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QUANTUM ENTREPRENEURSHIP: EXPLORING THE IMPACT OF QUANTUM COMPUTING ON GLOBAL STARTUP ECOSYSTEMS

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Abstract: *Quantum computing has rapidly emerged as one of the most consequential technological frontiers of the current decade, with its potential to fundamentally transform competitive dynamics across global innovation ecosystems increasingly acknowledged in both scientific and policy communities. Despite this growing recognition, the intersection of quantum computing and entrepreneurship—herein conceptualized as quantum entrepreneurship—remains substantially undertheorized and empirically underexplored. This study investigates the impact of quantum computing advancements on the formation, growth, and competitive positioning of startups within global entrepreneurial ecosystems. Drawing on the Resource-Based View (RBV), Dynamic Capabilities Theory, and Schumpeterian innovation theory as integrative theoretical anchors, this research develops a comprehensive conceptual framework that links quantum computing readiness, ecosystem support infrastructure, venture capital quantum orientation, human capital development, and government policy enablement to startup performance outcomes. Employing a quantitative cross-sectional research design, primary data were collected from 387 startup founders, chief technology officers, and ecosystem managers across 18 countries through a structured and pre-validated survey instrument. Structural Equation Modeling with Partial Least Squares (SEM-PLS) was applied to test seven directional hypotheses. Results indicate that quantum computing readiness (beta = 0.41, p < .001), ecosystem infrastructure quality (beta = 0.33, p < .001), and quantum-oriented venture capital access (beta = 0.29, p < .01) are significant positive predictors of startup performance. Human capital development and government policy enablement demonstrate significant indirect effects through mediating innovation capability mechanisms. These findings contribute the first large-scale empirical foundation for the emerging field of quantum entrepreneurship, generating actionable insights for founders, investors, and policymakers. The study also identifies critical research gaps and proposes a future-oriented research agenda for this nascent but strategically pivotal field.*

Keywords: *Quantum Computing, Startup Ecosystems, Entrepreneurship, Dynamic Capabilities, Technology Ventures*

Introduction

The global startup ecosystem has undergone unprecedented transformations driven by successive waves of technological disruption. Today, a new and arguably more profound technological paradigm is emerging: quantum computing. Distinguished from classical computing by its exploitation of quantum mechanical phenomena including superposition, entanglement, and quantum interference quantum computing offers computational capabilities that are exponentially superior to classical architectures for specific problem classes (Cao et al., 2023; Gill et al., 2022; Ezratty, 2023). The implications for entrepreneurship, business strategy, and economic value creation are profound yet remain insufficiently examined in the scholarly literature.

Quantum computing is projected to generate between $450 billion and $850 billion in global economic value within the next decade, with significant impact anticipated across pharmaceuticals, financial services, logistics, materials science, and cybersecurity (Bova et al., 2021; Gambetta et al., 2023; McKinsey Global Institute, 2021). The entry of startups into the quantum space has accelerated sharply, with more than 200 quantum-focused ventures receiving funding between 2021 and 2023 alone, collectively attracting over $2.35 billion in venture investment (PitchBook, 2023; Boston Consulting Group, 2023). Concurrently, incumbent technology firms including IBM, Google, IonQ, and Quantinuum have dramatically intensified quantum investments, creating a complex competitive landscape that simultaneously challenges and enables startup innovation (Alexeev et al., 2021; Bravyi et al., 2022).

Despite the practical salience of this phenomenon, academic research examining how quantum computing affects entrepreneurial behavior, startup formation, and venture performance remains fragmented and largely conceptual (Bova et al., 2021; Humble, 2021; Egger et al., 2023). Existing entrepreneurship literature provides rich theoretical frameworks including the Resource-Based View (Barney & Mackey, 2022), Dynamic Capabilities Theory (Teece, 2022), and Schumpeterian creative destruction (Akcigit & Ates, 2021) yet these frameworks have not been systematically applied to the quantum computing context. Moreover, empirical studies examining the relationship between quantum computing readiness and measurable startup performance outcomes are virtually absent from the literature.

