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Study of Quantum Entanglement and Its Applications in Quantum Computing

Shanu Yadav
Assistant Professor Department of Physics, R. D. S Public Girls College, Rewari
Shanuyadav225@gmail.com

Abstract
One of the key non-classical resources involved in the promise of quantum computing is quantum entanglement. It allows for correlations between qubits that are not possible by independent local states, thus it can be used for computational speed-up, quantum simulation, quantum error correction, quantum machine learning, and secure quantum communication. This paper explores the role of entanglement in quantum computing, and looks at its applications with a secondary-data based research design. This study will evaluate the progress of entanglement from a fundamental physical phenomenon to an engineering resource for processors, algorithms, and fault-tolerant architectures from peer-reviewed literature, institutional reports and public research data from 2018 to 2025. The paper is divided into five subheadings in the introduction, four subheadings in the literature review, a research methodology, and a results section with five secondary-data tables, and a conclusion. The findings reveal a significant acceleration in noisy intermediate-scale quantum devices between 2018 and 2025, along with efforts to prove quantum computational advantage, grow of variational algorithms and increased advancement toward logical qubits and quantum error correction. The evidence also shows that there are important limitations for practical quantum benefit, including decoherence, errors in quantum gates, difficulties loading data, benchmarking arguments, and the high cost of overhead error correction in fault-tolerant quantum computing. The authors conclude that entanglement is not just a theoretical property of quantum physics, but the resource that is needed to link hardware and software with applications. In the future, fidelity of entangling gates, scalable qubit connectivity, error-mitigated algorithms, and fault-tolerant logical qubit designs will all be important.

Keywords: quantum entanglement, quantum computing, qubits, NISQ, quantum algorithms, quantum error correction, quantum machine learning

1. Introduction

1.1 Background of Quantum Entanglement

Joint states of two or more quantum systems, in which the state of the whole cannot be written as a product of the states of its parts, are called quantum entanglements. A classical bit is a binary digit which takes a fixed value of either 0 or 1. Qubits in quantum information processing can be in a superposition of basis states, and several qubits can be entangled so that the results of measuring their respective values are highly correlated. For instance, the Bell state $|00\rangle + |11\rangle$ does not have a definite value for either qubit prior to measurement, but, once one qubit is measured,

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the result of the other qubit is correlated with it. This non-classical relation represents an essential resource for quantum teleportation, quantum algorithms, quantum cryptography and quantum error correction. From the point of view of quantum computation, entanglement can be used to make the computational state space of the quantum processor larger, and to represent and perform patterns that are extremely hard for classical computers to efficiently represent and perform (Harrow & Montanaro, 2017; Preskill, 2018).

Entanglement has moved from being a philosophical conundrum to an engineering goal. In addition to the number of qubits, modern quantum processors are judged by the quality of entangling operations, the coherence time, connectivity, error rate, and their ability to perform non-trivial circuits. If entanglement can't be reliably generated and maintained, a high qubit count is not very useful. For these reasons, the recent advances in superconducting, photonic, trapped-ion, and neutral-atom systems are assessed based on circuit depth, entangling-gate fidelity, logical error rate, and scalability of multi-qubit operations (Arute et al., 2019; Acharya et al., 2023).

