India's Quantum Ecosystem: 2025 Landscape, Opportunities, and the Road Ahead

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***Abstract*—Quantum computing represents a transformative leap in computational capabilities, with significant implications for cryptography, optimization, and scientific discovery. As global investment in quantum technologies intensifies, India has emerged as a key player through strategic initiatives such as the National Quantum Mission (NQM), which allocated Rs.6,000 crore in 2023 to advance indigenous capabilities. This paper presents a comprehensive review of India's quantum ecosystem as of 2025, spanning research institutions, industry involvement, government policy, and educational infrastructure. We trace the evolution from early quantum key distribution (QKD) experiments to current efforts in developing superconducting qubit processors and national QKD networks. Contributions from academic institutes (IISc, IITs), defense agencies (DRDO, ISRO), and private players (QNu Labs, TCS) are analyzed. Key challenges such as cryogenic infrastructure gaps, fabrication dependencies, and quantum talent outflow are discussed, alongside emerging opportunities in hybrid quantum-classical algorithm development and indigenous quantum hardware prototyping.**

***Index Terms*—Quantum Computing; India; National Quantum Mission; Quantum Technologies; Startups; Research Landscape; Policy; Education; QKD.**

I. Introduction

Quantum computing represents a paradigm shift in information processing, leveraging principles of quantum mechanics such as superposition, entanglement, and interference to solve problems that are intractable on classical computers. While the theoretical underpinnings of quantum computing trace back to the works of Feynman and Deutsch in the 1980s [1], [2], its practical development has accelerated in the past two decades, largely due to breakthroughs in quantum error correction, quantum algorithms, and the construction of early-stage quantum processors.

Globally, countries such as the United States, China, Canada, and members of the European Union have made significant strategic investments into quantum technologies. The United States, for instance, passed the National Quantum Initiative Act in 2018 [8], while China has reportedly invested over $10 billion in a national quantum research center [4]. These efforts reflect an international consensus that quantum computing is not merely a research challenge but a frontier with implications for national security, cryptography, materials science, pharmaceuticals, and artificial intelligence.

India, recognizing the transformative potential of quantum technologies, has actively positioned itself in the global quantum race. In the Union Budget 2020, the Government of India announced the *National Mission on Quantum Technologies and Applications (NMQTA)* with an initial outlay of INR 8000 crore (approximately USD 1 billion) over five years [5]. This allocation aims to advance indigenous capabilities in quantum computing, quantum communication, quantum sensing, and quantum materials. As of 2025, India's ecosystem includes multiple research institutions, startups, and governmental bodies working collaboratively to establish a national quantum stack.

Despite these investments, a consolidated overview of the Indian quantum computing landscape remains limited in academic literature. Prior studies have primarily focused on specific technical contributions or institutional initiatives without a systematic synthesis of national progress, challenges, and emerging opportunities [29].

In this paper, we present a structured review of India's quantum computing ecosystem as of 2025, categorizing major stakeholders, institutional efforts, research milestones, and industrial participation. The paper further highlights existing bottlenecks and provides an outlook for India's trajectory in quantum science and technology.

II. Timeline of Major Quantum Milestones in India

India's involvement in quantum technology has gained substantial momentum since 2018, transitioning from exploratory academic research to structured national initiatives and public–private collaborations. The timeline below highlights key policy interventions, institutional developments, and technological milestones from 2018 to 2025

A. 2018 – Initial Demonstrations and Proof-of-Concepts

India's first nationally significant quantum communication milestone was demonstrated by the Defence Research and Development Organisation (DRDO) in 2018, which achieved

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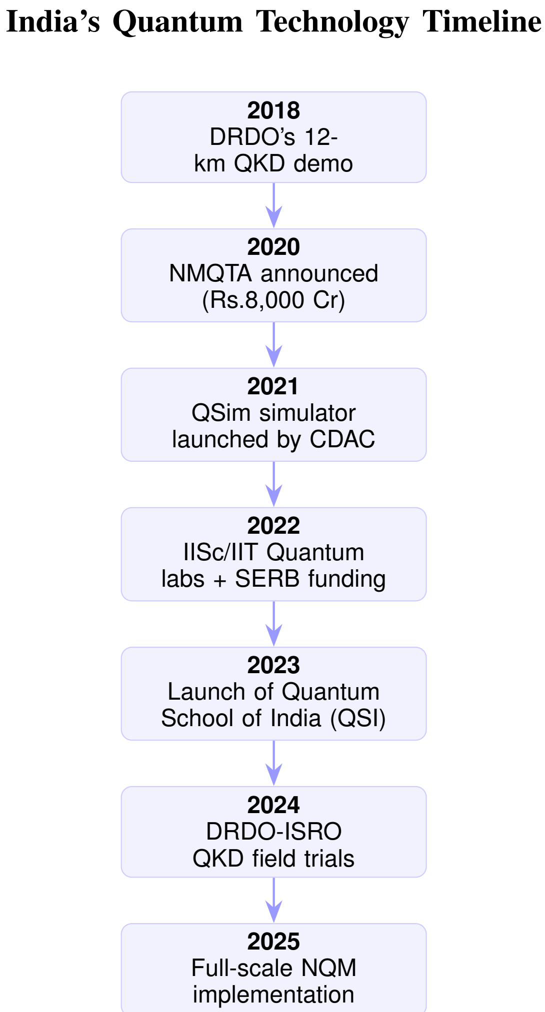

