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Perspective

Transforming research with quantum computing

Sukhpal Singh Gill[a,*,1], Rajkumar Buyya[b,2]

[a] School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK
[b] Cloud Computing and Distributed Systems (CLOUDS) Laboratory, School of Computing and Information Systems, The University of Melbourne, Australia

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ABSTRACT

Quantum computing is a novel method of computation that uses the principles of quantum mechanics to handle highly challenging situations in a very short amount of time. Quantum technology has the ability to significantly impact worldwide advancement, even prior to the complete deployment of quantum machines. Quantum technology for communication, computation, and sensors has the capacity to revolutionise many industries, and several nations are making investments in this promising field. This includes research investments from both the public and commercial sectors. This article delves into the recent quantum computing advancements and the potential opportunities made possible by quantum technology in the next few decades. We outline a vision and scientific innovation for embracing the quantum age, as well as explore the pioneering applications of quantum computing. We also highlight software tools and platforms for quantum programming to unlock the power of computing and revolutionize the world. Finally, we identify the groundbreaking impacts of quantum computing on next-generation research and discuss the benefits of unleashing its revolutionary capabilities.

1. Embracing the quantum era

The fast advancement of computational quantum research has enormous promise for reshaping the computing landscape (Feynman, 2018). Compared to today's computing machines, although comparable on simple calculations, quantum technology is faster, giving it advantages across multiple sectors useful for society (Gill et al., 2022). In the coming decade, it has the potential to transform defence, finance, chemistry, drug discovery, and cryptography, which require massive computing capability (Mikkelsen et al., 2007). Quantum computing can solve certain problems faster than conventional machines, making it valuable for certain businesses (Mikkelsen et al., 2007). For example, Grover's search method implements a progressive rotation from a beginning state to the solution state, resulting in a quadratically quicker unstructured search (Gebhart et al., 2021). Further, qubits in superposition offer ultrahigh-dimensional parallel computation as compared to classic computation with quantum calculation through visualization. Quantum scientists are also developing methods to stop the rise in attacks, such as post quantum cryptography (Chen et al., 2023). Finally, it will make companies' businesses more reliable and scalable. Quantum computing can analyse massive datasets, parallelize complicated problems, and compute faster than conventional computing technologies (Leuenberger and Loss, 2001).

* Correspondence to: School of Electronic Engineering and Computer Science, Queen Mary University of London, London E1 4NS, UK.
E-mail addresses: s.s.gill@qmul.ac.uk (S.S. Gill), rbuyya@unimelb.edu.au (R. Buyya).
[1] 0000–0002-3913–0369
[2] 0000–0001-9754–6496

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When we look at how quantum computing is used in real life, we can see how different fields, like deciphering modern encryption methods and modelling complex systems, are using the special features of quantum technology to solve a wide range of problems (Gilbert et al., 2023). These fields use basic laws from quantum physics, like wave-particle duality, superposition, and the uncertainty principle (Golec et al., 2024). Figure 1 shows an overview of quantum computing.

1.1. Roots and pillars of quantum computing

Traditional systems are essentially faster versions of basic digital devices, which only handle one "bit" of data, a binary 1 or 0. Like an on/off switch, 0 means "off" and 1 means "on". Conventional computers employ millions of bits, each representing a 0 or 1, to do any task. Nevertheless, quantum devices employ "qubits" instead of bits. Qubits can be any floating point number between 0 and 1, inclusive of both, thanks to quantum mechanics (Procopio et al., 2015). They can coexist or be present at any time. At the subatomic scale, quantum technology exploits the unique feature that quantum particles may be in several states at once (called "*superposition*"). Quantum techniques also make use of "*entanglement*", the next basic characteristic. Unlike conventional bits that assign bit values independently, qubits allow the arrangement of bits in an entangled state (Rab et al., 2017). While two entangled qubits, although physically separated, may maintain an associated global state, that is why it is possible to alter the properties of any entangled qubit by probing just one of them. Quantum machines should make complex problems simpler to tackle because of the massive expansion of parameter space, but there are unique difficulties in creating a huge-scale quantum machine (Youssefi et al., 2023). The biggest challenge to address is the "*decoherence*" of the quantum states used to encode qubits. Whenever qubits communicate with the outside world, they might lose their coherent properties, a phenomenon known as "*decoherence*" (Oppenheim et al., 2023). This is why it presents one of the most significant challenges to creating quantum gadgets across a wide spectrum.

