ethics of Quantum Technologies: A Scoping Review. *Int J Appl Philos.* 2024 Apr 10. <https://doi.org/10.5840/ijap202448201>
45. Swayne M. Researchers Outline Framework for Responsible Quantum Technology. *Quantum Insider* 2024 Apr 11. <https://thequantuminsider.com/2024/04/11/researchers-outline-framework-for-responsible-quantum-technology/>
46. Dixon TA, Freemont PS, Johnson RA, Pretorius IS. A global forum on synthetic biology: The need for international engagement. *Nat Commun* 2022; 13:31265. <https://doi.org/10.1038/s41467-022-31265-9>
47. Ivanov A, Bradley C, Taminiau T. 10-qubit register breaks new ground in quantum computing. *Phys World* 2019 Oct 2. <https://physicsworld.com/a/10-qubit-register-breaks-new-ground-in-quantum-computing/>
48. Boger Y. How quantum computing is accelerating drug discovery and development. *Forbes* 2024 Oct 15. <https://www.forbes.com/councils/forbesbusinessdevelopmentcouncil/2024/10/15/how-quantum-computing-is-accelerating-drug-discovery-and-development/>
49. Flöther FF, Griffin PF. How can quantum technologies be applied in healthcare, medicine and the life sciences? *Research directions: Quantum technologies.* 2023 Feb 8; 1:e7. <https://doi.org/10.1017/quit.2023.1>
50. Quantum computing in drug development. *McKinsey & Company.* 2021 Jun 18. <https://www.mckinsey.com/industries/life-sciences/our-insights/pharmas-digital-rx-quantum-computing-in-drug-research-and-development>
51. Quantum Biology: How Quantum Computing Can Unlock A New Dimension Of Treating Diseases. *Forbes* 2022 Dec 12. <https://www.forbes.com/councils/forbestechcouncil/2022/12/12/quantum-biology-how-quantum-computing-can-unlock-a-new-dimension-of-treating-diseases/>
52. Quantum sensing's immense potential for many sectors. *McKinsey & Company.* 2024 Jun 10. <https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/tech-forward/quantum-sensing-poised-to-realize-immense-potential-in-many-sectors>
53. Why we need to consider the ethical implications of quantum technologies. *Physics World.* <https://physicsworld.com/a/why-we-need-to-consider-the-ethical-implications-of-quantum-technologies/>