

A Review of Quantum Computing Progress in India's Emerging Technology Ecosystem

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Abstract: *Quantum computing is rapidly transforming the global technological landscape by enabling computational capabilities far beyond classical systems. In recent years, India has taken decisive steps to establish itself as a key contributor to this emerging field through strategic policy initiatives, academic excellence, and growing industry participation. The launch of the National Quantum Mission (NQM) marks a significant milestone in India's efforts to develop indigenous quantum computing hardware, secure quantum communication, quantum sensing, and advanced materials research. This paper examines the evolution of quantum computing innovations within India's technology ecosystem by analyzing recent literature, government initiatives, and notable institutional and industrial developments. The study identifies key achievements, challenges, and opportunities, offering insights into India's preparedness for global competition in quantum technologies. The findings suggest that while India has made commendable progress in ecosystem building, sustained investment, infrastructure development, and talent cultivation are essential for long-term success.*

Keywords: *Quantum Computing, National Quantum Mission, India, Innovation Ecosystem, Quantum Technology, Emerging Technologies.*

I. INTRODUCTION

Quantum computing leverages principles of quantum mechanics—such as superposition, entanglement, and quantum interference—to perform computations that are infeasible for classical computers. Applications of quantum computing span cryptography, optimization, drug discovery, climate modeling, and materials science, making it a strategic technology for economic and national security.

Globally, countries such as the United States, China, and members of the European Union have invested heavily in quantum research and development. Recognizing the strategic importance of this technology, India has also initiated focused efforts to strengthen its quantum capabilities. The approval of the National Quantum Mission (2023–2031) demonstrates India's intent to transition from foundational research to applied innovation and commercialization.

This paper aims to explore the current state of quantum computing innovations in India, analyze recent developments, and assess the effectiveness of policy-driven ecosystem building. It also highlights challenges faced by stakeholders and proposes recommendations for strengthening India's quantum technology landscape.

1.1 Research Objectives

To examine recent developments in quantum computing innovations within India's technology ecosystem.

To analyze the role of government policy, academia, and industry in shaping India's quantum landscape.

To identify key challenges hindering large-scale adoption and commercialization of quantum technologies in India.

To propose strategic recommendations for strengthening India's quantum innovation ecosystem.

1.2 Research Questions

How has India's quantum computing ecosystem evolved in the past three years?

What role does the National Quantum Mission play in accelerating innovation?

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What gaps exist between research output and practical implementation?
How can India enhance its global competitiveness in quantum technologies?

1.3 Research Contribution

This paper makes the following original contributions to the existing body of knowledge:

It provides a comprehensive ecosystem-level analysis of quantum computing in India by integrating policy, academic, and industry perspectives.

It synthesizes recent developments (2022–2025) under the National Quantum Mission, offering one of the most up-to-date reviews of India’s quantum landscape.

It identifies structural and commercialization bottlenecks that are underexplored in prior studies.

It proposes actionable, policy-relevant recommendations aimed at strengthening India’s global competitiveness in quantum technologies.

II. METHODOLOGY

This study adopts a systematic qualitative review methodology, suitable for analyzing emerging technologies where empirical datasets are still limited. The research follows a three-stage process:

1. Source Identification:

Peer-reviewed journals, government policy documents, institutional reports, and reputable industry white papers published between 2022 and 2025 were identified using academic databases and official portals.

2. Inclusion Criteria:

- Relevance to quantum computing or quantum technologies.
- Explicit focus on India or comparative global context.
- Publication within the last three years.
- Credible academic or institutional authorship.

3. Thematic Analysis:

Selected literature was analyzed using thematic coding to identify recurring patterns related to policy frameworks, academic research, industrial participation, infrastructure development, and challenges.

2.1 Conceptual Framework of India’s Quantum Innovation Ecosystem

This study conceptualizes India’s quantum computing ecosystem as an interaction among four core pillars:

- **Policy and Governance** (National Quantum Mission, funding mechanisms)
- **Academic and Research Institutions** (IISc, IITs, national laboratories)
- **Industry and Startups** (quantum software, hardware, and applications)
- **Enabling Infrastructure and Talent** (fabrication facilities, workforce development)

These pillars interact dynamically to influence innovation outcomes, commercialization readiness, and global competitiveness. Weakness in any pillar—particularly infrastructure or skilled manpower—can constrain overall ecosystem performance, highlighting the need for balanced development.

III. LITERATURE REVIEW

Recent literature over the past two to three years reflects a growing scholarly and policy-driven interest in India’s quantum ecosystem. Studies on quantum policy frameworks emphasize that the National Quantum Mission provides a structured roadmap for advancing quantum research across computing, communication, sensing, and materials science [1][2]. Scholars note that the mission’s hub-and-spoke model—anchored at premier institutions such as IISc Bengaluru and IITs—encourages interdisciplinary and inter-institutional collaboration.