1.2. Quantum supremacy: next frontier of technology

Quantum supremacy refers to the milestone when a quantum computer outperforms a classical computer in solving a specific task, showcasing the superior computational power of quantum technology (Dixit and Jian, 2022). It uses entanglement to tackle issues that prior unilateral calculations were unable to solve. Leading organisations worldwide are using quantum computing to substantially reduce human needs such as IBM, Google and others, which will affect encryption, medicinal research, and material science (Arute et al., 2019). Quantum supremacy first happened when a quantum computer outpaced a conventional computer by millions in calculation speed and efficiency (Arute et al., 2019). However, that is insignificant compared to projected technological improvements, such as quantum-scale problem solutions. Quantum computing is on the rise for the following reasons:

- **Solving Complex Problems:** Recent technological advances have caused several challenges in modern computing. While conventional systems were capable of multitasking, they required more time to solve complex problems such as complicated chemical structures, supply chains, financial modelling, and risk evaluation, while quantum computing qubits and quantum Artificial Intelligence (AI) have the potential to solve these issues quickly (Mikkelsen et al., 2007).
- **Business Opportunities:** Cloud-based quantum computing services are lowering the barrier to entry, allowing startups to experiment with quantum algorithms without their own quantum hardware (Gill et al., 2022). This democratisation of technology is a game-changer, enabling a diverse range of startups to explore quantum applications in their respective fields. Quantum research has the potential to greatly improve high-tech industries such as the agricultural sector, telecommunications, and smart transportation.

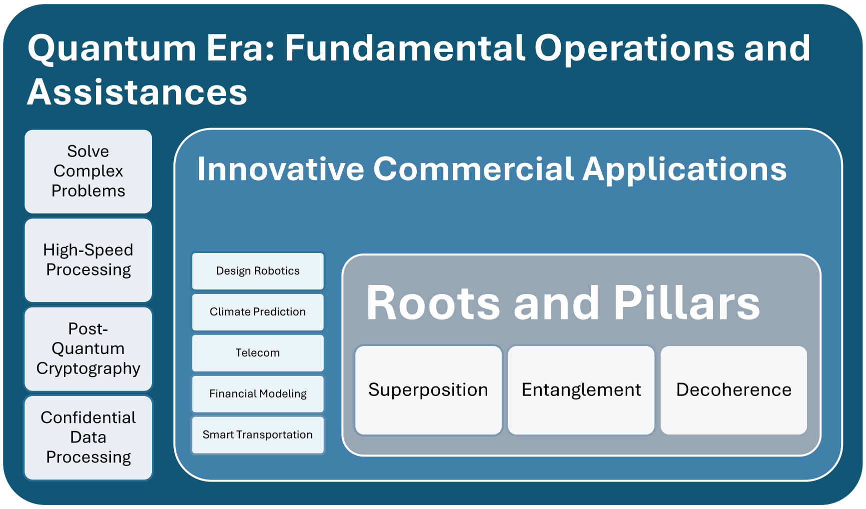

Fig. 1. An Overview of Quantum Computing.

- **Solving Impassable Nonlinear Equations:** Traditional computing are limited in capacity to solve the complex and nonlinear problems (Dixit and Jian, 2022). However, quantum technology allows precise and efficient non-linear operations. It can help understand and make easy challenging problems such as climate modelling, transportation optimisation, and other mission critical challenges.