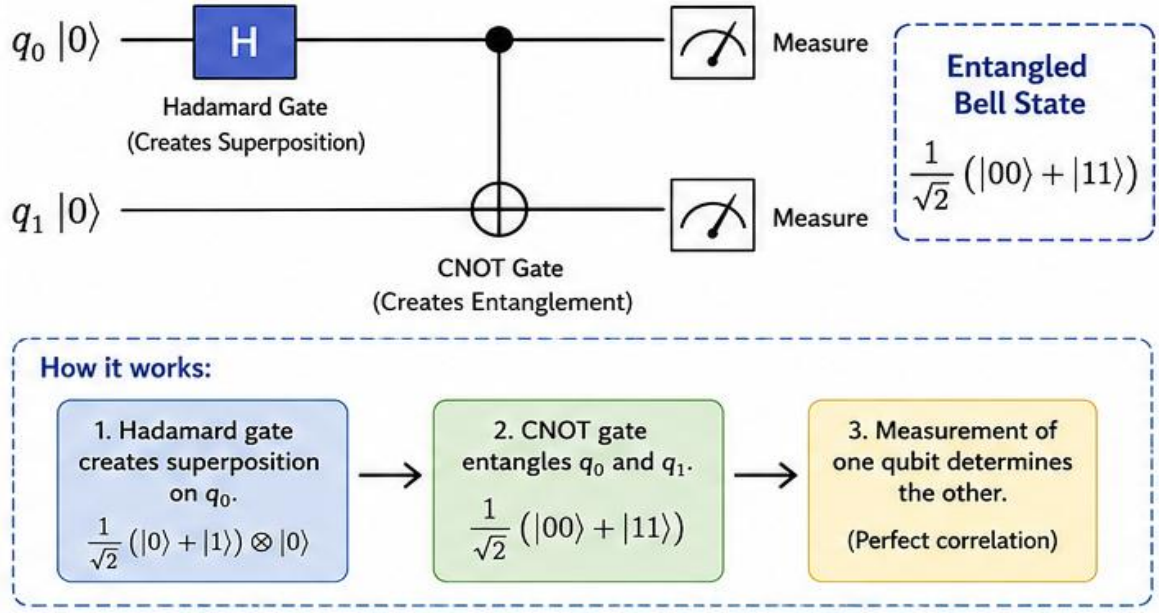

Figure 1. Bell-state preparation circuit showing how superposition and CNOT operation create two-qubit entanglement.

1.2 Concept of Quantum Computing

In quantum computing, which is a model of computation, information is carried by quantum-mechanical systems. In contrast to information being processed solely by deterministic Boolean operations, quantum computers rely on the use of unitary operations, measurement, and controlled interactions between qubits. Many important quantum algorithms require controlled multi-qubit operations like CNOT, controlled-phase, Toffoli decompositions, entangling layers in variational circuits, and more; entanglement is essential. If no entanglement were possible a quantum

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computer would be more like a set of independent probabilistic devices and wouldn't have the same theoretical computational benefit. In the era of noisy intermediate scale quantum technology, entanglement has thus become a scientific concept and a performance limitation (Preskill, 2018; Bharti et al., 2022).

Theoretical quantum algorithms, like Shor's factoring algorithm, Grover-type search, quantum phase estimation, and Hamiltonian simulation, demonstrate speed-ups for certain problem classes in quantum computing. But existing systems are problematic in terms of noise and the challenge of maintaining coherent entanglement across many qubits. This is why, for instance, near-term hybrid proposals like variational quantum eigensolvers (VQE) and quantum approximate optimization algorithms (QAOA) are so important: a quantum device is used to prepare entangled states, with a classical optimizer tuning the parameters of the circuit (Cerezo et al., 2021; Endo et al., 2021).

1.3 Significance of Entanglement in Quantum Speed-up

While entanglement is not always a sufficient resource for achieving speed-up, in many models of computation it is regarded as one of them. In a quantum algorithm, interference is employed to enhance the success of a correct result while diminishing the probability of an incorrect one, but sometimes interference takes place in highly entangled multi-qubit states. Bravyi et al. (2018) have theoretically shown that there are scenarios in which a shallow quantum circuit can have advantages over a classical circuit with the same complexity. Experimental demonstrations of quantum computational advantage also used the hard-to-classically simulate large entangled or non-classical quantum states, including random circuit sampling (Arute et al., 2019) and gaussian boson sampling (Zhong et al., 2020).

Meanwhile, care needs to be taken with entanglement. If there is not enough entanglement, computation power will be limited, but if too much entanglement is not controlled, there will be barren plateaus or hard-to-train circuits. Structured entanglement is thus essential to practical quantum computing, so as to carry enough information to encode correlations and explore useful regions of the Hilbert space without losing the calculation to noise. In quantum machine learning and optimization problems, the depth of the circuits, how data is encoded, and the cost of measurement are critical, as they determine whether a quantum model can be more efficient than a classical model (Biamonte et al., 2017; Cerezo et al., 2021).