This study addresses these gaps by introducing and operationalizing the concept of quantum entrepreneurship, defined as entrepreneurial activity that originates from, is enabled by, or strategically responds to advances in quantum computing technologies. The study pursues three primary objectives: (1) to develop a theoretically grounded framework linking quantum computing variables to startup performance; (2) to empirically test a set of directional hypotheses using a large cross-national sample; and (3) to generate actionable insights for entrepreneurs, investors, and policymakers operating at the quantum classical interface.The paper is structured as follows. Section 2 reviews the relevant literature and develops the study's hypotheses. Section 3 describes the research methodology. Section 4 presents the empirical results. Section 5 discusses the findings in relation to prior research, and Section 6 concludes with limitations and future research directions.

Literature Review

Theoretical Foundations

Resource-Based View (RBV)

The Resource Based View posits that sustainable competitive advantage derives from resources and capabilities that are valuable, rare, inimitable, and non-substitutable (Barney & Mackey, 2022; Warnier et al., 2023). In the context of quantum entrepreneurship, quantum computing infrastructure, proprietary quantum algorithms, and quantum-trained human capital constitute emergent strategic resources that confer distinctive competitive positions on early mover startups (Ferraro & Pfeffer, 2021; Egger et al., 2023). As quantum hardware becomes increasingly accessible through cloud-based platforms including IBM Quantum Network, Amazon Braket, and Microsoft Azure Quantum the competitive locus shifts from hardware ownership toward algorithmic innovation and application-domain expertise (Gambetta et al., 2023; Stilck Franca & Garcia Patron, 2021).

The RBV has been extensively applied to technology entrepreneurship, revealing that technology intensive firms that accumulate specialized knowledge assets and absorptive capacity tend to outperform competitors in turbulent environments (Nambisan et al., 2021; Singh et al., 2021). Applied to the quantum domain, this theoretical logic suggests that startups capable of developing and deploying quantum ready capabilities will achieve superior performance outcomes relative to classical only competitors. Recent extensions of RBV into digital and deep technology contexts have further emphasized the importance of dynamic resource reconfiguration as a source of sustained advantage (Ciampi et al., 2021; Mikalef & Gupta, 2021).

2.1.2 Dynamic Capabilities Theory

Teece (2022) extended and refined the Dynamic Capabilities framework, arguing that competitive advantage in rapidly changing environments depends on the organizational capacity to sense, seize, and reconfigure resources in response to environmental change. This framework is particularly relevant to the quantum computing context, where technological trajectories are evolving at an accelerated pace and the competitive landscape is characterized by high uncertainty, knowledge complexity, and regulatory ambiguity (Teece, 2022; Autio et al., 2022).
Quantum startups must simultaneously sense emerging opportunities created by advances in qubit stability, error correction, and quantum networking; seize those opportunities through rapid product development and ecosystem partnership formation; and reconfigure existing resources including human capital, technology stacks, and investor relationships to align with quantum-native business models (Nambisan et al., 2021; Denicolai et al., 2021). Empirical studies of deep technology entrepreneurship confirm that firms with higher dynamic capability endowments achieve superior innovation outputs and market performance, particularly in environments characterized by rapid technological change (Ciampi et al., 2021; Singh et al., 2021).

2.1.3 Schumpeterian Innovation Theory

Schumpeter's concept of creative destruction provides a macro level lens through which to understand the disruptive potential of quantum computing for existing industrial structures. Quantum computing represents a paradigmatic illustration of this dynamic: its emergence threatens to render entire classes of classical cryptographic systems obsolete while simultaneously creating vast new opportunities in drug discovery, optimization, and secure communications (Mosca, 2021; Bernstein & Lange, 2021).

Recent extensions of Schumpeterian theory into the digital economy context including contributions by Akcigit & Ates (2021) and Aghion et al. (2021) have emphasized the role of knowledge spillovers, intellectual property regimes, and market concentration in shaping entrepreneurial entry and exit dynamics. These insights apply with particular force to the quantum startup ecosystem, where intellectual property strategy, open-source community participation, and government research partnerships collectively shape competitive dynamics (Krelina, 2021; Ezratty, 2023).

Quantum Computing and the Global Startup Ecosystem

The quantum computing startup landscape has expanded dramatically in the period 2021-2026, with the number of active quantum ventures growing from approximately 200 in 2021 to over 450 by 2025 (PitchBook, 2023; Boston Consulting Group, 2023). Upstream in the value chain, quantum hardware startups are competing to achieve fault-tolerant quantum computation, the milestone widely regarded as the threshold for commercially viable quantum advantage (Bravyi et al., 2022; Ezratty, 2023). Downstream, quantum software and application startups are developing solutions targeting optimization, simulation, machine learning, and cryptographic security.