2. Pioneering the future: applications of quantum computing

Despite the fact that large-scale quantum computers remain in development and smaller quantum processing units are the only ones accessible, academics and businesses are nonetheless investigating several potential uses for quantum technology. Figure 2 shows innovative applications of quantum computing. It affects every aspect of human exploration and has the following key applications:

- **Data Security:** Quantum technologies are significantly more advanced than traditional computers. These machines are particularly popular right now because they can decipher encryption methods (Bernstein and Lange, 2017). There are still chances to develop quantum-resistant cryptography techniques to guarantee safe data transfer in the age of quantum technology, despite the fact that such innovations are already in practice. Quantum technology can provide practically unbreakable encryption, which could drastically improve data security, for example quantum key distribution.
- **Boosting AI:** Quantum computing can boost AI processing capability by using qubit features like superposition and entanglement. Collaboration between quantum computing and AI could enable possible advances in fields such as encryption, finance modelling, materials research, and health by taking on scientifically expensive tasks that conventional machines cannot handle (Biamonte et al., 2017). While research on quantum technology and AI integration is still in its early stages, we anticipate that collaborations

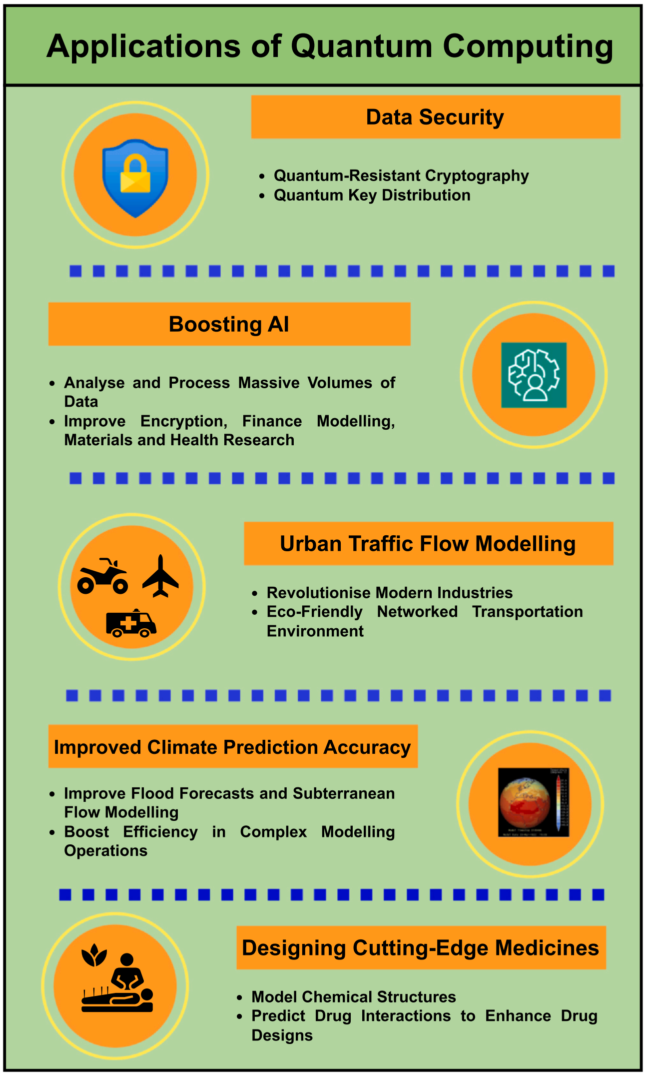

Fig. 2. Pioneering Applications of Quantum Computing.

between quantum computation and connectivity firms will accelerate this development. Quantum technology's better capacity to find data correlations could advance AI (Biamonte et al., 2017). Researchers are hopeful that quantum technology will have an effect on AI by making it possible for machines to analyse and process massive volumes of data at a rate far higher than computers.

