Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

A Review of Quantum Computing: Fundamental Concepts, Physical Implementations and Future Challenges

L. Sujitha
Departrment of Physics, Loyola Degree College (YSRR) YSR-Kadapa-A.P

Y. Ganga Devi
Departrment of Mathematics, Loyola Degree College (YSRR) YSR-Kadapa-A.P

Abstract - **Quantum computing represents a transformative paradigm that exploits the principles of quantum mechanics—superposition, entanglement, and quantum interference—to perform computations beyond the capabilities of classical computers. This review presents a comprehensive overview of the fundamental concepts underlying quantum computation, including qubits, quantum gates, quantum algorithms and measurement theory. It further examines major physical implementations of quantum computers, such as superconducting circuits, trapped ions, photonic systems, spin-based qubits, and topological approaches, highlighting their operational principles, advantages, and technological limitations. Key challenges hindering large-scale quantum computation—decoherence, error rates, qubit scalability, and fault tolerance—are critically discussed. Additionally, recent progress in quantum error correction, hybrid quantum–classical algorithms, and hardware optimization is summarized. The review concludes by outlining future research directions and potential applications of quantum computing in cryptography, materials science, optimization, and drug discovery. By integrating theoretical foundations with experimental advancements, this article aims to provide a clear and accessible reference for students, researchers, and scientists entering the rapidly evolving field of quantum computing.**

Keywords: **Quantum computing; Qubits; Quantum algorithms; Physical implementations; Decoherence; Quantum error correction; Scalability.**

1. INTRODUCTION

The rapid advancement of computation has been one of the most influential drivers of scientific and technological progress over the past century.[1] Classical computing, built on the principles of Boolean logic and semiconductor-based transistors, has enabled remarkable achievements ranging from large-scale data processing to artificial intelligence.[1,2]However, as device dimensions approach atomic scales and computational demands continue to grow exponentially, classical computing faces fundamental physical and practical limitations. [3] Moore's law, which predicted the doubling of transistor density every two years, is slowing due to issues such as heat dissipation, quantum tunneling, and power consumption. [4] These challenges have motivated the exploration of alternative computing paradigms that can surpass classical limits. [5] Among them, quantum computing has emerged as one of the most promising and revolutionary approaches.

Quantum computing is fundamentally grounded in the laws of quantum mechanics, which govern the behavior of matter and energy at atomic and subatomic scales. [6] Unlike classical bits that exist strictly in binary states of 0 or 1, quantum bits, or qubits, can exist in coherent superpositions of states. This unique property, along with quantum entanglement and interference, allows quantum computers to process information in ways that are not accessible to classical systems. [1,5] As first conceptualized by pioneers such as Richard Feynman and David Deutsch, quantum computers are particularly well-suited for simulating quantum systems and solving specific classes of problems exponentially faster than their classical counterparts. [4,6]

Over the past few decades, quantum computing has evolved from a purely theoretical concept into an active experimental and engineering discipline. [1] Early theoretical milestones, including Shor's algorithm for integer factorization and Grover's algorithm for unstructured search, demonstrated the potential computational advantages of quantum systems. These breakthroughs provided strong motivation for experimental realization, as they showed that quantum computers could have profound implications for cryptography, optimization, materials science and complex system modeling. [7] In particular, Shor's algorithm posed a serious challenge to widely used public-key cryptographic schemes, thereby highlighting both the power and the societal impact of quantum computation. [6,8]

At the heart of quantum computing lies the qubit, which can be physically realized using a variety of quantum systems. [7]Several physical implementations have been proposed and experimentally demonstrated, including superconducting circuits, trapped ions, neutral atoms, photonic systems, and solid-state spin qubits. [9] Each platform offers distinct advantages in terms of coherence time, gate fidelity, scalability and ease of control, while also presenting unique technical challenges. For example, superconducting qubits benefit from fast gate operations and compatibility with existing microfabrication technologies, whereas trapped ion systems offer exceptionally long coherence times and high-fidelity quantum gates. [10]Understanding the physical principles underlying these implementations is crucial for evaluating their potential for large-scale quantum computation. [11]

Despite significant progress, building a practical, fault-tolerant quantum computer remains an enormous scientific and engineering challenge. Quantum systems are inherently fragile and highly sensitive to environmental disturbances, leading to decoherence and loss of quantum information. [11] Errors arising from noise, imperfect control, and measurement limitations can quickly accumulate and destroy quantum advantage. [10,12] As a result, quantum error correction and fault-tolerant architectures have become central research areas. Unlike classical error correction, quantum error correction must preserve quantum coherence while correcting errors without directly measuring the quantum state. [3]This requirement introduces additional complexity and resource overhead, making scalability one of the most critical obstacles in the field. [5]