Entrepreneurial ecosystem studies have increasingly emphasized the systemic nature of startup performance, highlighting the role of anchor institutions, talent pipelines, regulatory frameworks, and investor networks in determining venture outcomes (Stam & van de Ven, 2021; Spigel & Harrison, 2021). The quantum startup ecosystem exhibits distinctive characteristics: it is geographically concentrated in major clusters across the United States, United Kingdom, China, Germany, Canada, and Australia; more heavily dependent on government co investment than most prior technology waves; and more deeply embedded in academic research networks (European Commission, 2021; OECD, 2023; World Economic Forum, 2022).

Studies of deep technology entrepreneurship provide relevant precedent for understanding the unique challenges quantum startups face, including long development timelines, high capital requirements, significant commercialization uncertainty, and acute talent scarcity (Lassance et al., 2022; Nitu et al., 2021). Government programs such as the U.S. National Quantum Initiative, the EU Quantum Flagship, the UK National Quantum Strategy, and national programs in China, Japan, and Australia have created differentiated policy environments that materially affect quantum venture formation and growth (OECD, 2023; European Commission, 2021).

Hypotheses Development

Quantum Computing Readiness and Startup Performance

Quantum computing readiness refers to the extent to which a startup has developed the technical competencies, organizational processes, and strategic orientations necessary to leverage quantum computing for value creation. Drawing on the RBV (Barney & Mackey, 2022) and building on empirical evidence from digital transformation research (Vial, 2021; Li et al., 2021), we conceptualize quantum readiness as encompassing quantum algorithmic expertise, quantum hardware access, quantum software development capability, and strategic quantum awareness.

Prior research consistently demonstrates that higher levels of technological preparedness are associated with superior innovation outputs, market responsiveness, and financial performance (Ciampi et al., 2021; Mikalef & Gupta, 2021). Extending this logic to the quantum context:

> **H1:** *Quantum computing readiness is positively associated with startup performance.*

Ecosystem Infrastructure Quality and Startup Performance

Entrepreneurial ecosystem theory holds that the quality of surrounding infrastructure comprising mentorship networks, research institutions, talent pipelines, and financial markets materially influences startup outcomes (Stam & van de Ven, 2021; Spigel & Harrison, 2021). For quantum startups, ecosystem infrastructure quality is particularly critical given the extraordinary capital intensity and knowledge complexity involved. Access to quantum capable laboratory facilities, proximity to research universities, and participation in national quantum consortia have been identified as significant enablers of quantum venture formation and growth (European Commission, 2021; OECD, 2023).

Recent empirical evidence from Audretsch et al. (2022) and Theodoraki et al. (2022) demonstrates that ecosystem infrastructure quality moderates the relationship between individual firm capabilities and performance outcomes, particularly for early-stage ventures in high-uncertainty technological domains. Accordingly:

> **H2:** *Entrepreneurial ecosystem infrastructure quality is positively associated with startup performance.*

Venture Capital Quantum Orientation and Startup Performance

Venture capital quantum orientation defined as the degree to which a venture capital firm possesses quantum domain expertise, maintains a quantum investment thesis, and provides quantum specific value added services represents a critical dimension of investor quality. In the quantum domain, development timelines to commercial deployment may span five to fifteen years, amplifying the importance of patient, knowledgeable capital (Boston Consulting Group, 2023; OECD, 2023).

Research by Colombo et al. (2021) and Tomy & Pardede (2022) has established that investor domain expertise and value added capabilities significantly predict portfolio company outcomes. In the quantum context, investors with technical credibility and regulatory network access can substantially accelerate commercialization timelines. We therefore hypothesize:

> **H3:** *Quantum-oriented venture capital access is positively associated with startup performance.*

Human Capital Development and Startup Performance

Human capital development in quantum relevant disciplines constitutes a foundational resource for quantum entrepreneurship. The global quantum workforce shortage is documented across multiple assessments, with estimates suggesting a deficit of tens of thousands of quantum-trained professionals by 2025 (Bova et al., 2021; Humble, 2021; OECD, 2023). Startups with superior access to, and systematic internal development of, quantum human capital are expected to achieve stronger performance outcomes.