- **Urban Traffic Flow Modelling:** Quantum computing and related breakthroughs have the ability to revolutionise several industries, transportation being only one of them. Despite electric car adoption, transporting products is costly and emits large volumes of carbon footprints (Yarkoni, 2020). For instance, the development of more efficient, lightweight, and less ecologically harmful batteries has the opportunity to completely alter an approach to transportation power generation and consumption. Quantum technology could enable an eco-friendly, networked transportation environment (Wehner et al., 2018). To transform things, data must flow seamlessly. Despite traffic modelling complexity, Volkswagen experts are employing and testing quantum preliminary algorithms to manage traffic congestion in China, Spain, and Portugal city centres (Wang et al., 2021).
- **Improved Climate Prediction Accuracy:** Modern advanced predictions need substantial upgrades for societally relevant applications, including flood forecasts, urban modelling, subterranean flow modelling, and similar complex jobs. If commercialised quantum technologies become possible, future global computing devices may be able to function with far greater temporal and geographical resolution (Singh et al., 2022). It is critical to conduct a thorough investigation of numerical climate predictions generated by quantum technology. The use of quantum technology can improve quantitative climate prediction, as traditional computers are unable to produce precise predictions due to their limitations, which can boost efficiency in complex modelling operations. The Met Office of the UK believes quantum machines can enable much more advanced modelling than current methods for futuristic prediction.[3]
- **Designing Cutting-Edge Medicines:** Quantum computers will accelerate drug research, revolutionising it. Scientists are using quantum algorithms to model chemical structures, predict drug interactions, and enhance drug designs (Wang et al., 2023). ProteinQure, a biotech company, is exploring the use of quantum computers for protein modelling in drug development. Quantum technology might lead to improved treatments for cancer and cardiovascular disease, two of the major causes of mortality worldwide. In the future, quantum-assisted drug discovery can fill medical gaps and speed up groundbreaking cures (Blunt, 2022).

3. Technological innovation in a nutshell

New studies on quantum-compatible programs have uncovered many promising areas, such as programming languages, error-correcting firmware, scheduling and optimization at the physical level, scheduling and improvement at the conceptual level, and infrastructure command over software upgrades (Gill, 2024). Both academia and companies are highly motivated to develop early quantum computers because of their potential to surpass the processing capabilities of current powerful machines for specific functions (Serrano et al., 2022). Multiple well-established businesses, including Chinese companies including QUDOOR and ZTE, in addition to multinational corporations including IBM, Microsoft, Google, and Intel, are currently making major investments to develop large-scale quantum computer technology (Heim et al., 2020). Additionally, smaller firms like D-Wave and striving startups, such as Rigetti and IonQ, are actively involved in this endeavor (Nguyen et al., 2024). In parallel to the growth of quantum devices, quantum programming and algorithms have seen tremendous improvement over the past few years.

3.1. Software tools and platforms for quantum programming

Quantum programming tools play a crucial role by simplifying the creation and implementation of quantum algorithms, thus enabling researchers and developers to harness the power of quantum computing for solving complex problems more efficiently (Serrano et al., 2022). Figure 3 shows popular software tools and platforms for quantum programming. ETH Zurich's Silq[4] builds quantum programmes in Python – developed in June 2020, whereas Google's Cirq[5] builds, updates, and calls Noisy Intermediate Scale Quantum (NISQ) circuits for quantum machines and simulations – developed in July 2018 (Chen et al., 2023). IBM's Python-based quantum Software Development Kit (SDK) called Qiskit (Quantum Information Science Kit)[6] was developed in March 2017, lets developer build quantum circuits and develop quantum programs that can be executed quantum computers (Heim et al., 2020). Microsoft developed Q Sharp (Q#)[7] in December 2017, offering several standard libraries with pre-defined quantum functions and powerful debugging and simulation tools. In November 2018, Rigetti Computing created PyQuil[8] to develop and run Python code for quantum algorithms. PyQuil is rapidly creating Quil programmes using quantum gates and conventional operations. In December 2021, Quantinuum developed TKET to create and execute gate-based quantum computer programs. Additionally, Quantinuum designed TKET[9] to solve problems in chemical, material science, finance, and optimisation. Recently, the CLOUDS Lab at the University of Melbourne has developed a novel iQuantum Simulator toolkit for quantum cloud computing by supporting the deployment of applications on multiple quantum computing resources offered by different vendors as cloud services (Nguyen et al., 2024).