Fig. 1. Vertical timeline of India's quantum technology milestones (2018–2025)

Quantum Key Distribution (QKD) over a 12-km free-space optical channel. This marked India's entry into secure quantum communication R&D and laid the foundation for future satellite-based QKD development [3].

B. 2020 – Formal Announcement of National Mission

In the Union Budget 2020–21, the Government of India announced the National Mission on Quantum Technologies and Applications (NMQTA) with a financial outlay of Rs.8000 crore ($1 billion USD) over five years [6]. This mission aimed to develop quantum computing, secure communication, sensing, and quantum materials with a multi-stakeholder structure led by the Department of Science and Technology (DST).

Concurrently, CDAC (Centre for Development of Advanced Computing) began quantum software training workshops and initiated faculty development programs in collaboration with IBM India [7].

C. 2021 – Institutional Scaling and Early Software Ecosystem

The year 2021 saw the beginning of institutional consolidation in the quantum domain. Initiatives such as the DST-QuEST (Quantum Enabled Science and Technology) program were operationalized, funding over 20 research proposals on quantum cryptography, simulation, and materials science [9]. CDAC also deployed the Quantum Computer Simulator (QSim) platform in collaboration with IISc and IIT-Roorkee [10].

D. 2022 – Lab Infrastructure and Academic Expansion

New laboratories focused on quantum computing hardware were launched at IISc Bengaluru, IIT Madras, and IISER Pune, focusing on superconducting qubit systems and cryogenic control [11]. These efforts were supported by DST's QuEST program and aligned with the global trend toward indigenous quantum processor development.

India also saw its first national-scale call for proposals in Quantum Materials and Quantum Sensing domains through the SERB-IMPRINT initiative [12].

E. 2023 – Quantum Education and Grassroots Programs

The Quantum School of India (QSI) was launched as the first nationwide quantum literacy platform, with support from academic institutions and industry partners such as IBM and AWS Braket. Quantum computing courses were introduced on NPTEL by IIT Madras and IIT Kharagpur, significantly expanding access to formal quantum education [20].

Moreover, undergraduate-focused programs such as the TCS Quantum Challenge and the IBM-AICTE Quantum Internship Pilot were introduced to promote experiential learning and cross-disciplinary skill-building [23].

F. 2024 – Field Trials and Strategic Security Deployments

In 2024, DRDO conducted pilot tests of a satellite-based QKD platform in partnership with ISRO, aimed at demonstrating long-distance secure communication. A prototype quantum-secure terrestrial link between two government nodes was also tested in Delhi-NCR, representing India's first secure operational deployment of quantum communication infrastructure [27].

Additionally, India commenced participation in bilateral talks with Japan's Q-NET and the EU's Quantum Flagship to explore cross-border quantum interoperability and IP frameworks [31].

G. 2025 (Ongoing) – Implementation of National Quantum Mission

By 2025, the National Quantum Mission (NQM) entered full-scale implementation with four key technology verticals:

1) Quantum Computing & Communication
2) Quantum Sensing and Metrology
3) Quantum Materials and Devices

Over 50 academic institutions and industry partners have been inducted into working groups across these verticals. A multi-tiered roadmap for indigenous hardware development, algorithm optimization, and quantum-safe cryptography export is currently under review by the Quantum Advisory Board [35].

III. Ecosystem Mapping

The Indian quantum technology ecosystem comprises a multi-tier structure involving key government bodies, premier academic institutions, emerging startups, and corporate entities. This section classifies the stakeholders contributing to the national quantum technology landscape.

A. Government Agencies

Central government agencies play a foundational role in policy, funding, and national infrastructure:

- **MeitY**: Drives projects in quantum cryptography and quantum communication under national e-governance frameworks [7].
- **DST**: Leads the National Mission on Quantum Technologies and Applications (NMQTA) [5]. Thematic Hubs (T-Hubs) have been established across IITs and IISc for specialization in computing, communication, sensing, and materials [30].
- **DRDO**: Active in secure QKD trials and quantum processor development in collaboration with academic partners [3], [27], [28].
- **ISRO**: Involved in satellite-based quantum communication initiatives in conjunction with DRDO [27].