In addition to hardware-related challenges, the development of efficient quantum algorithms and software frameworks is essential for realizing the full potential of quantum computing. While a small number of algorithms have demonstrated theoretical speedups, identifying new algorithms that provide practical advantages for real-world problems remains an open research question. [13] Hybrid quantum–classical approaches, such as variational quantum algorithms, have gained considerable attention as near-term solutions for noisy intermediate-scale quantum (NISQ) devices. [14]These methods leverage classical optimization techniques alongside quantum processors to address problems in chemistry, optimization, and machine learning, even with limited qubit counts and imperfect hardware. [15]

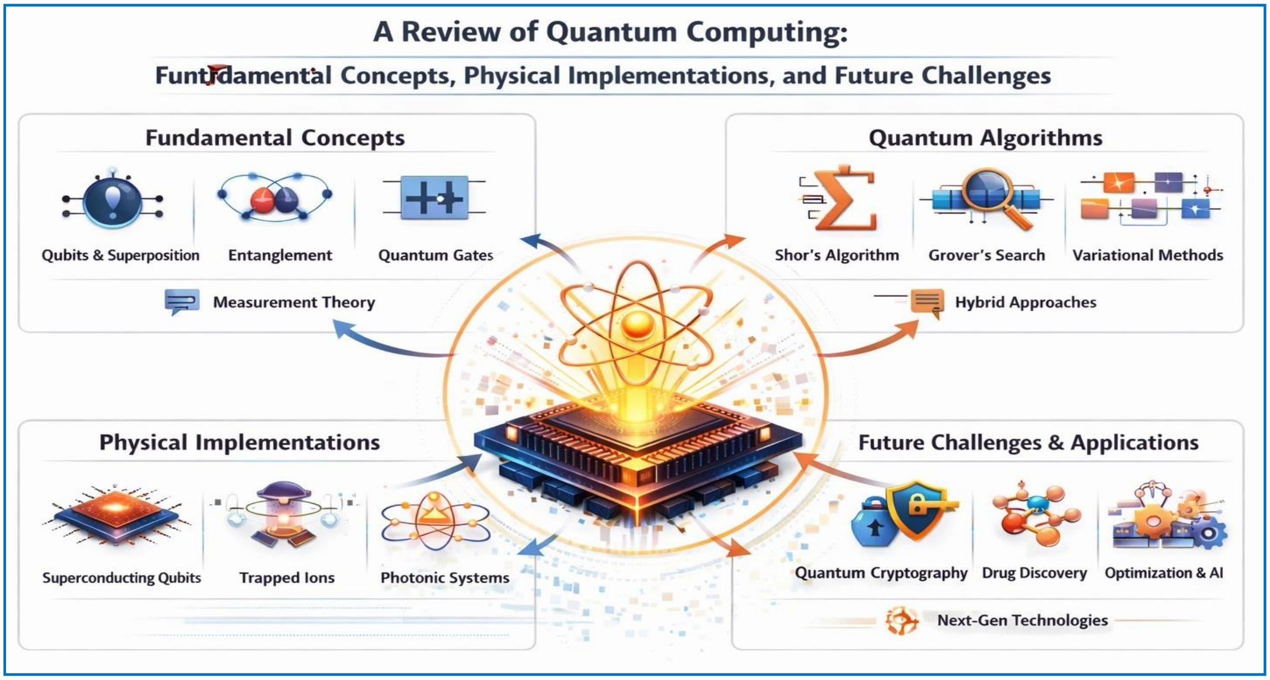
The interdisciplinary nature of quantum computing further underscores its importance and complexity. The field integrates concepts from quantum physics, computer science, materials science, electrical engineering, and information theory. [3,4] Advances in one area often drive progress in others, creating a dynamic and rapidly evolving research landscape. For physicists, quantum computing offers not only a technological goal but also a powerful framework for exploring fundamental questions about quantum information, measurement and entanglement. [14] From a broader perspective, the successful development of quantum computers has the potential to reshape industries, redefine cybersecurity, and enable scientific discoveries that are currently beyond reach. [16]

Given the rapid pace of development and the diversity of approaches, there is a growing need for comprehensive reviews that synthesize fundamental concepts, experimental progress, and future challenges in quantum computing. [15] A clear understanding of both theoretical foundations and physical implementations is essential for students and researchers entering the field, as well as for scientists seeking to apply quantum computing techniques to their own disciplines. This review aims to address this need by providing an integrated overview of quantum computing, focusing on its core principles, leading physical platforms and the major challenges that must be overcome to achieve scalable and reliable quantum systems. [9,10]

In this article, we first introduce the basic principles of quantum computation, including qubits, quantum gates, and quantum algorithms. [1] We then examine the most prominent physical implementations of quantum computers, comparing their operational mechanisms and technological readiness. [4] Subsequently, we discuss key challenges such as decoherence, error correction and scalability, along with recent strategies proposed to mitigate these issues. Finally, we outline future directions and potential applications, emphasizing the role of quantum computing as a transformative technology at the intersection of physics and information science. [1,6] Through this comprehensive perspective, the review seeks to provide a solid foundation for understanding the current state and future prospects of quantum computing.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