1.4 Applications in Quantum Computing

There are several applications that use entanglement. Entangled states are correlated electrons and quantum many-body systems more naturally than classical bit strings in quantum simulation and computational chemistry. In quantum machine learning, entangled feature spaces could enable the use of quantum kernels and quantum classifiers which are difficult to simulate classically. Entangling layers are used in optimization to store the candidate solutions and correlation between decision variables in a quantum circuit. Sharps and Shor type algorithms for quantum computers

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that are powerful enough could break some cryptographic schemes such as RSA and elliptic-curve systems, and quantum communication using entanglement will introduce novel security principles. In the context of error correction, entanglement is employed to spread out quantum information among numerous physical qubits, allowing one to detect errors without directly measuring the protected logical state (Campbell et al., 2017; McArdle et al., 2020; Gidney & Ekerå, 2021).

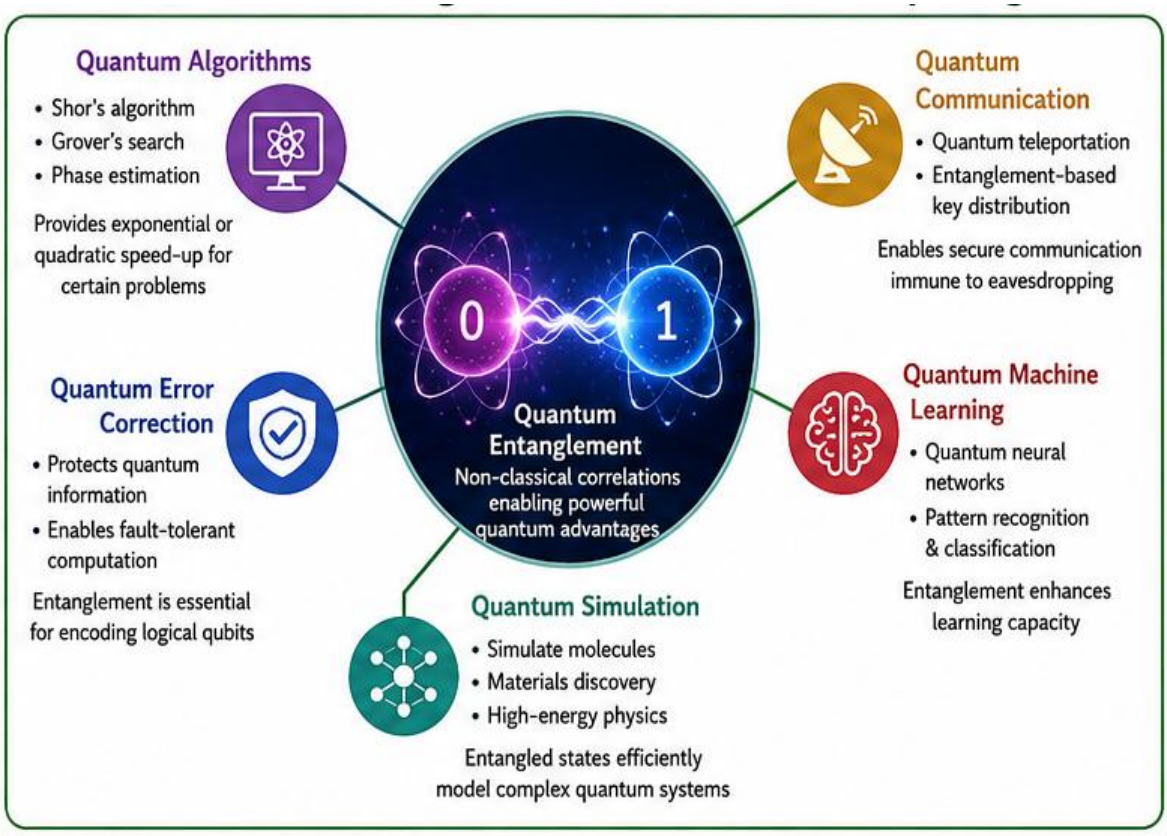

Figure 2. Conceptual framework: entanglement as a common resource connecting algorithms, hardware, error correction, and application domains.