B. Academic Institutions

Academic institutions form the research and talent backbone, facilitating hardware, simulation, and algorithm development.

- **IISc Bengaluru**: Hosts the national hub for quantum computing and has ongoing work in superconducting qubits and control electronics [11].
- **IIT Madras**: Leads the hub on quantum communication and engages in photonic quantum systems research [29].
- **IIT Bombay, IIT Delhi**: Handle quantum sensing/metrology and quantum materials/devices respectively under the DST-NQM program [30].
- **C-DAC**: Developed the QSim toolkit, an open-source platform for simulating quantum circuits [10].
- **Raman Research Institute (RRI)**: Home to the QuIC Lab, focused on photonic quantum technologies, entanglement, and heralded photon sources [33].
- **TIFR**: Currently leading the development of India's first full-stack quantum computer in partnership with DRDO [34].

C. Startups

Several startups are operationalizing quantum technologies with domain-specific innovations:

- **QpiAI**: Specializes in hybrid quantum-classical modeling and AI-assisted quantum workflows.
- **QNu Labs**: India's first QKD commercial vendor, delivering quantum cybersecurity products such as quantum random number generators [29].
- **BosonQ Psi**: Focuses on quantum-enhanced engineering simulations for aerospace and automotive sectors.

D. Corporate and Industry Engagement

Private enterprises are increasingly participating via in-house research groups, university collaborations, and workforce training:

- **TCS**: Hosts quantum innovation challenges and collaborates with academic institutions for talent development [23].
- **Infosys**: Building consulting and implementation capabilities in quantum strategy.
- **IBM India**: Provides quantum hardware access via the IBM Quantum Network, supporting Indian universities and developers [29].

E. Optional: Quantum Stack in India

An architectural view of the "Quantum Stack in India" may be visualized by layering stakeholder involvement across the following strata:

- *Quantum Devices and Materials*: DRDO, IISc, IIT Delhi, TIFR
- *Control Electronics and Middleware*: IISc, RRI
- *Quantum Compilers and Algorithms*: IIT Madras, CDAC
- *Simulators and Emulators*: CDAC, QpiAI, IISER Pune
- *Applications and Integration*: Infosys, BosonQ Psi, TCS
- *Education and Training*: Quantum School of India, IISERs, IITs

IV. Hardware Research in India

The evolution of quantum computing in India is increasingly underpinned by the emergence of indigenous hardware research and development. From superconducting qubit prototypes to quantum communication networks and cryogenic control systems, Indian institutions are gradually building a self-reliant and technically capable quantum ecosystem.

One of the most significant breakthroughs has been in the domain of superconducting qubits. In 2024, the Defence Research and Development Organisation (DRDO), in collaboration with the Tata Institute of Fundamental Research (TIFR), announced the successful end-to-end testing of a 6-qubit superconducting quantum processor [28]. This system, built and tested indigenously, demonstrated not only qubit initialization and gate operations but also fidelity characterization under cryogenic conditions. The development marks a critical inflection point in India's capacity to build scalable quantum processors, situating the country among a handful of nations with demonstrated hardware capabilities.

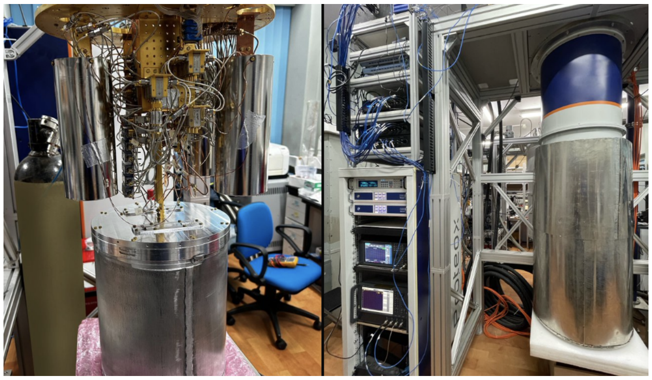

Fig. 2. India's first 6-qubit superconducting quantum processor developed by DRDO in collaboration with TIFR (2024). Image source: The Quantum Insider [41]. Reproduced under academic fair use.