[3] https://www.metoffice.gov.uk/about-us/who-we-are/innovation/supercomputer
[4] https://silq.ethz.ch/
[5] https://quantumai.google/cirq
[6] https://www.ibm.com/quantum/qiskit
[7] https://github.com/microsoft/qsharp
[8] https://pyquil-docs.rigetti.com/
[9] https://www.quantinuum.com/developers/tket

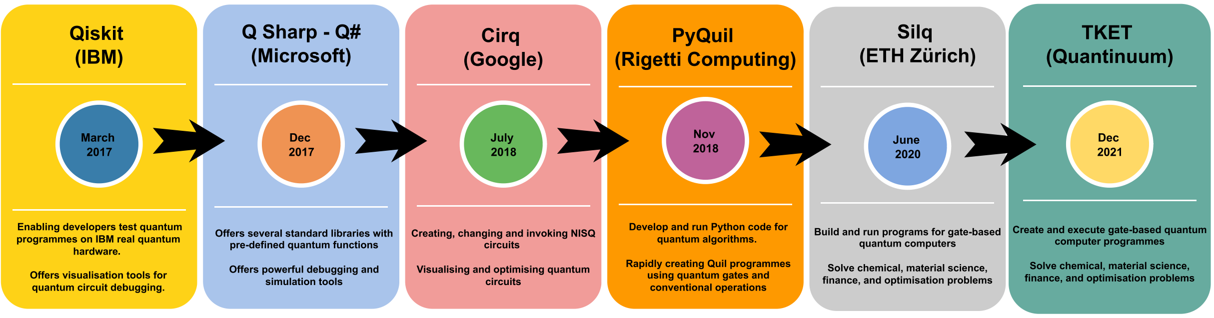

Fig. 3. Software Tools and Platforms for Quantum Programming.

3.2. Open challenges of quantum software engineering

Cloud computing-based companies such as IBM, Microsoft Azure Quantum, and Amazon Braket provide hardware and software platforms for accessing quantum computing resources via networks without purchasing hardware. This will assist quantum computing researchers in developing, executing, and testing quantum algorithms using a variety of quantum processors and simulation tools (Murillo et al., 2024). But there are a few challenges with it, including platform independence (which can lead to vendor lock-in among device manufacturers and programmers), complexity of circuits (which can encapsulate intriguing methods and complicated functioning), and compatibility (since these programmes are available in Python or assembly-level languages) (Khan et al., 2023). In addition, quantum circuit design is typically a fairly difficult undertaking, so it is essential that its components be as reusable as possible. Further developers may develop specific types, creating additional abstractions on which to construct their code, all with the purpose of offering quantum programmers an additional abstraction level (Dwivedi et al., 2024).

4. Unlock the future: the transformative capabilities of quantum computing

Our findings from this work shed light on several open research questions in the field of quantum computing. Additionally, we have identified several unresolved challenges and potential avenues for future research, all of which are currently under investigation globally. Figure 4 shows the transformative effects of quantum computing on next generation research.