1.5 Objectives of the Study

The aim of this paper is to explore the role of quantum entanglement as a useful resource in quantum computing and, using secondary data from the past five years (2018-2025), to analyze the applications of quantum entanglement in this domain. Specific objectives are to explain the conceptual connection between entanglement and quantum computing, to review the literature related to entanglement, NISQ algorithms, quantum machine learning, quantum simulation, and fault-tolerant quantum computing, to organize secondary data about recent developments and applications, to analyse opportunities and challenges of entanglement-based quantum information processing, and to discuss future research directions. The scope is restricted to gate based and sampling oriented quantum computing and focuses on the recent advances in superconducting,

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photonic and logical-qubit approaches. It does not conduct new experiments in the laboratory, but rather it pulls together published evidence.

2. Literature Review

2.1 Entanglement as a Computational Resource

In the literature, entanglement is considered to be a resource that sets quantum information processing apart from classical computation. Harrow and Montanaro (2017) surveyed the field of quantum computational supremacy and proposed that there are certain sampling problems and families of circuits that are good candidates for showing quantum advantage. Preskill (2018) coined the phrase "noisy intermediate-scale quantum" for machines with several tens to hundreds of qubits, meaning they could be used to compute in regimes that exceed the capability of a classical computer but are not yet in the realm of fault-tolerant quantum computing. In this literature, the growth of state space complexity is associated with entanglement. We can represent amplitudes over 2^n basis states with a system of n qubits, but only circuits which can perform controlled multi-qubit interaction can create the type of non-separable states which make this space useful for computation.

It's important to note the difference between entanglement that's formal, and entanglement that's useful. There are many random quantum states which are very entangled, but not necessarily useful for practical problems. There must be circuits that correspond to a computational objective which generate useful entanglement. Examples include variational algorithms, where one forms parameterized entangled states and fine tunes the parameters of the state to minimize an energy or cost function. The structured entangled stabilizer states are generated to protect information in quantum error correction. Entanglement is the key to quantum simulation to model correlations in quantum matter. The question is increasingly evolving from one of whether entanglement exists, to how it can be controlled, benchmarked and turned into computational value (Campbell et al., 2017; Cerezo et al., 2021).

2.2 NISQ Devices and Quantum Advantage

One of the key areas of quantum computing research in recent years is the NISQ era. Preskill (2018) suggested that the near-term applications of quantum devices would not immediately transform the world, but that they may open up new possibilities for the study of quantum many-body physics, and even for the testing of computational advantage. Random circuit sampling has been reported by Arute et al. (2019) on Google's Sycamore processor based on a 53-qubit programmable superconducting device. The experiment was not intended as a practical commercial product, but as a means of illustrating the need for controllable entanglement in circuits which are not easily simulated classically. Zhong et al. (2020) also showed that non-classical correlations can lead to sampling tasks that are not as easily performed classically, with the report of quantum computational advantage for a photonic processor that implements Gaussian boson sampling.

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It is also acknowledged in the literature that quantum advantage is questionable and situational. Classical algorithms and supercomputing methods are continually improving and quantum advantage claims should be compared against the best classical algorithms available. Prior to fault-tolerant quantum computing, Kim et al. (2023) found evidence of quantum utility on a 127 qubit IBM processor and employing error-mitigation strategies. While this did not resolve the debate, it suggested that potentially useful pre-fault-tolerant computation can be realised with larger processors, better entangling gates and judicious error mitigation. As a whole, the NISQ literature reveals the need for entanglement, but it is not enough, as quality, depth, design of the benchmark and classical comparison are also crucial factors (Bharti et al., 2022; Endo et al., 2021).