Fig.1. Graphical abstract- Quantum Computing



2. METHODOLOGY

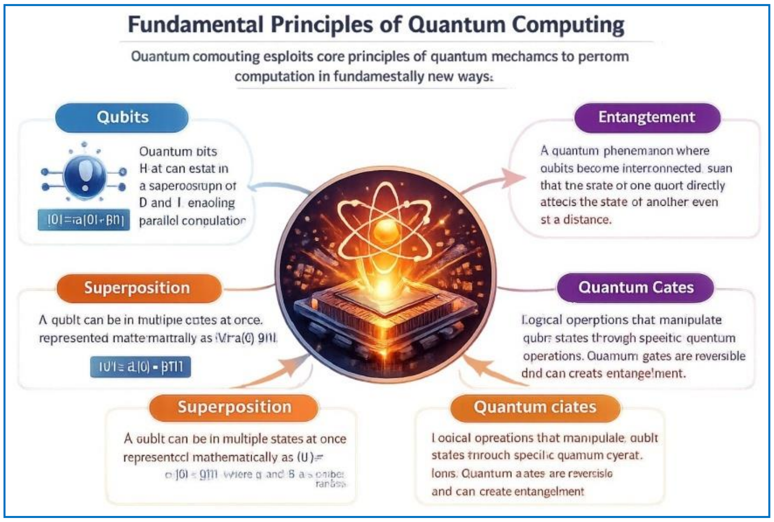
This review was conducted using a systematic literature survey of peer-reviewed articles, review papers and authoritative preprints related to quantum computing. Major scientific databases including Web of Science, Scopus, IEEE Xplore, SpringerLink, Nature Portfolio, and arXiv were consulted. Literature published mainly between 2018 and 2025 was prioritized, with seminal works included for foundational concepts. Relevant studies were selected based on their focus on quantum computing principles, physical implementations, and technological challenges. Information was categorized into fundamental concepts, hardware platforms, and future challenges. A qualitative comparative analysis was performed to evaluate different qubit technologies and architectures. Emphasis was placed on experimentally validated results and widely accepted theoretical models. This approach ensures a comprehensive and reliable overview of the current state of quantum computing research.

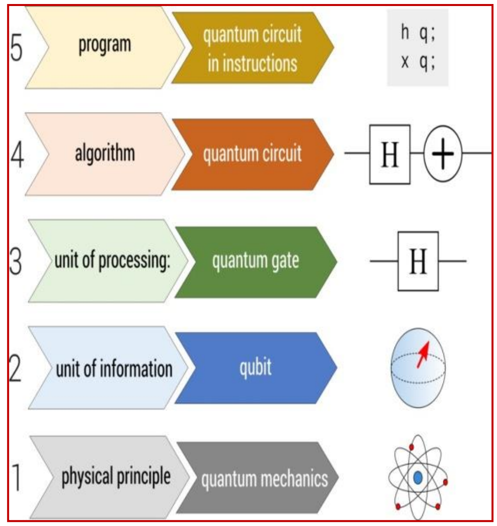
3. FUNDAMENTAL PRINCIPLES OF QUANTUM COMPUTING

Quantum computing is built upon the fundamental laws of quantum mechanics, which describe the behavior of matter and energy at microscopic scales.[2,7] Unlike classical computing systems that rely on deterministic binary logic, quantum computers exploit inherently probabilistic quantum phenomena to process information. [8] The core principles—qubits, superposition, entanglement, quantum gates, and measurement—form the theoretical foundation of quantum computation and distinguish it fundamentally from classical information processing. [9]

Fig.2 Image of fundamental Principles

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026





3.1. Qubits

The basic unit of quantum information is the **quantum bit or qubit**. In contrast to a classical bit that exists exclusively in one of two states (0 or 1), a qubit can exist in a linear combination of both states simultaneously. Mathematically, the state of a qubit is represented as ∣ψ⟩=α∣0⟩+β∣1⟩|\psi\rangle = \alpha|0\rangle + \beta|1\rangle∣ψ⟩=α∣0⟩+β∣1⟩, where α\alphaα and β\betaβ are complex probability amplitudes satisfying ∣α∣2+∣β∣2=1|\alpha|^2 + |\beta|^2 = 1∣α∣2+∣β∣2=1. Qubits can be physically realized using various quantum systems such as electron spin, photon polarization, superconducting circuits, or trapped ions. The ability of qubits to encode information in quantum states enables parallelism that is unattainable in classical systems.