This prediction is consistent with human capital theory and extensive entrepreneurship research documenting the relationship between founding team technical expertise and venture performance (Salamzadeh & Dana, 2021; Nitu et al., 2021). We hypothesize:

> **H4:** *Human capital development in quantum competencies is positively associated with startup performance.*

Government Policy Enablement and Startup Performance

Government policy plays a constitutive role in shaping the quantum startup landscape through direct research funding, procurement commitments, regulatory frameworks, talent development programs, and international cooperation agreements (Krelina, 2021; European Commission, 2021). Major national quantum initiatives including the U.S. National Quantum Initiative Act, the EU Quantum Flagship Programme, the UK National Quantum Strategy, and China's national quantum investment program have collectively created differentiated policy environments that materially affect startup resources and opportunities (OECD, 2023; World Economic Forum, 2022).

Audretsch et al. (2022) and Theodoraki et al. (2022) have demonstrated the positive effects of science and technology policy and public R&D investment on new venture formation and performance in deep technology domains. We extend this logic:

> **H5:** *Government policy enablement for quantum computing is positively associated with startup performance.*

2.3.6 Mediating Role of Innovation Capability

Innovation capability the organizational capacity to develop novel products, processes, and business models is widely conceptualized as a critical mediator between resource endowments and performance outcomes (Denicolai et al., 2021; Nambisan et al., 2021). In the quantum entrepreneurship context, quantum computing readiness is expected to operate partly through its effect on innovation capability, which generates performance advantages through superior product differentiation, speed to market, and intellectual property creation (Ciampi et al., 2021; Mikalef & Gupta, 2021).

> **H6:** *Innovation capability mediates the relationship between quantum computing readiness and startup performance.*

2.3.7 Moderating Role of Technological Uncertainty

Technological uncertainty the degree of ambiguity surrounding the performance trajectory and commercial feasibility of an emerging technology constitutes a critical boundary condition for the hypothesized relationships. In the quantum domain, substantial uncertainty persists regarding timelines for fault tolerant quantum computation, scalability of qubit modalities, and commercial viability of near term NISQ era applications (Ezratty, 2023; Gill et al., 2022; Cao et al., 2023). Drawing on contingency theory and uncertainty performance research (Le & Nguyen, 2022), we predict:

> **H7:** *Technological uncertainty moderates the relationship between quantum computing readiness and startup performance, such that the positive relationship is stronger under conditions of lower technological uncertainty.*

Method

Research Design

This study employs a quantitative, cross-sectional survey research design. The rationale for this approach is threefold. First, the study seeks to test theoretically derived directional hypotheses across a large and geographically diverse sample, necessitating a structured data collection instrument capable of standardized measurement. Second, the cross national scope spanning 18 countries requires a methodology that facilitates comparability across heterogeneous institutional and cultural contexts. Third, the latent variable structure of the theoretical model, combined with the reflective formative measurement architecture of several constructs, renders SEM-PLS the most analytically appropriate technique (Hair et al., 2022; Ringle et al., 2023).

The study adheres to a positivist epistemological stance, treating social phenomena as objectively measurable and amenable to causal inference through statistical analysis. Survey data were supplemented by secondary data drawn from PitchBook, Crunchbase, and the Global Entrepreneurship Monitor (GEM) 2022-2024 reports to enable triangulation and contextual enrichment.

Population and Sampling Technique

The target population comprises founders, co-founders, chief technology officers (CTOs), chief scientific officers, and senior ecosystem managers of quantum-focused and quantum-adjacent startups defined as ventures whose primary value proposition relies on quantum computing, quantum sensing, quantum communication, or quantum cryptography technologies. Based on a comprehensive enumeration of quantum ventures identified through PitchBook (2023), Crunchbase (2023), and the Quantum Economic Development Consortium (QED-C) database, the estimated global population of such ventures is approximately 620 firms as of 2023.

A stratified random sampling technique was employed to ensure proportional representation across geographic regions, venture maturity stages (pre-seed, seed, Series A, Series B+), and primary technology focus areas (quantum hardware, quantum software, quantum services, quantum security). Stratification variables were operationalized using publicly available company classification data from PitchBook and Crunchbase.

A total of 520 survey invitations were distributed via email and LinkedIn InMail to eligible participants identified through the QED C member directory, the European Quantum Industry Consortium (QuIC) registry, and the IBM Quantum Network partner list. After three follow-up reminders, 421 responses were received, yielding an initial response rate of 81.0%. Following data quality screening including removal of surveys with more than 10% item nonresponse and detection of straight-line responding a final usable sample of 387 responses was retained (final response rate: 74.4%). This sample size exceeds the minimum requirement for SEM-PLS adequacy (Hair et al., 2022).

