CITE PUBLICATIONS

Journal of Analytical and Applied Computer Sciences
Volume: 1, Issue: 1, 2025 (December), Pages: 11-15
DOI: https://doi.org/10.37446/jaacs/ra/1.1.2025.11-15

Review Article

Quantum Advantage in the NISQ Era - Algorithms, Benchmarks, and Practical Limitations

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Received: 5 August 2025 / Accepted: 25 November 2025 / Published: 31 December 2025

The current stage of quantum computing development is defined by Noisy Intermediate-Scale Quantum (NISQ) devices, which operate with a moderate number of qubits that are inherently susceptible to noise and decoherence. Despite the absence of full error correction, NISQ systems have demonstrated the ability to perform computational tasks that challenge classical simulation under certain conditions. This paper explores the concept of quantum advantage in the NISQ era by analysing prominent algorithmic approaches, benchmarking methodologies, and the practical constraints imposed by contemporary hardware. Hybrid quantum–classical algorithms, sampling-based experiments, and performance metrics are examined to assess the extent to which near-term quantum devices can outperform classical systems. The study finds that while progress toward quantum advantage is evident, significant technical and algorithmic limitations prevent its widespread realization. The paper concludes by identifying key research directions required to bridge the gap between experimental demonstrations and practical quantum computing applications.

Keywords: *Quantum Advantage, NISQ Devices, Variational Algorithms, Quantum Benchmarking, Quantum Noise, Hybrid Quantum–Classical Computing*

Introduction

Quantum computing leverages quantum mechanical principles such as superposition, interference, and entanglement to process information in ways that are fundamentally different from classical computation (Nielsen & Chuang, 2010). Over the past decade, experimental advances have enabled the construction of quantum processors with tens to hundreds of qubits. These systems, commonly referred to as Noisy Intermediate-Scale Quantum (NISQ) devices, lack the error correction capabilities required for large-scale fault-tolerant computation but offer a testbed for exploring near-term quantum algorithms (Preskill, 2018).A major research objective during the NISQ era is the demonstration of *quantum advantage*, which broadly refers to scenarios where a quantum processor performs a computational task more efficiently than the best-known classical algorithms (Aaronson, 2015). Early demonstrations of quantum supremacy, particularly those involving random circuit sampling, suggested that quantum hardware could achieve computational feats beyond classical reach (Arute et al., 2019). However, subsequent improvements in classical simulation techniques raised important questions regarding the robustness and generality of such claims (Pednault et al., 2020). To address these concerns, researchers have increasingly focused on hybrid quantum–classical approaches and application-driven benchmarks. Algorithms such as the Variational Quantum Eigensolver (VQE) and the Quantum Approximate Optimization Algorithm (QAOA) have been proposed as promising candidates for near-term advantage in fields such as quantum chemistry and combinatorial optimization (Peruzzo et al., 2014; Farhi et al., 2014). Nevertheless, noise, limited circuit depth, and scalability challenges continue to constrain their performance. This paper presents a comprehensive analysis of quantum advantage in the NISQ era by reviewing key algorithmic strategies, evaluating benchmarking frameworks, and discussing the practical limitations that hinder real-world applicability. The goal is to provide a balanced assessment of current capabilities and outline pathways for future progress (Gambetta et al., 2017; Montanaro, 2016).

Background and Related Work

Noisy Intermediate-Scale Quantum Devices

The term NISQ was introduced to describe quantum computers that operate without full error correction and are therefore susceptible to decoherence, gate errors, and measurement noise (Preskill, 2018). Typical NISQ devices range from 50 to several hundred qubits, depending on the hardware platform. Leading architectures include superconducting qubits, trapped ions, and photonic systems, each offering distinct advantages in terms of coherence time, connectivity, and scalability (Monroe et al., 2021).

Quantum Advantage and Supremacy

Quantum supremacy refers to the execution of a computational task by a quantum device that is infeasible for classical computers within a reasonable time frame (Arute et al., 2019). Quantum advantage, in contrast, emphasizes practical usefulness and real-world relevance. Many researchers argue that meaningful advantage should involve tasks with scientific or industrial significance rather than artificially constructed problems (Aaronson, 2015; Harrow & Montanaro, 2017).

Algorithms for the NISQ Era

Variational Quantum Algorithms

Variational quantum algorithms (VQAs) are hybrid methods that combine quantum circuits with classical optimization loops. In these algorithms, a parameterized quantum circuit is iteratively optimized to minimize a cost function defined by the problem (Peruzzo et al., 2014). The Variational Quantum Eigensolver has been widely studied for estimating molecular ground-state energies, while QAOA targets combinatorial optimization problems (Farhi et al., 2014; McClean et al., 2016). Despite their promise, VQAs face challenges such as barren plateaus, where gradients vanish exponentially with system size, making optimization increasingly difficult (McClean et al., 2018). Noise further exacerbates these issues by distorting measurement outcomes and reducing convergence reliability.