Parallelly, India has accelerated progress in quantum communication networks, particularly through Quantum Key Distribution (QKD) technologies. The DRDO showcased an initial fiber-based QKD demonstration over 12 kilometers as early as 2018 [3], which laid the groundwork for further trials. By 2024, DRDO and the Indian Space Research Organisation (ISRO) conducted field tests of QKD integration with satellite communication protocols, thereby establishing the feasibility of space-based quantum-secure links [27]. These efforts reflect a national ambition to embed quantum cryptography in military-grade communication and strategic infrastructure.

Cryogenic infrastructure, essential for operating low-temperature quantum processors, is being simultaneously developed across premier research institutions. The Indian Institute of Science (IISc), IISER Pune, and the National Physical Laboratory (NPL) have initiated specialized laboratories for quantum device testing under milliKelvin regimes [11], [33]. These facilities include dilution refrigerators, cryo-electronics, and low-noise microwave signal generators required for superconducting qubit manipulation. Notably, IISER Pune has collaborated with international vendors and academic groups to tailor cryogenic platforms optimized for India's developing quantum processors.

Furthermore, the Raman Research Institute (RRI) has been spearheading experimental validation of cryo-compatible control systems and has also initiated work on hybrid architectures integrating photonic and superconducting elements [33]. This multi-institutional push is now being consolidated under the four Thematic Hubs recently launched by the Department of Science and Technology (DST) as part of the National Quantum Mission [30], [35].

Together, these hardware initiatives mark a strategic shift from quantum simulation platforms to full-stack quantum device fabrication and deployment. As the Indian quantum ecosystem matures, hardware self-sufficiency will be instrumental in both national security and scientific leadership.

V. Software and Algorithms

India's quantum computing ecosystem has experienced a parallel thrust in software stack development, emphasizing quantum algorithms, simulation platforms, and optimization frameworks. These efforts are vital not only for accelerating theoretical and applied research but also for ensuring readiness as quantum hardware gradually becomes accessible and scalable.

A notable contributor to this momentum has been the promotion of open-source frameworks such as Qiskit. IBM's Qiskit India Hub, launched in partnership with IIT Madras, has enabled collaborative access to IBM's quantum hardware and fostered the development of domain-specific quantum algorithms [18]. This hub has also supported national workshops, student fellowships, and quantum coding hackathons aimed at building a skilled quantum software workforce across Indian institutions.

The Bengaluru-based startup QpiAI has emerged as a significant domestic player in the quantum software and AI-integrated quantum optimization space. Its flagship platform, QpiAI-Pro, allows the design and simulation of quantum-classical hybrid algorithms tailored for industries such as logistics, finance, and aerospace [19]. The company has also announced QpiAI-Quantum, a gate-based simulation engine that supports variational circuits, quantum neural networks (QNNs), and error mitigation tools, with integration capabilities across both cloud and on-premise hardware. These platforms align with India's growing interest in near-term intermediate-scale quantum (NISQ) applications.

In terms of algorithmic research, Indian institutions are exploring key subfields such as quantum neural networks (QNNs), variational quantum eigensolvers (VQE), and quantum simulations of physical systems. VQE, in particular, has gained attention due to its applicability in quantum chemistry and condensed matter physics. Collaborative work between IISc and IISER Pune has yielded optimization frameworks that tailor VQE performance on noisy simulators using reinforcement learning-inspired parameter initializations [39]. Simultaneously, researchers at IIT Bombay and C-DAC have been investigating QNN architectures optimized for quantum-enhanced image classification and time-series forecasting [7].

India's local strengths in quantum software are amplified by the presence of a highly active open-source community, centralized policy funding (e.g., QuEST by DST), and the integration of quantum courses in top-tier institutes such as IISc, IIT Madras, and IISER Bhopal. These academic pipelines have been instrumental in developing indigenous algorithm libraries, educational simulators (like QSim), and hybrid cloud platforms accessible via national supercomputing infrastructure [9], [10].

Overall, India's software-oriented contributions offer a competitive edge in quantum algorithm development, particularly in domains where computational complexity is high, and quantum-classical hybridization is feasible. The consolidation of these efforts through the National Quantum Mission is expected to yield scalable frameworks capable of leveraging both indigenous and global quantum hardware resources.

VI. Education Initiatives

A well-orchestrated educational framework is foundational to the development of a long-term quantum technology ecosystem. Recognizing this, the National Quantum Mission (NQM) has allocated a significant fraction of its multi-year budget specifically toward quantum education and skill development. This includes funding for curriculum creation, lab infrastructure, fellowship programs, and faculty training across premier technical institutions in India [35].

Indian Institutes of Technology (IITs) have taken a leading role in integrating quantum computing into formal academic curricula. Notably, IIT Madras and IIT Kharagpur offer full-length undergraduate and postgraduate quantum computing courses through the National Programme on Technology Enhanced Learning (NPTEL) platform. These MOOCs have attracted a diverse range of participants from academia, industry, and government sectors, contributing to an emerging quantum-literate workforce [36].