3.2. Superposition

Superposition is a fundamental quantum principle that allows a qubit to exist in multiple states at the same time until it is measured. This property enables a quantum computer with nnn qubits to represent 2n2^n2n possible states simultaneously. [16]Superposition does not imply that all computations are performed independently but rather that quantum algorithms exploit interference effects to amplify correct solutions while suppressing incorrect ones. The controlled manipulation of superposition through quantum gates lies at the heart of quantum speedup in algorithms such as Grover's search algorithm. [17]

3.3. Entanglement

Quantum entanglement is a non-classical correlation between two or more qubits such that the state of one qubit cannot be described independently of the others, even when they are separated by large distances. Entangled states exhibit strong correlations that defy classical explanations and have been experimentally verified. [18] In quantum computing, entanglement plays a critical role in enabling quantum teleportation, superdense coding and multi-qubit gate operations. [19] It is also essential for achieving exponential advantages in certain quantum algorithms, as entanglement allows information to be distributed across the entire quantum system. [20]

3.4. Quantum Gates

Quantum information processing is achieved through **quantum gates**, which are unitary operations that manipulate the state of qubits in a reversible manner. Single-qubit gates, such as the Pauli-X, Hadamard and phase gates, control superposition and phase relationships, while multi-qubit gates, such as the controlled-NOT (CNOT) gate, generate and control entanglement. [21] Quantum circuits are constructed by applying sequences of these gates to qubits, analogous to logic circuits in classical computing. [22]The universality of certain gate sets ensures that any quantum computation can be decomposed into a finite sequence of elementary quantum gates.

3.5. Measurement Theory

Measurement in quantum computing plays a dual role: it extracts classical information from a quantum system while simultaneously collapsing the quantum state. Upon measurement, a qubit in superposition probabilistically collapses to one of its basis states, with probabilities determined by the squared magnitudes of its amplitudes. Measurement is inherently destructive, meaning that quantum information cannot be copied or perfectly preserved once observed. [22] This principle, known as the no-cloning theorem, imposes fundamental constraints on quantum computation and communication. Consequently, quantum algorithms are designed to minimize measurements and extract results only at the final stage of computation. [23]

The principles of qubits, superposition, entanglement, quantum gates, and measurement theory collectively define the operational framework of quantum computing. These concepts enable new modes of information processing that extend beyond classical limits and form the foundation for the development of advanced quantum algorithms and scalable quantum technologies. [24]

4. QUANTUM ALGORITHMS AND COMPUTATIONAL ADVANTAGE

One of the most compelling motivations for the development of quantum computers is their ability to execute certain algorithms more efficiently than classical computers. [26] Quantum algorithms are designed to exploit uniquely quantum mechanical features such as superposition, entanglement, and interference to achieve computational advantages. [25] While quantum computers do not outperform classical systems for all problems, they offer significant speedups for specific classes of computational tasks, thereby redefining the limits of efficient computation. [27]

4.1. Shor's Algorithm

Shor's algorithm is one of the most celebrated quantum algorithms, as it demonstrates an exponential speedup over the best-known classical algorithms for integer factorization and discrete logarithms. [29] These problems form the mathematical foundation of widely used public-key cryptographic systems such as RSA. [28] Shor's algorithm leverages quantum parallelism and the quantum Fourier transform to efficiently determine the periodicity of modular exponentiation functions, enabling factorization in polynomial time. [29] Although large-scale implementation remains challenging due to hardware limitations, the theoretical implications of Shor's algorithm have had profound impacts on cryptography, leading to the emergence of post-quantum cryptographic research. [30]

4.2. Grover's Algorithm

Grover's algorithm provides a quadratic speedup for unstructured search problems. While a classical algorithm requires O(N)O(N)O(N) operations to search an unsorted database of NNN elements, Grover's algorithm can accomplish the task in O(N)O(\sqrt{N})O(N) steps. [21] This improvement is achieved through amplitude amplification, where repeated quantum operations increase the probability of measuring the correct solution. [23]Although the speedup is not exponential, Grover's algorithm has broad applicability across optimization, database search and decision problems. It also serves as a foundational technique that can be adapted and embedded within more complex quantum algorithms. [13]

4.3. Variational Quantum Algorithms

As current quantum hardware is limited by noise and decoherence, **variational quantum algorithms (VQAs)** have emerged as practical approaches for near-term quantum devices. These algorithms combine quantum circuits with classical optimization routines to solve problems iteratively. [11] The quantum processor evaluates a cost function, while a classical computer updates circuit parameters to minimize or maximize the objective. [17] Prominent examples include the Variational Quantum Eigensolver (VQE) and the Quantum Approximate Optimization Algorithm (QAOA). VQAs are particularly promising for applications in quantum chemistry, materials science, and combinatorial optimization, where exact classical solutions are computationally prohibitive. [8]

4.4. Hybrid Quantum–Classical Algorithms

Hybrid quantum–classical algorithms extend the variational approach by strategically dividing computational tasks between quantum and classical processors. [2] This paradigm acknowledges the current limitations of quantum hardware while still exploiting quantum advantages where possible. Hybrid frameworks are central to the noisy intermediate-scale quantum (NISQ) era, enabling meaningful computations with limited qubit counts and imperfect gate fidelities. [7] By integrating classical preprocessing, quantum evaluation, and classical post-processing, these algorithms offer a realistic pathway toward achieving quantum advantage in practical applications. [9]