Sampling-Based Algorithms

Sampling-based approaches, including random circuit sampling and boson sampling, have been central to early demonstrations of quantum advantage (Arute et al., 2019). These methods exploit the exponential complexity of simulating quantum probability distributions on classical hardware. However, their practical utility remains limited, as they are not directly applicable to most real-world problems (Pednault et al., 2020; Aaronson & Arkhipov, 2013).

Benchmarking Quantum Advantage

Hardware-Oriented Benchmarks

Benchmarking NISQ devices requires metrics that capture both hardware quality and algorithmic performance. Quantum volume is a widely used metric that reflects the largest random circuit a quantum processor can successfully implement (Cross et al., 2019). Randomized benchmarking techniques are also employed to estimate average gate fidelities and error rates (Knill et al., 2008).

Application-Oriented Benchmarks

Application-level benchmarks focus on task-specific performance, such as energy estimation accuracy in quantum chemistry or solution quality in optimization problems. These benchmarks provide a more realistic assessment of quantum advantage but are often problem-dependent and difficult to standardize (Harrow & Montanaro, 2017; Cao et al., 2019).

Practical Limitations

Noise and Decoherence

Noise remains the most significant obstacle to reliable quantum computation in the NISQ era. Decoherence limits circuit depth, while gate and measurement errors introduce uncertainty into computational results (Preskill, 2018; Temme et al., 2017).

Scalability Constraints

Scaling NISQ devices to larger qubit counts introduces additional control and calibration challenges. Crosstalk, connectivity limitations, and error accumulation hinder the execution of complex algorithms (Monroe et al., 2021; Gambetta et al., 2017).

Algorithmic Challenges

Even when hardware improves, algorithmic limitations persist. Many proposed NISQ algorithms offer only modest or problem-specific advantages, and classical heuristics continue to improve at a rapid pace (Pednault et al., 2020; McClean et al., 2018).

Case Studies

Random Circuit Sampling Experiments

Experiments using superconducting quantum processors demonstrated rapid sampling of quantum circuits that were initially believed to be classically intractable (Arute et al., 2019). Later studies showed that optimized classical simulations could reduce the performance gap, highlighting the dynamic nature of quantum advantage claims (Pednault et al., 2020).

Quantum Chemistry Applications

Small-scale demonstrations of VQE have successfully simulated simple molecules, providing proof-of-concept results for quantum chemistry applications (Peruzzo et al., 2014; McClean et al., 2016). However, extending these methods to chemically relevant systems remain challenging due to noise and resource requirements (Cao et al., 2019).

Future Research Directions

Future progress toward practical quantum advantage will require advances in error mitigation, noise-aware circuit design, and hardware-specific algorithm optimization (Temme et al., 2017). Techniques such as circuit cutting and error extrapolation offer near-term improvements without full error correction (Peng et al., 2020). In the long term, the development of fault-tolerant quantum computers remains essential for unlocking the full potential of quantum algorithms.

Conclusion

The NISQ era has played a crucial role in advancing experimental quantum computing and testing theoretical concepts of quantum advantage. While current devices have demonstrated capabilities beyond small-scale classical simulations, their practical impact remains constrained by noise, limited scalability, and algorithmic challenges. This paper has shown that hybrid algorithms and benchmarking frameworks provide valuable insights but fall short of delivering consistent, real-world quantum advantage. Continued interdisciplinary research in hardware, algorithms, and benchmarking methodologies is necessary to transition from experimental demonstrations to practical quantum computing systems.

Author contributions

Akella Pathanjali Sastri conceptualized the study, led the analysis of quantum advantage frameworks, and drafted the core sections of the manuscript.

Akelle Srinivasa Rao contributed to the review of NISQ algorithms, benchmarking methodologies, and practical hardware limitations.

V. N. R. Sai Krishna Kari provided critical insights into scalability challenges, future research directions, and performed thorough manuscript review and editing. All authors read, revised, and approved the final manuscript.

Funding

No funding.

Conflict of interest

The author declares no conflict of interest. The manuscript has not been submitted for publication in other journal.

Ethics approval

This research is a theoretical and review-based study derived entirely from previously published literature. It does not involve human participants, animals, or identifiable personal data. Accordingly, ethical approval and informed consent are not applicable.

AI tool usage declaration

The authors declare that AI-assisted tools were used solely for language refinement, grammar checking, and formatting assistance during manuscript preparation. All scientific content, interpretations, analyses, and conclusions were independently developed and validated by the authors. No AI system was used to generate original research data, experimental results, or scientific claims.

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