Complementing this, the Quantum School of India (QSI), established in 2023, has become the country's first dedicated institution focused exclusively on quantum education and translational research. QSI offers multidisciplinary quantum programs spanning computing, communication, and quantum-enhanced AI. Its national network connects faculty from IISc, IIT-BHU, and IISER Mohali, enabling distributed instruction and collaborative projects [20].

Public-private collaborations have further enhanced quantum learning access. Several institutions have integrated IBM's Qiskit and AWS Braket as part of their courseware. IBM India, in collaboration with select IITs and IIIT Hyderabad, conducts regular training programs, including quantum hackathons, internships, and Qiskit summer schools [37]. Similarly, AWS India provides cloud access to quantum processors and instructional modules on variational algorithms and quantum annealing through AWS Educate and Braket for Academia initiatives [38].

These diverse education pathways—ranging from MOOCs and formal degrees to industry-driven certifications—are instrumental in building a talent pipeline to meet the growing demands of quantum research and industry. Table I summarizes key Indian institutions offering dedicated quantum programs as of 2025.

VII. Indian Startups Overview

The quantum computing landscape in India has seen a significant surge in entrepreneurial ventures. Several startups are pushing the boundaries of quantum technology, each focusing on different aspects of quantum computing, from quantum hardware to cryptography and machine learning. In this section, we provide an in-depth overview of three notable Indian startups: QpiAI, BosonQ, and QNu Labs. Each of these startups demonstrates innovative approaches to quantum technology and has shown promising progress in terms of funding, maturity level, and real-world applications.

A. *QpiAI*

QpiAI is a prominent startup that focuses on leveraging quantum computing for advancements in quantum optimization and machine learning (ML). The company specializes in *QOSMOS*, a platform that merges quantum algorithms with machine learning techniques to solve real-world optimization problems. QpiAI aims to revolutionize industries like logistics, finance, and artificial intelligence by offering quantum-enhanced solutions. Their expertise lies in the intersection of quantum hardware and machine learning, with a strong emphasis on algorithmic development to tackle complex problems more efficiently than classical counterparts.

QpiAI has received notable funding from both venture capitalists and government bodies, enabling the company to accelerate its research and development. Despite being a relatively young company, it has reached a stage where it has developed prototype algorithms, and its solutions are being tested in various sectors. The startup has collaborated with key academic institutions and corporate partners, contributing to the scaling of quantum-enhanced machine learning tools.

QpiAI's contributions are documented in [19], which outlines the development of its Quantum Hybrid Software Stack.

Use-case: Quantum optimization for supply chain management, ML-driven analytics for financial modeling, and AI model training acceleration.

Funding: QpiAI has secured an undisclosed amount in seed funding, with additional support from research grants.

Maturity Level: Prototype development stage, with a focus on algorithm testing and collaborations with industry leaders.

Fig. 3. Internal configuration of QpiAI's cryogenic quantum system (2024). Image source: QpiAI.tech [42]. Reproduced under academic fair use for educational purposes.

TABLE I
MAJOR INDIAN INSTITUTIONS OFFERING QUANTUM PROGRAMS

Institution	**Program Type**	**Platform / Affiliation**
IIT Madras	UG/PG NPTEL Courses	Qiskit, AWS Braket
IIT Kharagpur	Online Quantum Computing Course	NPTEL
Quantum School of India (QSI)	BSc/MSc/PhD Programs	National Quantum Mission
IISER Mohali	Elective Modules	In-house and IBM Q
IIIT Hyderabad	Electives and Research Projects	IBM Qiskit
IIT-BHU	MSc Quantum Tech. Modules	QpiAI, AWS

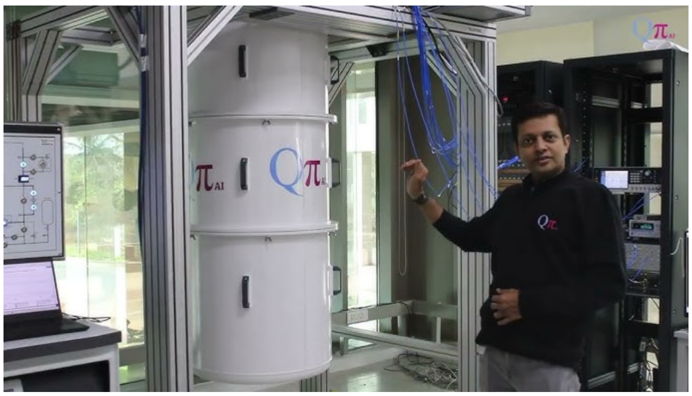

Fig. 4. Assembled view of QpiAI's cryogenic quantum system. Still captured from official YouTube demonstration [43]. Used under academic fair use.