Quantum algorithms form the backbone of quantum computational advantage, demonstrating how quantum mechanics can be harnessed to outperform classical computation in specific domains. From the theoretical breakthroughs of Shor's and Grover's algorithms to the practical promise of variational and hybrid methods, quantum algorithms continue to drive progress toward scalable and application-oriented quantum computing. [3,8]

5. PHYSICAL IMPLEMENTATIONS OF QUANTUM COMPUTERS

The realization of a practical quantum computer critically depends on the physical system used to implement qubits and quantum operations. [7] Various quantum platforms have been developed and experimentally demonstrated, each based on different physical principles and offering distinct advantages and limitations. Among the most prominent implementations are superconducting circuits, trapped ions, photonic systems, spin-based qubits and topological qubits.[21,3] Understanding these platforms is essential for evaluating their scalability, performance, and suitability for large-scale quantum computation. [2]

5.1. Superconducting Circuits

Superconducting qubits are among the most advanced and widely used quantum computing platforms. These systems are based on superconducting materials operated at cryogenic temperatures, where electrical resistance vanishes and quantum coherence can be maintained. [6] Qubits are typically implemented using Josephson junctions, which provide nonlinear inductance essential for qubit control. Superconducting circuits offer fast gate operations, compatibility with microfabrication technologies and ease of integration into complex circuits. [2] Major technology companies have adopted this approach; however, challenges such as relatively short coherence times and sensitivity to environmental noise remain significant obstacles to scalability. [10]

5.2. Trapped Ion Systems

Trapped ion quantum computers use individual ions confined by electromagnetic fields in ultra-high vacuum environments. Qubits are encoded in the internal electronic or hyperfine states of the ions, which exhibit exceptionally long coherence times. [8,9] Quantum gates are implemented using laser-induced interactions that couple the ions' internal states to their collective motion. Trapped ion systems are known for high-fidelity gate operations and precise qubit control. [1,5] Despite these advantages, scalability remains challenging due to the complexity of controlling large numbers of ions and the increasing technical demands of laser systems. [7,11]

5.3. Photonic Systems

Photonic quantum computing employs photons as qubits, typically encoded in properties such as polarization, path, or time bins. Photons are inherently resistant to decoherence and are well-suited for long-distance quantum communication. [11,18] Photonic systems excel in applications such as quantum cryptography and quantum networking. However, implementing deterministic two-qubit gates with photons is difficult, often requiring probabilistic methods or additional resources. [3,27] Advances in integrated photonics and single-photon sources continue to improve the feasibility of scalable photonic quantum computers.

5.4. Spin-Based Qubits

Spin-based qubits utilize the spin states of electrons or nuclei in solid-state systems, such as quantum dots, diamond nitrogen-vacancy centers, or silicon-based architectures. [1,7] These systems benefit from long coherence times and compatibility with existing semiconductor fabrication technologies. Spin qubits are particularly attractive for large-scale integration and on-chip quantum processing. [6,9] Nonetheless, precise control of spin interactions and mitigation of decoherence caused by surrounding nuclear spins remain key technical challenges. [2,7,9]

5.5. Topological Qubits

Topological qubits represent a more theoretical and emerging approach to quantum computation. They are based on exotic quasiparticles, such as Majorana fermions, whose quantum states are inherently protected from local disturbances. [7,3,8] This topological protection could significantly reduce error rates and simplify quantum error correction. Although experimental evidence for stable topological qubits is still limited, this approach holds promise for achieving robust and fault-tolerant quantum computation in the long term. [3,10]

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

Each physical implementation of quantum computers offers a unique balance between coherence, controllability, scalability, and technological maturity. [11] Continued progress in materials science, device engineering, and quantum control is essential for overcoming current limitations and realizing practical, large-scale quantum computing systems. [12]

6. CHALLENGES IN SCALABLE QUANTUM COMPUTING

Despite remarkable progress in quantum hardware and algorithms, the realization of large-scale, practical quantum computers remains a formidable challenge. Quantum systems are inherently fragile and highly susceptible to environmental disturbances, making scalability one of the most critical issues in quantum computing. [13] Key challenges include decoherence, noise, high error rates, and the demanding requirements of quantum error correction and fault-tolerant computation. [14]

6.1. Decoherence

Decoherence refers to the loss of quantum coherence due to unwanted interactions between a quantum system and its surrounding environment. Such interactions cause qubits to lose their superposition and entanglement properties, effectively collapsing quantum states into classical ones. [11] Decoherence limits the time available for quantum computations and is one of the primary obstacles to building reliable quantum processors. [13] Although advances in materials, isolation techniques, and cryogenic engineering have improved coherence times, completely eliminating decoherence remains fundamentally impossible. [16]

6.2. Noise and Error Rates

Quantum operations are affected by various sources of **noise**, including thermal fluctuations, electromagnetic interference, and imperfections in control signals. These noise sources introduce errors during qubit initialization, gate operations, and measurement. [11] Compared to classical systems, acceptable error thresholds in quantum computing are extremely low, as even small error rates can rapidly accumulate across multi-qubit circuits. Reducing noise through improved hardware design and precise control remains an active area of research. [18]