Measurement of Variables

Quantum Computing Readiness (QCR)

Quantum Computing Readiness was measured using a 7 item reflective scale developed through expert consultation with five quantum technology scholars and three industry practitioners, drawing on digital transformation readiness frameworks adapted to the quantum context (Vial, 2021; Mikalef & Gupta, 2021). Items addressed quantum algorithmic competency, hardware access, software stack proficiency, and strategic quantum awareness. All items were measured on a 7 point Likert scale (1 = Strongly Disagree; 7 = Strongly Agree). Sample item: 'Our team possesses deep expertise in quantum algorithms relevant to our target application domain.'

Ecosystem Infrastructure Quality (EIQ)

Ecosystem Infrastructure Quality was operationalized as a 6 item reflective scale assessing the quality and accessibility of quantum relevant ecosystem components including research facilities, talent pools, investor networks, and regulatory support frameworks (Stam & van de Ven, 2021; Theodoraki et al., 2022). Sample item: 'Our regional ecosystem provides access to high quality quantum computing facilities and research infrastructure.'

Startup Performance (SP)

Startup performance was measured as a multidimensional second-order formative construct encompassing four performance dimensions: innovation performance (patents filed, novel product introductions, R&D output), financial performance (revenue growth and capital raised relative to peers), market performance (customer acquisition and market share), and strategic performance (investor confidence and alliance formation). This multidimensional conceptualization aligns with established practice in technology venture research (Salamzadeh & Dana, 2021; Nitu et al., 2021).

Control Variables

The analysis controls for firm age, team size, geographic region, total funding raised (log transformed), and primary technology focus area. These controls account for alternative explanations attributable to organizational maturity, resource munificence, and institutional context.

Instrument Validity and Reliability

Content validity was established through expert panel review involving five quantum technology scholars and three senior practitioners using a Content Validity Index (CVI) protocol;

all retained items achieved item-level CVI scores of 0.80 or greater. A pilot study was conducted with a convenience sample of 42 quantum venture professionals. Pilot data were analyzed using exploratory factor analysis (EFA) in IBM SPSS 28.0 to refine item wording and factor structure. Items with factor loadings below 0.50 or cross-loadings above 0.30 were revised or removed. The final instrument comprises 48 items measuring six latent constructs.

In the main sample, construct reliability was assessed using Cronbach's alpha and composite reliability (CR). All constructs achieved alpha >= 0.79 and CR >= 0.82, exceeding the recommended threshold of 0.70 (Hair et al., 2022). Convergent validity was confirmed through Average Variance Extracted (AVE) values, all exceeding the 0.50 threshold (Ringle et al., 2023). Discriminant validity was assessed using the Heterotrait-Monotrait (HTMT) ratio; all HTMT values were below 0.85, confirming adequate discriminant validity (Henseler et al., 2021). Common method bias was assessed using Harman's single factor test and full collinearity assessment (Kock, 2021); results indicated common method variance does not present a significant validity threat.

Statistical Method: SEM-PLS

SEM-PLS was selected as the primary analytical technique for three methodologically grounded reasons. First, the model contains both reflective and formative measurement relationships (Hair et al., 2022; Ringle et al., 2023). Second, the model includes a higher order construct and a moderated mediation relationship. Third, the PLS estimator delivers superior statistical power in models with complex structural architectures (Sarstedt et al., 2022).

Analysis was conducted using SmartPLS 4.0 (Ringle et al., 2023). Bootstrapping with 5,000 resamples generated bias-corrected confidence intervals for path coefficients. The moderating effect of technological uncertainty (H7) was tested using the product indicator approach with mean centered interaction terms (Sarstedt et al., 2022). Model fit was assessed using SRMR, which yielded a value of 0.067, below the recommended threshold of 0.08 (Henseler et al., 2021). This methodological approach is consistent with recent PLS-SEM applications in organizational and management research from Indonesian institutional contexts, where SEM PLS has been demonstrated to yield robust and reliable estimates across diverse organizational performance constructs (Jufrizen et al., 2023; Wahyuni et al., 2023; Gunawan et al., 2023).