B. BosonQ

BosonQ, founded with the aim of advancing quantum computing for complex simulations, is pioneering the application of quantum-driven computational fluid dynamics (CFD). This startup is focusing on developing quantum algorithms to enhance simulations for industries such as aerospace, automotive, and energy. The company seeks to harness the power of quantum computing to solve fluid dynamics problems that are computationally expensive for classical computers, offering a potential breakthrough in the design of more efficient systems.

The company's approach involves quantum-enhanced algorithms for simulating turbulent flow, heat transfer, and fluid-structure interaction. By employing quantum techniques, BosonQ intends to significantly reduce the time and computational cost of simulations, leading to faster innovation cycles in industries reliant on fluid dynamics.

Use-case: Quantum-enhanced CFD simulations for optimizing fluid flow in aerospace, automotive, and energy sectors.

Funding: BosonQ has attracted funding from both private investors and governmental grants, with a focus on expanding its algorithmic research and industry applications.

Maturity Level: Early-stage, with initial proofs of concept in CFD simulations, and ongoing partnerships with academic and industry researchers.

C. QNu Labs

QNu Labs stands at the forefront of quantum cryptography research in India. Specializing in Quantum Key Distribution (QKD) and encryption technologies, QNu Labs aims to build a secure communication infrastructure for the digital age. The company is developing quantum-safe encryption systems that use QKD to enable ultra-secure communication networks, resistant to the threats posed by future quantum computers. In particular, QNu Labs focuses on deploying quantum key distribution solutions for governmental, financial, and corporate applications.

QNu Labs has successfully developed hardware and software solutions that can be integrated into existing communication networks, providing a seamless transition to quantum-secure communications. Their work on quantum cryptography has been pivotal in securing sensitive data transmissions, and the company continues to innovate in this critical area, with a long-term vision of contributing to global standards in quantum-safe cryptography.

QNu Labs' encryption systems are discussed in various industry reports, including [27], which highlights their contributions to quantum-safe communications.

Use-case: Secure communication networks using QKD for defense, banking, and government sectors.

Funding: QNu Labs has raised significant funding through a combination of private investment and strategic partnerships with international technology firms and government agencies.

Maturity Level: Established, with several commercial deployments and ongoing R&D for advanced cryptographic solutions.

VIII. CORPORATE INVOLVEMENT

The role of corporate entities in advancing quantum computing in India has been pivotal, with major companies like Infosys, IBM, TCS, and Wipro leading efforts in both research and development. These corporations have formed strategic partnerships, established dedicated research teams, and set up laboratories to push the boundaries of quantum technologies. This section outlines the key corporate initiatives and their involvement in the quantum computing ecosystem.

A. *Infosys + IBM Partnership*

In a significant development for quantum computing in India, Infosys has entered into a strategic partnership with IBM to drive innovation in quantum technologies. This collaboration focuses on combining Infosys' expertise in IT consulting and systems integration with IBM's cutting-edge quantum computing platform, IBM Quantum. The partnership aims to leverage quantum algorithms to address real-world business problems, such as supply chain optimization, financial modeling, and machine learning applications.

As part of the collaboration, Infosys provides access to quantum computing resources, enabling Indian businesses to develop quantum applications through the IBM Quantum Experience, a cloud-based quantum computing platform. This partnership exemplifies the growing trend of private sector involvement in quantum research, ensuring that quantum technologies are brought closer to practical business applications.

The impact of the partnership has been discussed in several reports and articles, such as those published by [37].

Use-case: Quantum-enhanced financial modeling, supply chain optimization, and AI-driven business solutions.

Funding: The partnership between Infosys and IBM is supported by significant investment from both companies, as well as strategic backing from Indian government initiatives aimed at promoting quantum research and technology.

Maturity Level: Ongoing collaboration with a focus on developing quantum-enhanced solutions for various business sectors.

B. *TCS QIS Team*

Tata Consultancy Services (TCS) has established a dedicated Quantum Information Science (QIS) team that plays a crucial role in India's quantum computing landscape. This team focuses on developing quantum software solutions and algorithms, contributing to global quantum research while also preparing India for the next generation of computing technologies. TCS' QIS team works on building algorithms for quantum optimization, machine learning, and cryptography, with a vision to develop applications for both industry and academia.

In addition to software development, TCS has been active in fostering collaborations with international research institutions and universities, promoting the growth of quantum technologies. Their quantum research team also works on creating tools to bridge the gap between classical and quantum computing, making it easier for businesses to adopt quantum solutions when they become commercially viable.