6.3. Quantum Error Correction

To mitigate errors, **quantum error correction (QEC)** schemes have been developed that encode logical qubits into multiple physical qubits. Unlike classical error correction, QEC must preserve quantum coherence without directly measuring the quantum information. [13] Techniques such as surface codes and stabilizer codes can detect and correct certain types of errors, provided the physical error rates are below a specific threshold. However, QEC introduces substantial resource overhead, often requiring thousands of physical qubits to represent a single fault-tolerant logical qubit. [30]

6.4. Fault Tolerance

Fault-tolerant quantum computing aims to ensure reliable computation even in the presence of errors, as long as those errors remain below threshold levels. [29] Achieving fault tolerance requires precise gate operations, robust error correction and highly scalable architectures. The complexity of implementing fault-tolerant protocols places stringent demands on hardware and control systems, making it one of the most significant challenges in quantum computing research. [22]

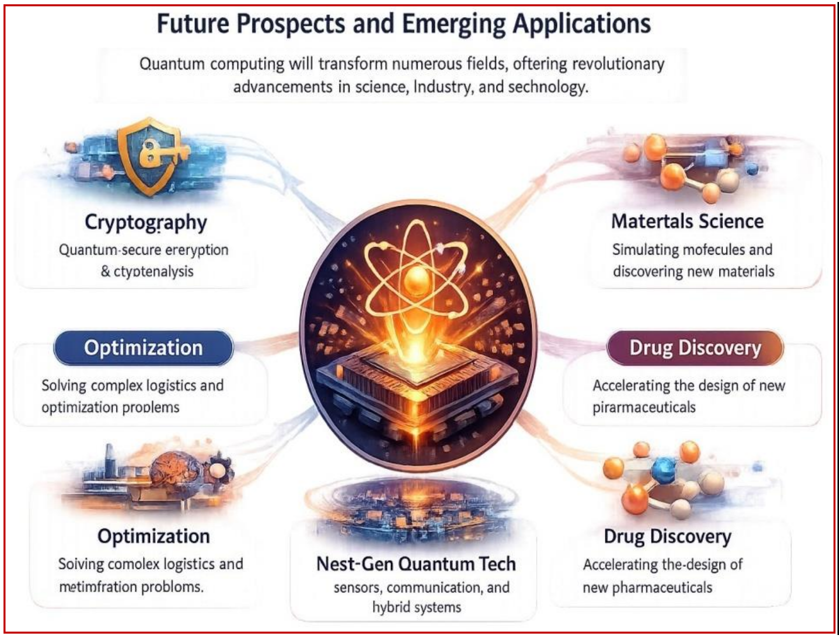
In finally overcoming decoherence, noise, and error accumulation while implementing efficient quantum error correction and fault-tolerant architectures is essential for scalable quantum computing. Addressing these challenges will determine the feasibility of transitioning quantum computers from experimental prototypes to practical, large-scale technologies. [17]

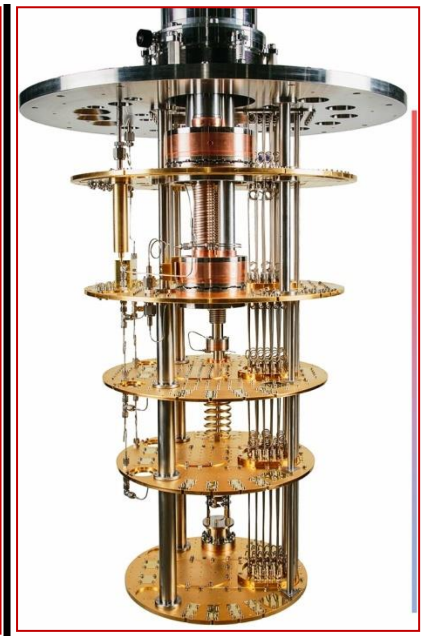
7. FUTURE PROSPECTS AND EMERGING APPLICATIONS

Quantum computing holds significant promise for transforming a wide range of scientific, industrial, and societal domains. [19] As hardware platforms mature and quantum algorithms continue to evolve, quantum computers are expected to address complex problems that are intractable for classical systems. [20] Future prospects are closely linked to advances in cryptography, materials science, optimization, drug discovery, and the development of next-generation quantum technologies. [2,7]

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

Fig 3. Future Prospects of Quantum Computing





7.1. Cryptography and Cybersecurity

One of the most immediate and impactful applications of quantum computing lies in **cryptography**. Powerful quantum algorithms, particularly Shor's algorithm, have the potential to break widely used public-key cryptographic schemes, prompting the development of post-quantum cryptography. [2,3] At the same time, quantum technologies enable fundamentally secure communication methods such as quantum key distribution (QKD), which relies on the principles of quantum mechanics to detect eavesdropping. These developments are expected to reshape global cybersecurity infrastructures in the coming decades. [2,6]