1. **Quantum Simulations:** Quantum computing can simulate complex molecular structures, making it promising for molecule or chemical simulation and drug discovery (Daley et al., 2022). The structure of a molecule helps scientists understand how it bonds with other atoms, which is essential for pharmaceutical development (Heim et al., 2020). Because atomic interactions are so complex, current machines cannot simulate them accurately. Scientists think quantum computers can mimic every complex human tissue molecule in enough time to expedite drug and treatment research.
2. **Commercialization:** As quantum computing advances, large companies and entrepreneurs will commercialise quantum systems and associated goods (Hughes et al., 2022). With cloud-based quantum computing platforms, businesses can experiment with quantum computation methods and applications without purchasing expensive new equipment (MacQuarrie et al., 2020). Business owners should consider partnerships with quantum computing vendors to benefit from this revolutionary technology.
3. **Quantum-Inspired Optimization:** Companies increasingly utilise quantum-inspired optimisation techniques to solve complex optimisation problems (Wehner et al., 2018). Quantum technology is used to address combinatorial optimisation problems, including route, financial trading systems, and resource allocation. Quantum mechanics-influenced optimisation can save companies money, boost efficiency, and improve operations.
4. **Robotics:** Quantum computing has the potential to greatly speed up calculations; robotics in sectors such as medicine, transportation, cryptography, and finance use Graphics Processing Units (GPUs) to handle compute-intensive issues (Mannone et al., 2023). Quantum-powered robotics could also tap into quantum technology hosted in the cloud to solve a wide range of problems. Quantum technology might save manufacturing costs by improving multi-robot welding, assembling, and painting. Using quantum technology in research and development, manufacturing, logistics, production, transportation will benefit the car industry.
5. **Quantum AI (QAI):** Quantum Machine Learning (QML) and enhanced algorithms have the potential to change AI in a variety of industries, including automotive and medicine (Biamonte et al., 2017). In particular, quantum technology might accelerate autonomous car adoption. Many mobility startups, like Ford, GM, and Volkswagen, use neural networks to handle visual and video data. AI-trained autonomous vehicles will make important driving decisions (Biamonte et al., 2017). Quantum machines, which can do complicated computations with several variables, may train AI systems faster. However, other initiatives devoted to QAI have recently surfaced, such as NASA's Quantum Artificial Intelligence Laboratory (QuAIL), the JD AI research centre, and Baidu's open-source machine learning framework, Paddle Quantum (Singh et al., 2022). Nonetheless, when it comes to actual use, combining AI with quantum technology remains in its infancy. Significant challenges include developing algorithms for QML, preparing quantum datasets for application in industrial-scale QAI, and employing quantum neural networks.