2.3 Applications in Simulation, Chemistry, and Machine Learning

Application areas that seem most convincing are quantum simulation and quantum chemistry, since quantum computers are quantum systems themselves. Kandala et al. (2017) presented a hardware efficient variational quantum eigensolver for small molecules and quantum magnets. In the age of quantum computing, Cao et al. (2019) discussed the quantum chemistry and focused on the importance of quantum algorithms in electronic-structure problems. McArdle et al. (2020) also noted that in the future, quantum phase estimation could be useful in quantum computational chemistry, while in the near future, variational algorithms. These works demonstrate the usefulness of entanglement: molecules and materials are often one of the strongly correlated electrons that cannot be compactly represented on classical computers.

A new and fast-growing field is quantum machine learning. According to Biamonte et al. (2017), quantum machine learning refers to quantum algorithms and quantum software that could be used to expedite or enhance machine-learning applications. Havlíček et al. (2019) showed quantum-enhanced feature spaces, classical data encoded into high dimensional Hilbert spaces, which can be mapped by quantum circuits, and then applied to supervised learning. But there are significant challenges to quantum machine learning, too, as highlighted in the literature, including input-output limitations, noise, finite sampling, and the challenge of demonstrating meaningful benefit compared to strong classical models. If entanglement is used to facilitate expressive feature maps, only a hard and useful problem can make the application valuable—one different, but not just that.

2.4 Fault tolerance, error correction and scalability

Fault tolerance is the way forward from the fragile NISQ devices to the reliable quantum computers. If the states of the physical qubits are not entangled, there's no way to copy a quantum state, and if the state is measured, it can interfere with quantum information, so that means we need to encode logical qubits in the state of many physical qubits. Campbell et al. (2017) discussed the progress towards fault-tolerant universal quantum computation, and all important features of the hardware architecture, gate set, code design, and magic-state resources are crucial. Recent experiments by Acharya et al. demonstrated that scaling a surface-code logical qubit can start to make quantum errors go down, which is an important step towards scalable error correction. This

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trend was followed by more recent results pre-2025, which involved testing below-threshold surface-code operation (Acharya et al., 2024).

Scalability is not just simply about the number of qubits. It also needs high fidelity entangling gates, rapid measurement, real-time decoding, cryogenic or photonic control systems and software capable of compiling algorithms into the limited hardware connectivity. The scale problem is also true for the resource estimates for breaking classical cryptography: Gidney and Ekerå (2021) projected that in their realistic estimates factoring RSA-2048 would require millions of noisy physical qubits, though improvements in architectures could bring this number down. So the literature proposes that the next step towards quantum computing is to make the fragile physical entanglement more stable, in the form of a logical entanglement.

3. Research Methodology

The methodology of this study is Secondary Data, Methodology is qualitative and descriptive. No primary lab experiment, survey, simulation was performed. Data were obtained by searching peer-reviewed journal articles, review papers, official research announcements and publicly accessible institutional material primarily from 2018 until 2025. The reference list is based on 20 original scholarly sources published between 2015 and 2024, while 2025 is a status horizon, not a primary experiment, in which further developments are explained. The analysis is centered around four aspects: theoretical significance, hardware advancement, algorithmic use and scalability for error correction.

Selection criteria were: relevance to quantum entanglement or quantum computing; publication in recognized journal or conference venue as well as official research platforms; contribution to quantum advantage, NISQ algorithms, applications, and fault tolerance; development period from 2018 to 2025. Popular articles were not considered for the review, unless they were used as background verification. The tables in the results section are not the author's experimental measurements, but are secondary-data syntheses. The tables in each section provide a summary of the field for milestones, hardware/benchmark progress, applications, error correction, and challenges. This is suitable because quantum computing is a fast-moving and evolving field with the valuable evidence spread out across many studies and not in one dataset.

There are limitations on the method. Firstly, secondary data are dependent on the validity of the original studies. Second, quantum claims of benchmark performance can sometimes be adjusted as new classical algorithms become available. Finally, hardware metrics reported by different groups are not necessarily directly comparable across platforms since various types of systems (superconducting, photonic, trapped ion, and neutral atom) measure them differently. Fourth, the usefulness of many demonstrations is still open to question. To minimize these restrictions, the paper separates the concepts of demonstration, utility and practical benefit. A demonstration proves the ability to do a hard task with a quantum device; a useful task more useful than a classical

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one under realistic costs and accuracy requirements proves the practical advantage; a scientifically meaningful calculation is required before full fault tolerance.