Research focusing on indigenous quantum hardware development highlights India’s progress in building early-stage quantum processors. Notable contributions include superconducting and photonic quantum systems developed through



collaborations between startups and research institutions [3]. These efforts signify a shift from theoretical research to experimental and applied quantum engineering.

Literature on quantum communication and cryptography documents successful demonstrations of quantum key distribution (QKD) and entanglement-based secure communication, indicating India's potential in cybersecurity and defense-related applications [4].

However, several studies also identify persistent challenges, such as limited access to fabrication facilities, dependence on imported components, shortage of trained quantum engineers, and delays in funding disbursement [5][6]. Overall, recent literature portrays India's quantum ecosystem as promising but still in a formative stage.

3.1 Identified Research Gap

While existing studies document individual aspects of India's quantum initiatives—such as policy frameworks or experimental demonstrations—there is a lack of integrated ecosystem-level analysis that simultaneously examines policy, academia, and industry interactions. Moreover, limited attention has been given to implementation bottlenecks and commercialization readiness. This paper addresses these gaps by providing a holistic and updated ecosystem perspective.

IV. FINDINGS AND DISCUSSION

4.1 Policy-Driven Ecosystem Development

The National Quantum Mission has emerged as the cornerstone of India's quantum strategy. By allocating substantial funding and defining clear objectives, the mission has strengthened coordination among government agencies, academic institutions, and industry partners. The establishment of thematic hubs has enhanced research focus and reduced duplication of efforts.

4.2 Academic and Research Contributions

India's premier institutions have played a critical role in advancing quantum algorithms, hardware prototypes, and quantum communication experiments. Increased publication output and participation in international collaborations reflect growing academic maturity in this domain.

4.3 Industry and Startup Engagement

Indian startups and technology firms are increasingly contributing to quantum software platforms, hybrid quantum-classical algorithms, and early-stage hardware systems. These developments signal the emergence of a nascent quantum industry, although large-scale commercialization remains limited.

4.4 Key Challenges

Despite progress, significant challenges persist. Limited fabrication infrastructure, high costs of cryogenic and control systems, and scarcity of skilled manpower constrain rapid advancement. Additionally, translating research outputs into market-ready solutions remains a major hurdle.

Despite notable progress, India's quantum ecosystem is currently characterized by research intensity exceeding commercialization readiness, reflecting a transitional phase common to emerging quantum economies. Unlike mature ecosystems in the US and EU, where venture capital and defense-linked procurement accelerate commercialization, India's ecosystem is still transitioning from laboratory-scale innovation to deployable solutions. Bridging this gap requires coordinated policy execution, private investment incentives, and long-term industry engagement.

V. OBSERVATIONS / RESULTS

The analysis reveals the following key observations:

India has successfully established a national-level framework for quantum technology development.



Research output and experimental demonstrations have increased noticeably since 2022. Industry participation is growing but remains concentrated in early-stage innovation. Infrastructure and human resource constraints continue to slow ecosystem maturation. These results indicate that India is transitioning from an exploratory phase to a structured development phase in quantum computing.

| Dimension | Key Developments | Current Status |
|------------------------|---|---------------------|
| Policy Framework | National Quantum Mission, thematic hubs | Strong, centralized |
| Academic Research | Algorithms, QKD, hardware prototypes | Rapidly growing |
| Industry Participation | Startups, hybrid algorithms | Early-stage |
| Infrastructure | Fabrication, cryogenics | Limited |
| Human Capital | Training, education programs | Insufficient |
| Commercialization | Market-ready solutions | Nascent |

Table 1: Synthesis of India's Quantum Computing Ecosystem

VI. FUTURE RESEARCH DIRECTIONS

Future studies can focus on:

- Quantitative assessment of India's quantum research output using bibliometric analysis.
- Comparative evaluation of India's quantum ecosystem with China, the US, and the EU.
- Sector-specific quantum applications in finance, healthcare, and defense.
- Workforce readiness and quantum education models in developing economies.

Such research will support evidence-based policymaking and ecosystem maturity.

VII. CONCLUSION AND RECOMMENDATIONS

Quantum computing represents a critical frontier in India's technological future. The country has made meaningful strides through policy initiatives, academic excellence, and emerging industry participation. However, sustained progress will depend on addressing existing gaps in infrastructure, talent, and commercialization pathways.

7.1 Recommendations

Strengthen funding mechanisms with faster disbursement and long-term continuity.

Expand quantum education programs at undergraduate and postgraduate levels.

Encourage stronger industry-academia partnerships for technology transfer.

Invest in domestic fabrication and testing facilities to reduce external dependence.

Promote international collaborations for knowledge exchange and standardization.

With strategic execution and continued investment, India has the potential to become a global hub for quantum innovation.

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