The corporate involvement of TCS is highlighted in [23], which discusses the company's continued efforts in quantum research and application development.

Use-case: Quantum software development for optimization, machine learning, and cryptographic applications.

Funding: TCS's quantum research initiatives are funded through both internal R&D budgets and strategic investments from the Indian government in quantum technology research.

Maturity Level: Active development stage, with a focus on research and creating quantum software solutions for various industries.

C. *Wipro's Quantum Lab*

Wipro has also made significant strides in the quantum computing sector through the establishment of its quantum lab. This initiative is focused on building and advancing quantum algorithms and hardware. The lab is involved in the development of quantum software tools for industries such as healthcare, manufacturing, and finance, with the goal of enabling businesses to leverage quantum computing for complex data analysis, drug discovery, and predictive modeling.

Wipro's quantum lab aims to collaborate with academic institutions, global quantum networks, and government research bodies to foster innovation in quantum technologies. Through its quantum computing efforts, Wipro hopes to enhance its digital transformation services, offering quantum-powered solutions to its clients. This involvement in quantum research reflects the company's commitment to integrating advanced technologies into its business solutions, ensuring that it remains at the forefront of the IT services industry.

The role of Wipro in quantum technology is discussed in the corporate reports and academic literature, including those cited in [25].

Use-case: Quantum-powered solutions for healthcare data analysis, manufacturing simulations, and financial forecasting.

Funding: Wipro's quantum lab is funded through the company's R&D arm, alongside public sector grants and partnerships with academic institutions.

Maturity Level: Research and development phase, with growing collaborations with global quantum players and industry stakeholders.

IX. Current Challenges

The development of quantum computing in India faces several hurdles that must be overcome to establish a competitive and sustainable ecosystem. These challenges span across the hardware supply chain, infrastructure development, talent acquisition, and the impact of global competition. A detailed exploration of these issues is crucial for understanding the path ahead.

A. *Hardware Supply Chain*

One of the primary obstacles for quantum computing in India is the lack of a robust and indigenous hardware supply chain. Quantum processors, which rely on delicate and sophisticated components, such as superconducting qubits, require advanced fabrication techniques and specialized materials that are not readily available in India. This dependency on foreign supply chains limits the scalability and independence of the quantum technology ecosystem in the country [13], [40]. Strengthening this supply chain by fostering local semiconductor industries, collaborating with global players, and establishing state-of-the-art fabrication facilities could be vital for the country's long-term success in quantum research and development.

B. Cryogenics Infrastructure Gap

The Indian quantum research community also faces a significant gap in the cryogenics infrastructure required for experiments involving superconducting qubits and other quantum devices. Cryogenic systems, which are essential for cooling qubits to extremely low temperatures, are a critical component of quantum computing hardware. While some institutions in India, such as the Indian Institute of Science Education and Research (IISER), have undertaken efforts to develop cryogenic systems [14], the infrastructure remains limited compared to global standards. A coordinated effort to build scalable and cost-effective cryogenic facilities could accelerate quantum research in the country and enhance India's position in the global quantum race.

C. Talent Drain

India's quantum computing ecosystem is also grappling with a significant talent drain, where highly skilled researchers and engineers are migrating to more developed markets with better funding, infrastructure, and research opportunities. This trend undermines the growth of domestic quantum research and development, which heavily relies on a skilled workforce. Addressing this issue requires not only the creation of attractive research and development environments within India but also the establishment of collaborative international partnerships that allow for knowledge exchange and joint research opportunities [16].

D. Global Competition and Intellectual Property (IP) Issues

As quantum computing emerges as a strategically significant technology, global competition has intensified, particularly from countries with well-established quantum research initiatives, such as the United States, China, and the European Union. India faces challenges in maintaining a competitive edge, both in terms of technological development and intellectual property (IP) protection. International collaborations and ensuring robust IP laws are essential to safeguard the innovations developed within the country and maintain a competitive global standing [32].

X. Opportunities and Roadmap

Despite these challenges, India is poised to capitalize on several emerging opportunities in the quantum computing sector. By addressing the barriers and focusing on specific areas of growth, India can establish itself as a key player in the global quantum ecosystem.

A. Role in the Global Supply Chain

India can play a pivotal role in the global quantum supply chain by focusing on the manufacturing of components and subsystems critical for quantum computing systems. As the demand for quantum computing hardware rises, there is an increasing need for high-quality, cost-effective components such as qubits, cryogenic systems, and quantum networking equipment. By leveraging its strong IT infrastructure, manufacturing capabilities, and large pool of skilled engineers, India can become a key supplier of these critical components, thus contributing to the global quantum ecosystem [15].