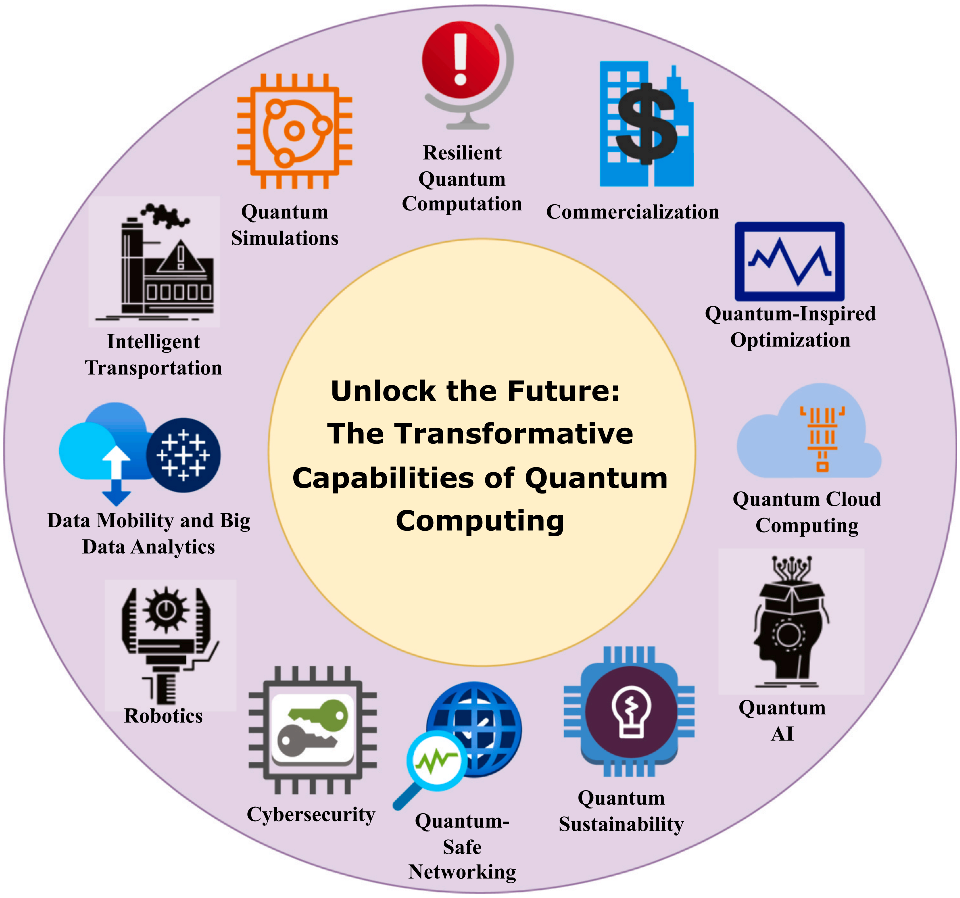

Fig. 4. Transformative Effects of Quantum Computing on Next Generation Research.

6. **Quantum Sustainability:** The use of AI in quantum technology can improve computation speed, reliability, and secrecy. But there's a catch: running them and keeping them at a comfortable temperature requires an enormous amount of electricity (Reed et al., 2012). Green energies combined with brown power can meet the energy requirements of these quantum machines in the future. Further, as quantum computers increase in capability, cooling equipment becomes also more expensive and burdensome, both financially and sustainably. Powering a quantum computer with millions of qubits is too challenging and costly right now as a limitation of NISQ quantum era.
7. **Quantum-Safe Networking:** The safety of current encryption methods is at risk due to the rise of powerful quantum computing. Companies will safeguard their conversations and private data with quantum-resistant cryptography (Pirandola and Braunstein, 2016). Quantum-safe cryptographic approaches, such as quantum key distribution and lattice-based encryption, would secure digital assets and data privacy post-quantum (Illiano et al., 2022).
8. **Cybersecurity:** Organisations will use quantum-enhanced cybersecurity to defend their digital assets and infrastructure. These include quantum-resistant encryption and key distribution (Bernstein and Lange, 2017). Quantum computing-enhanced cybersecurity can help companies prepare for emerging threats in today's digital environment. A quantum machine may resolve mathematical inquiries in microseconds; hence, a post-quantum encryption system protects traditional data encryption (MacQuarrie et al., 2020). The purpose of post-quantum digital technology was to safeguard the foundations and techniques of symmetrical cryptography against quantum attacks. Current commercial quantum machines cannot replace traditional supercomputers due to the difficulty in scaling up the amount of qubits achieved at this point.
9. **Data Mobility and Big Data Analytics:** Quantum technology could enable an eco-friendly, networked transportation environment. To transform things, data must flow seamlessly from auto-computers to external computers (Grandi et al., 2024). Quantum machines can handle enormous amounts of data faster than classical computers, making data sharing possible. Using quantum technology, massive datasets may be quickly and easily managed, and data can be fed into AI systems for finer-grained pattern and anomaly detection.
10. **Intelligent Transportation:** To overcome obstacles and create future innovative transportation generations, it is crucial to embrace the quantum technology breakthrough. Modern transportation planning is under constant strain to solve massive problems, including how to achieve net zero (Singh and Gill, 2023), enhance passenger experiences, and incorporate novel travel options (Yang et al., 2023). In these areas, quantum technology has great potential. For instance, quantum sensors and optical

Table 1
Summary of Next Generation Trends and Open Challenges.