7.2. Materials Science and Chemistry

Quantum computing offers unprecedented capabilities for simulating **quantum many-body systems**, a task that is extremely challenging for classical computers. Accurate quantum simulations can accelerate the discovery of novel materials, high-temperature superconductors, and efficient catalysts. In chemistry, quantum computers can model molecular structures and reaction pathways with high precision, enabling breakthroughs in energy storage, catalysis, and chemical synthesis. [1,8]

7.3. Optimization and Artificial Intelligence

Many real-world problems, including logistics, scheduling, and financial modeling, can be formulated as **optimization problems**. Quantum algorithms and hybrid quantum–classical approaches show promise in exploring large solution spaces more efficiently than classical methods. Additionally, quantum machine learning may enhance pattern recognition and data analysis by leveraging quantum parallelism, potentially complementing classical artificial intelligence techniques. [7]

7.4. Drug Discovery and Healthcare

In **drug discovery**, quantum computing can improve the accuracy of molecular simulations, protein–ligand interactions, and binding energy calculations. These capabilities could significantly reduce the time and cost involved in developing new pharmaceuticals. Quantum-enhanced modeling also holds potential for personalized medicine and advanced biomedical research. [2]

7.5. Next-Generation Quantum Technologies

Beyond computation, quantum research is driving the development of **next-generation quantum technologies**, including quantum sensors, quantum communication networks, and quantum-enhanced metrology. The integration of these technologies into hybrid quantum–classical systems is expected to expand practical applications and accelerate the transition toward a quantum-enabled technological era. [4]

According to this review the future of quantum computing is marked by both transformative potential and ongoing challenges. Continued interdisciplinary research and technological innovation will be essential for realizing the full impact of quantum computing across science, industry and society. [3,8]

Conclusion

Quantum computing represents a paradigm shift in information processing by harnessing fundamental principles of quantum mechanics. This review highlighted key concepts, major quantum algorithms, and leading physical implementations shaping current research. Despite significant progress, challenges such as decoherence, error correction, and scalability remain critical barriers. Emerging hybrid approaches and fault-tolerant architectures provide promising pathways toward practical quantum advantage. Continued interdisciplinary research will be essential to transform quantum computing from experimental systems into impactful real-world technologies.

Acknowledgements

The authors sincerely acknowledge Department of Physics, Loyola Degree College (YSRR), YSR-Kadapa, Andhra Pradesh, for providing the necessary academic support and research facilities. We extend our gratitude to Dr.V. Uday Kiran for their guidance and encouragement throughout the preparation of this review.

REFERENCES

[1] Alexeev, Y., Farag, M. H., Patti, T. L., Wolf, M. E., Ares, N., Aspuru-Guzik, A., ... & Benjamin, S. C. (2025). Artificial intelligence for quantum computing. *Nature Communications, 16*, 10829. https://doi.org/10.1038/s41467-025-65836-3

[2] García-Molina, P., Martin, A., Garcia de Andoin, M., ... et al. (2024). Mitigating noise in digital and digital–analog quantum computation. *Communications Physics, 7*, 321. https://doi.org/10.1038/s42005-024-01812-5

[3] Singh, S., Gu, F., de Bone, S., … et al. (2025). Modular architectures and entanglement schemes for error-corrected distributed quantum computation. *npj Quantum Information*. https://doi.org/10.1038/s41534-025-01146-2

[4] Khan, S. A., Afroz, A. H., & Ali, S. S. (2025). Decoherence impediments in quantum computing and fundamental challenges of quantum error correction. *Asian Journal of Research in Computer Science, 18*(12), 228–239. https://doi.org/10.9734/ajrcos/2025/v18i12800

[5] "Exploring quasi-geometric frameworks for quantum error-correcting codes: a systematic review." (2025). *Quantum Information Processing, 24*, 292. https://doi.org/10.1007/s11128-025-04904-5

[6] "Toward scalable fault-tolerant photonic quantum computers." (2026). *The Journal of Supercomputing, 82*, 51. https://doi.org/10.1007/s11227-025-08132-7

[7] Kumar, S. (2024). A review on quantum computing. *International Journal of Physics and Mathematics, 6*(2), 84–85. http://www.physicsjournal.net/archives/2024.v6.i2.A.166/a-review-on-quantum-computing

[8] "A Comprehensive Review of Quantum Circuit Optimization: Current Trends and Future Directions." (2025). *Quantum Reports, 7*(1), 2. https://doi.org/10.3390/quantum7010002

[9] Raseena, V. (2025). Quantum computing: foundations, algorithms, and architectures. *Frontiers in Quantum Science and Technology*. https://www.frontiersin.org/journals/quantum-science-and technology/articles/10.3389/frqst.2025.1723319

[10] Memon, Q. A. (2024). Quantum computing: navigating the future of computation, challenges, and technological breakthroughs. *Quantum Reports, 6*(4), 39. https://www.mdpi.com/2624-960X/6/4/39