B. Quantum-Safe Security Export

The development of quantum-safe cryptography is another area where India can seize significant opportunities. Quantum computing poses a direct threat to current cryptographic protocols, but it also presents an opportunity to develop advanced quantum-safe encryption techniques. Given the rising global concerns around cybersecurity, India can take a leadership role in developing and exporting quantum-safe security solutions. By capitalizing on the expertise of local research institutes and startups in the field of quantum cryptography, India can address both domestic and international security concerns, creating a niche market for quantum-safe technologies [17].

C. Quantum Pharmaceutical and Simulation for Local Use Cases

One of the most promising areas for quantum computing applications in India is in pharmaceuticals and healthcare. The ability of quantum computers to simulate complex molecular structures and drug interactions offers immense potential for advancing medical research. India, with its strong pharmaceutical sector, could harness quantum computing for drug discovery, personalized medicine, and biotechnology applications. By focusing on local healthcare challenges, quantum simulations could be tailored to address issues such as affordable drug development, precision medicine, and diagnostic tools [21].

D. Predictions for 2030

Looking ahead to 2030, it is predicted that India will have made significant strides in quantum computing research, both in hardware and software. With the establishment of robust quantum infrastructure, India is likely to be home to a flourishing quantum industry, comprising quantum startups, academic institutions, and government initiatives. These developments will likely position India as a global leader in specific applications such as quantum communication, quantum cryptography, and simulation. The government's support through policies, funding, and the establishment of national-level quantum centers is expected to fuel innovation and attract global partnerships. Furthermore, India's strong IT and software industry will provide a foundation for integrating quantum computing into real-world applications, thus accelerating the adoption of quantum technologies in various sectors [22], [24].

XI. Discussion

This review has presented a comprehensive analysis of the historical evolution, current ecosystem, and emerging opportunities in quantum computing in India. The paper examined developments across both hardware and software fronts, highlighting key government initiatives, institutional contributions, startup activity, and potential areas for strategic growth. Special emphasis was placed on indigenous hardware research, software tool development, and the unique challenges facing India's quantum roadmap.

To support the writing and synthesis process, large language models (LLMs), specifically OpenAI's ChatGPT, were utilized during the manuscript drafting phase. These tools assisted the author in refining technical language, rephrasing complex concepts, and improving the organization of thematic content. In adherence to general academic standards for transparency, it is declared that the final version of the manuscript was critically reviewed, independently fact-checked, and fully authored by the undersigned. All conclusions, interpretations, and perspectives expressed in this review are the result of the author's own academic evaluation of publicly accessible literature and data.

Given the rapid pace of advancements in the field of quantum technology, particularly within the Indian context, it is acknowledged that new developments may have occurred following the completion of this manuscript. The author has made every effort to ensure that the information is accurate and up to date as of early 2025. Any inadvertent errors or omissions are unintentional, and readers are welcome to contact the author directly for clarifications or updates.

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Conflicts of Interest:The authors declare no conflicts of interest.

XII. Conclusions

India's quantum computing journey has progressed remarkably since the first QKD demonstrations in 2018, culminating in the establishment of a structured national quantum ecosystem by 2025. The National Quantum Mission (NQM) has provided crucial momentum, enabling indigenous hardware development, algorithm research, and workforce training across premier institutions. However, as this study reveals, challenges persist in cryogenic infrastructure, supply chain dependencies, and global competition for quantum talent.

Three key observations emerge from our analysis:

- India has demonstrated capability in quantum communication (QKD) and intermediate-scale quantum algorithms, but lags in fault-tolerant quantum processor development compared to global leaders.
- The startup ecosystem shows promising specialization in quantum cybersecurity (QNu Labs) and hybrid quantum-classical applications (QpiAI), though scaling remains constrained by limited venture capital.
- Educational initiatives like the Quantum School of India and NPTEL courses are addressing skill gaps, but require deeper integration with industry needs.

The work of Prof. L. Venkataramanan and colleagues [26] provides valuable theoretical foundations for India's quantum algorithm development, particularly in error correction techniques essential for scalable quantum computing. Their contributions underscore the importance of fundamental research alongside applied developments.

To consolidate India's quantum advantage, we recommend:

1) Establishing a national quantum foundry to address hardware supply chain vulnerabilities
2) Creating bilateral research partnerships under the NQM framework
3) Developing quantum curriculum standards aligned with industry requirements

As the global quantum landscape evolves rapidly, India's ability to translate its strong theoretical foundations into technological leadership will depend on sustained policy support and strategic international collaborations. The next five years will be critical for transitioning from quantum research to deployable quantum solutions.

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