No.	Next Generation Research Areas	Open Challenges	Further Reading
1	Quantum Simulations	How can quantum computers be made fast enough to simulate every complex human tissue molecule for medical and pharmaceutical research?	Nature (Daley et al., 2022) and Nature Reviews Physics (Heim et al., 2020)
2	Commercialization	How will enterprises experiment with quantum computation methodologies and applications using cloud-based quantum computing platforms without buying expensive new equipment?	IEEE Transactions on Education (ToE) (Hughes et al., 2022) and Nature Reviews Physics (MacQuarrie et al., 2020)
3	Quantum-Inspired Optimization	How can quantum technology solve combinatorial optimisation challenges like routing, financial trading, and resource allocation?	Science (Wehner et al., 2018)
4	Robotics	How to reduce production costs using multi-robot welding, assembly, and painting?	Elsevier Swarm and Evolutionary Computation (Mannone et al., 2023)
5	Quantum AI	How to develop QML algorithms, prepare quantum datasets for industrial-scale QAI applications, and employ quantum neural networks?	Nature (Biamonte et al., 2017)
6	Quantum Sustainability	How to develop an energy-efficient quantum computer with millions of qubits?	Nature (Reed et al., 2012)
7	Quantum-Safe Networking	How will quantum-resistant cryptography protect company communications and data?	Nature (Pirandola and Braunstein, 2016)
8	Cybersecurity	How can current commercial quantum devices replace supercomputers by scaling up qubits?	Nature (Bernstein and Lange, 2017) and Nature Reviews Physics (MacQuarrie et al., 2020)
9	Data Mobility and Big Data Analytics	How might quantum technology facilitate the efficient management of large datasets?	EPJ Web of Conferences (Grandi et al., 2024)
10	Intelligent Transportation	How can we use quantum computing to enhance the efficiency of transport networks and reduce delays?	IEEE IEEE Transactions on Intelligent Transportation Systems (TITS) (Yang et al., 2023) and IEEE TITS (Cooper, 2021)
11	Quantum Cloud Computing	How can cloud computing make available quantum computing's on-demand processing power?	Elsevier Journal of Economy and Technology (Golec et al., 2024)
12	Resilient Quantum Computation	How might quantum machines improve their operational errors and background noise?	Nature communications (Procopio et al., 2015) and Springer (Akhai and Kumar, 2024)

imaging could enhance our travel efficiency and ease, while quantum mechanics-enhanced navigation tools could potentially decrease traffic delays (Cooper, 2021). Quantum technology is currently being tested in areas such as improving transport effectiveness, reducing congestion, and enhancing traffic flow on highways and railroads.

11. **Quantum Cloud Computing:** Quantum technologies as a cloud service allow organisations to use on-demand processing power without investing in equipment and networks (Golec et al., 2024). Placing the quantum machine on a cloud-based system enables it to provide services to users through an application programming interface (API), and distributing its computation capacity across nodes such as the edge and fog reduces delay and network congestion. Cloud servers provide the quantum computer's network design, storage, and operational settings, as well as communicating the computation outputs to the network's farthest point. By enhancing effectiveness and resilience, quantum computing, in conjunction with cloud and edge computing, plays a significant role in the corporate sector. Industries' cloud-based quantum computing environments, application development tools, and maintenance services will allow businesses to experiment with quantum concepts and programs. Business owners could use quantum cloud technologies to boost innovation.
12. **Resilient Quantum Computation:** Quantum technology is capable of factoring numbers and completing specific scientific scenarios far more quickly than the famous traditional computer programmes, according to recent studies (Akhai and Kumar, 2024). Because quantum superpositions with different levels of flexibility are naturally fragile, operational errors and background noise seem to be much bigger problems that need to be solved for quantum processing to work well than for traditional computing (Procopio et al., 2015).

Table 1 presents the summary of next generation trends and open challenges along with further reading.

5. Revolutionise the world: moving target for quantum advantage

While acknowledging the ongoing debate surrounding quantum research, further exploration of both the arguments advocating for and against its support can provide a more comprehensive understanding of its potential benefits and challenges. To evaluate design progress, engineers set basic short-term goals for projects of any size. The supremacy-class processors will benefit enterprises, universities, and other institutions engaged in algorithm research and NISQ processor applications. Creative academics are the most significant asset for quantum computing improvements; thus, we expect more scientists to enter the sector to design helpful concepts now that corporations have access to a new computing resource.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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