4. Results and Discussion

The findings reveal a clear trend: entanglement plays a key role in each of the key building blocks of quantum computers, but using entanglement to achieve a practical advantage is technically challenging. There are four major phases that can be divided between the years 2018 and 2025. Theoretical and experimental assertions of advantage became more strident. Second, the "near term" strategy was dominated by NISQ algorithms. Third, the number of qubits and the quality of control on hardware platforms increased. Fourth, the emphasis changed from the number of qubits to error correction, logical qubits and utility-oriented benchmarks.

Table 1. Major entanglement-related quantum-computing milestones, 2018–2025

Year	Milestone	Entanglement/quantum resource involved	Interpretation
2018	NISQ era clearly framed in research literature	Multi-qubit noisy entanglement in 50–100+ qubit devices	Showed that near-term devices are useful research tools but not yet world-changing computers
2019	Random circuit sampling on Sycamore	Entangled superconducting-qubit circuits across 53 working qubits	Important benchmark demonstration of quantum computational advantage
2020	Photonic quantum computational advantage using Jiuzhang	Non-classical photonic correlations and large output state space	Extended advantage demonstrations beyond superconducting circuits
2021	Resource estimates for cryptographic impact	Fault-tolerant entangled logical qubits needed for Shor-type algorithms	Showed that practical cryptographic attacks require large-scale error-corrected machines
2022	NISQ algorithms consolidated through major reviews	Hybrid entangled variational circuits	Clarified near-term algorithm categories and limitations

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2023	Pre-fault-tolerant utility evidence on 127-qubit device	Entangled dynamics of a quantum many-body model with error mitigation	Suggested that useful scientific calculations may emerge before full fault tolerance
2024	Surface-code and logical-qubit progress	Encoded logical qubits using many entangled physical qubits	Strengthened the path from physical to logical entanglement
2025	Status horizon: practical fault tolerance remains under development	Scalable logical entanglement remains the key requirement	Field focus shifts from qubit count to reliable logical operations

Source/Note: Synthesized from Preskill (2018), Arute et al. (2019), Zhong et al. (2020), Gidney and Ekerå (2021), Bharti et al. (2022), Kim et al. (2023), and Acharya et al. (2023, 2024).

The field progressed from proof of principle advantage to utility and error correction, as suggested in Table 1. The 2019 and 2020 demonstrations were significant in that they sampled from distributions which were extremely difficult to simulate exactly using quantum systems. These tasks were, however, not the actual solutions of the industrial problems. By 2023 and 2024 the question was increasingly being asked whether entangled processors can yield scientifically meaningful results and whether logical qubits can outperform physical qubits. The change is significant because the goal of quantum computing in practice is not to achieve a lot of entanglement but reliable entanglement.

Table 2. Selected hardware and benchmark developments relevant to entanglement, 2018–2025

Period	**Platform**	**Representative evidence**	**Main lesson for quantum computing**
2018–2019	Superconducting qubits	Programmable circuits and random circuit sampling	Fast gates and chip fabrication make superconducting qubits a leading NISQ platform
2020	Photonic sampling	Gaussian boson sampling with large output state space	Photons can create hard sampling problems but programmability and loss remain critical

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2021–2022	Hybrid algorithms on NISQ devices	Variational algorithms and error mitigation reviews	Useful computation requires algorithm-hardware co-design
2023	127-qubit superconducting processor	Quantum utility experiment with error mitigation	Scale alone is insufficient; error mitigation and observable design matter
2024–2025	Logical-qubit and surface-code progress	Encoded qubits and below-threshold/error-suppression work	Fault tolerance depends on converting physical entanglement into protected logical entanglement

Source/Note: Secondary synthesis based on Arute et al. (2019), Zhong et al. (2020), Endo et al. (2021), Kim et al. (2023), Acharya et al. (2023), and Acharya et al. (2024).