[11] Desdentado, E., Calero, C., & Moraga, M.Á. et al. (2025). Quantum computing software solutions, technologies, evaluation and limitations: a systematic mapping study. *Computing, 107*, 110. https://doi.org/10.1007/s00607-025-01459-2

[12] Bausch, J., Senior, A. W., Heras, F. J. H., … et al. (2024). Learning high-accuracy error decoding for quantum processors. *Nature, 635*, 834–840. https://doi.org/10.1038/s41586-024-08148-8

[13] Zhang, Y., Zhang, X., Sun, J., Lin, H., Huang, Y., Lv, D., & Yuan, X. (2025). Fault-tolerant quantum algorithms for quantum molecular systems: A survey [Preprint]. arXiv. https://doi.org/10.48550/arXiv.2502.02139

[14] Wu, F., Guo, J., Xia, T., … et al. (2025). Quantum design automation: foundations, challenges, and the road ahead [Preprint]. arXiv. https://arxiv.org/abs/2511.10479

[15] Kang, H., Harper, B., Usman, M., & Sevior, M. (2025). Time-adaptive single-shot crosstalk detector on superconducting quantum computer [Preprint]. arXiv. https://arxiv.org/abs/2502.14225

[16] Saklakov, D. (2025). Microgravity and near-absolute zero: A new frontier in quantum computing hardware [Preprint]. arXiv. https://arxiv.org/abs/2512.11091

[17] Hu, G. (2025). Single-electron spin qubits in silicon for quantum computing [Conference paper]. https://pure.tudelft.nl/ws/portalfiles/portal/246137527/icomputing.0115.pdf

[18] Deshmukh, A. (2024). The role of quantum decoherence in quantum computing systems. *Journal of Quantum Science and Technology, 1*(2), 37–43. https://doi.org/10.36676/jqst.v1.i2.14

[19] Lund, B. D. (2025). Quantum computing: a concise introduction. *MDPI Electronics, 5*(4), 173. https://www.mdpi.com/2673-8392/5/4/173

[20] Koo, H. C., Kwon, J. H., Eom, J., Chang, J., Han, S. H., & Johnson, M. (2009). Control of spin precession in a spin-injected field-effect transistor. *Science, 325*(5947), 1515–1518. https://doi.org/10.1126/science.1176987

[21] Appelbaum, I., Huang, B., & Monsma, D. J. (2007). Electronic measurement and control of spin transport in silicon. *Nature, 447*(7142), 295–298. https://doi.org/10.1038/nature05876

[22] Büch, H., Mahapatra, S., Rahman, R., Morello, A., & Simmons, M. Y. (2013). Spin readout and addressability of phosphorus-donor clusters in silicon. *Nature Communications, 4*, Article 2017. https://doi.org/10.1038/ncomms3027

[23] Brataas, A., Bauer, G. E. W., & Kelly, P. J. (2006). Non-collinear magnetoelectronics. *Physics Reports, 427*(4–5), 157–255. https://doi.org/10.1016/j.physrep.2006.01.001

[24] Trowbridge, C. J., Norman, B. M., Kato, Y. K., Awschalom, D. D., & Sih, V. (2014). Dynamic nuclear polarization from current-induced electron spin polarization. *Physical Review B, 90*(8), Article 085122. https://doi.org/10.1103/PhysRevB.90.085122

[25] Kulkarni, A., Prajapati, S., & Kaushik, B. K. (2018). Transmission coefficient matrix modeling of spin-torque-based qubit architecture. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems, 26*(8), 1461–1470. https://doi.org/10.1109/TVLSI.2018.2811685

[26] Kulkarni, A., Prajapati, S., Verma, S., & Kaushik, B. K. (2018). Optimal Boolean logic quantum circuits decomposition for spin-torque based n-qubit architecture. *IEEE Transactions on Magnetics, 54*(10), Article 4100109. https://doi.org/10.1109/TMAG.2018.2831218

[27] Ji, Y., Hoffmann, A., Jiang, J. S., Pearson, J. E., & Bader, S. D. (2007). Nonlocal spin injection in lateral spin valves. *Journal of Physics D: Applied Physics, 40*(5), 1280–1284. https://doi.org/10.1088/0022-3727/40/5/S01

[28] Farshchi, R., & Ramsteiner, M. (2013). Spin injection from Heusler alloys into semiconductors: A materials perspective. *Journal of Applied Physics, 113*(19), Article 191101. https://doi.org/10.1063/1.4804967

[29] Bluhm, H., Foletti, S., Neder, I., Rudner, M., Mahalu, D., Umansky, V., & Yacoby, A. (2011). Dephasing time of GaAs electron-spin qubits coupled to a nuclear bath exceeding 200 µs. *Nature Physics, 7*(2), 109–113. https://doi.org/10.1038/nphys1856

[30] Schreiber, L. R., & Bluhm, H. (2014). Quantum computation: Silicon comes back. *Nature Nanotechnology, 9*(12), 966–968. https://doi.org/10.1038/nnano.2014.259