As can be seen in table 2, there are hardware platforms that offer certain strengths and others that offer different strengths. A key advantage of superconducting qubits is that they are fast gate-operated and can be microfabricated. The potential of travel of photons and the natural ability to support optical interference make photonic systems desirable for sampling and communication. But a platform that's not solved all the problems of scale, error and programmability has yet to emerge. However, in all platforms, there is a common requirement that the entanglement has to be generated reliably. An entangling-gate error is an error that impacts directly the meaning of a computation, as are the errors of photon loss, cross-talk, and measurement. However, the optimal hardware approach is not just the platform with the most qubits, it's the platform that can generate, manipulate, and safeguard entanglement on scale.

Table 3. Application areas of entanglement in quantum computing

Application area	Entanglement role	Near-term status	Long-term potential
Quantum simulation	Represents correlated many-body quantum states	Most natural early application for NISQ and utility experiments	Materials, magnetism, condensed matter, high-energy models
Quantum chemistry	Encodes correlated electronic structure	Small molecules and model systems demonstrated with VQE-type methods	Drug discovery, catalysts, batteries, reaction mechanisms

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Optimization	Creates correlated candidate solution states	Hybrid algorithms tested, but advantage is not yet proven broadly	Logistics, scheduling, portfolio models, combinatorial search
Quantum machine learning	Creates quantum feature spaces and expressive circuits	Promising but limited by data loading, noise, and benchmarking	Specialized kernels, generative models, quantum data analysis
Cryptography impact	Large-scale entanglement needed for fault-tolerant Shor-type algorithms	Current machines not sufficient for breaking strong public-key systems	Need for quantum-safe cryptography and future cryptanalysis
Error correction	Encodes one logical qubit into entangled physical qubits	Rapid progress in surface codes and logical-qubit demonstrations	Reliable large-scale fault-tolerant quantum computation

Source/Note: Compiled from Campbell et al. (2017), Biamonte et al. (2017), Kandala et al. (2017), Cao et al. (2019), McArdle et al. (2020), Cerezo et al. (2021), and Gidney and Ekerå (2021).

Table 3 again indicates that there is no single use for entanglement—it is a cross-cutting resource. It is useful for modelling reality in simulation and chemistry. It might generate spaces of representation that are difficult to produce classically, in machine learning and optimization. Cryptography: indirectly relevant: fault tolerant entangled operations required to run algorithms that threaten public-key encryption. In error correction, it plays a direct role, as the protected logical state is spread over several physical qubits. The best case for near-term relevance is quantum simulation, and the best for transforming computation in the long run is fault-tolerant computation.

Table 4. Secondary data on error correction and fault-tolerant development

Stage	**Representative development**	**Entanglement function**	**Research implication**
Theory and code design	Roadmaps toward fault-tolerant universal computation	Defines how logical qubits and gates can be protected	Provides architecture-level direction
NISQ error mitigation	Hybrid algorithms with noise-aware post-processing	Does not fully correct errors but extracts useful observables	Bridges near-term devices and long-term fault tolerance

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Surface-code scaling	Larger code distance improves logical performance in experiments	Uses many entangled physical qubits to protect one logical qubit	Shows beginning of scalable quantum error correction
Logical-qubit demonstrations	Encoded operations can outperform physical baselines in selected settings	Turns fragile physical entanglement into more stable logical entanglement	Indicates transition from NISQ to reliable quantum computing
2025 status horizon	Fault-tolerant machines remain under construction	Requires millions or large numbers of physical qubits depending on architecture	Main bottleneck is reliable logical operations at scale

Source/Note: Based on Campbell et al. (2017), Endo et al. (2021), Acharya et al. (2023), Acharya et al. (2024), and Gidney and Ekerå (2021).

As presented in Table 4, fault tolerance is the most crucial future challenge. In some observables, NISQ error mitigation can be useful to diminish the bias but cannot replace with error correction. A fault-tolerant machine should be able to continuously detect and correct errors, and preserve quantum information. This necessitates repeated measurement of the syndrome, rapid classical decoding, and physical systems with a long coherence time to allow correction cycles. It is entanglement, then, that provides quantum power and engenders engineering challenges: the processing hardware must generate highly non-classical states, and those states are extremely sensitive to noise.

Table 5. Main challenges and research directions in entanglement-based quantum computing

Challenge	**Observed problem in 2018–2025 literature**	**Likely research direction**	**Expected impact**
Decoherence	Entangled states decay through environmental interaction	Better materials, isolation, cryogenics, photonic loss reduction	Longer useful circuit depth
Gate error	Entangling gates are usually noisier than single-qubit gates	Pulse engineering, tunable couplers, calibration automation	Higher circuit fidelity

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Scalability	More qubits increase control and cross-talk complexity	Modular architectures and improved connectivity	Larger entangled processors
Benchmarking	Classical simulation baselines improve over time	Transparent benchmarks and reproducible tasks	More reliable claims of advantage
Algorithm utility	Many algorithms are promising but not yet practically superior	Problem-specific quantum-classical workflows	Clearer commercial and scientific value
Error correction overhead	Logical qubits require many physical qubits	Efficient codes, real-time decoding, better physical fidelity	Path to fault-tolerant computation

Source/Note: Derived from Preskill (2018), Cerezo et al. (2021), Endo et al. (2021), Bharti et al. (2022), Kim et al. (2023), and Acharya et al. (2023).

The data in Table 5 shows why it is important to take quantum computing progress with a grain of salt. While the number of qubits has been a discussion point in public, it is clear from the table that quantum advantage requires more than just that number of qubits. A smaller processor with very high fidelity entangling operations might be more useful science-wise than a larger processor that has noisy gates. Likewise, a mathematically beautiful algorithm could be impractical if the state preparation or measurement costs or noise erode the advantage. So the conclusion is that entanglement is essential, but must be created via hardware, algorithms and error correction.

5. Conclusion

The study of quantum entanglement and its applications in quantum computing were studied in this paper with a secondary-data-based research design. From the evidence, it can be seen that the key resource that connects theory and practice of quantum computing is entanglement. It provides a way of representing non-classical correlations on qubits, provides algorithms that can outperform classical computation, can be used for quantum simulation of many-body systems, can give quantum machine learning models expressive feature spaces, and forms the basis of quantum error correction. Between 2018 and 2025, the field advanced quickly, with the NISQ era being conceptually defined, with quantum computational advantage being realized in a few select sampling applications, the variational algorithms being adopted as the primary near-term approach, with quantum utility being explored in larger processors, and logical-qubit experiments being strengthened to support the path toward fault-tolerant quantum computing. The study also reveals that the practical quantum computing is not completed. Entanglement is fragile. Today's processors can compute only so deeply due to decoherence, errors of the gates, cross-talk, and noise from measurements and limited connectivity. There are many demonstrations of

computational hardness that do not immediately suggest any practical applications. The success of quantum machine learning and optimization is yet to be demonstrated with significant advantages over classical approaches. All of these are more quantum in nature as they involve quantum states directly, but even here the scale required to make an impact in industry is significant. The effects of cryptography are potentially very harmful in the future, but existing machines are not yet a fraction of the fault tolerance required to crack robust public-key systems. The key takeaway is that realizing reliable logical entanglement is the crucial next step to making quantum computing a reality. NISQ devices can create entangled states, but in order to maintain and use them for long calculations, the fault-tolerant machines are needed. Quantum error correction is thus not an afterthought, but rather the link between laboratory demonstrations and practical quantum advantage. Future studies include the development of high fidelity entangling gates, scalable modular hardware, efficient error correcting codes, real-time decoding, clear benchmarks and algorithms that solve well defined scientific or industrial problems. Under such conditions, entanglement will remain a quantum effect of the unknown, but also become a tool for computation. It is important to take quantum entanglement as an operating principle of quantum computing and not a separate topic. Without the ability to create entanglement, control it and use it in a useful way, a quantum computer is not powerful enough. The path of quantum processors from 2018 to 2025 indicates progress from proof-of-concept experiments to utility and fault tolerance. Progress is great, but a realistic assessment is needed. The potential for quantum computing is real but it will require the ability to transform entangled physical systems into stable, scalable and application-oriented computing machines.

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