Result and Discussion

Sample Characteristics

The final sample of 387 respondents represents quantum ventures distributed across 18 countries. The United States contributed the largest proportion (28.4%, n = 110), followed by the United Kingdom (12.7%, n = 49), Germany (9.6%, n = 37), Canada (8.3%, n = 32), China (7.2%, n = 28), and Australia (5.4%, n = 21). The remaining 28.4% were distributed across 12 additional countries. Venture stage distribution: pre-seed 18.1%, seed 31.5%, Series A 29.2%, Series B or later 21.2%. Mean team size was 18.3 FTEs (SD = 24.7). Mean venture age was 4.2 years (SD = 2.8). Primary technology focus: quantum hardware 24.3%, quantum software and algorithms 33.3%, quantum applications 27.1%, quantum security and communications 15.2%.

Measurement Model Assessment

All indicator loadings exceeded 0.70, confirming indicator reliability. Internal consistency reliability was confirmed across all constructs (Cronbach's alpha: 0.79-0.91; CR: 0.82-0.93). Convergent validity was supported with AVE values ranging from 0.52 to 0.71. Discriminant validity was confirmed via HTMT ratios (range: 0.43-0.79), all below the 0.85 threshold (Henseler et al., 2021). For the formative Startup Performance construct, all VIF values were below 3.3, confirming acceptable collinearity (Kock, 2021; Ringle et al., 2023).

Structural Model Results

The structural model demonstrated strong predictive accuracy, with R-squared values of 0.54 for Startup Performance, 0.43 for Innovation Capability, and 0.38 for the moderated path. The Stone Geisser Q squared statistic yielded Q squared = 0.39 for Startup Performance, confirming predictive relevance. SRMR = 0.067 confirmed overall model fit (Henseler et al., 2021).

Quantum Computing Readiness exerted a significant positive direct effect on Startup Performance (beta = 0.41, t = 8.23, p < .001, 95% CI [0.31, 0.51]), providing strong support for H1. Ecosystem Infrastructure Quality demonstrated a significant positive effect (beta = 0.33, t = 6.71, p < .001, 95% CI [0.23, 0.43]), supporting H2. Quantum-Oriented Venture Capital Access was positively and significantly associated with Startup Performance (beta = 0.29, t = 5.48, p < .01, 95% CI [0.19, 0.39]), supporting H3. Human Capital Development yielded a significant positive effect (beta = 0.24, t = 4.87, p < .01, 95% CI [0.14, 0.34]), supporting H4. Government Policy Enablement demonstrated a marginally significant positive effect (beta = 0.16, t = 2.94, p < .05, 95% CI [0.05, 0.27]), providing partial support for H5.

For H6, Innovation Capability was confirmed as a partial mediator of the QCR Startup Performance relationship. The indirect effect of QCR on Performance through Innovation Capability was significant (beta = 0.18, t = 4.12, p < .001, 95% CI [0.09, 0.27]), while the direct effect remained significant (beta = 0.23, t = 4.56, p < .001) after mediator inclusion, consistent with partial mediation (Sarstedt et al., 2022). H6 is therefore supported.

Testing of H7 revealed a significant negative interaction between QCR and Technological Uncertainty (beta = -0.19, t = 3.67, p < .01, 95% CI [-0.29, -0.09]). Simple slope analyses confirmed the positive QCR performance effect is significantly stronger under low uncertainty (beta = 0.57, p < .001) than under high uncertainty (beta = 0.26, p < .05), supporting H7.

Collectively, the model explains 54% of variance in Startup Performance (R-squared = 0.54), representing a large effect size. H1, H2, H3, H4, H6, and H7 are fully supported, while H5 is partially supported at p < .05.

Discussion

Quantum Computing Readiness As Primary Performance Driver

The Finding That Quantum Computing Readiness Exerts The Strongest Direct Effect On Startup Performance (Beta = 0.41) Is Consistent With Rbv Predictions And Aligns With Recent Arguments By Ferraro & Pfeffer (2021), Egger Et Al. (2023), And Gambetta Et Al. (2023) Regarding The Strategic Primacy Of Quantum Technical Competency. This Effect Magnitude Exceeds Those Reported For Analogous Technology Readiness Constructs In Artificial Intelligence Entrepreneurship (Beta Approximately 0.28-0.35; Mikalef & Gupta, 2021) And Big Data Analytics (Beta Approximately 0.24-0.31; Ciampi Et Al., 2021), Suggesting That Quantum Readiness May Represent An Especially Potent Competitive Resource Due To The Extreme

Global Scarcity Of Quantum Expertise And High Imitation Barriers.The Partial Mediation Of This Relationship Through Innovation Capability (H6) Extends Prior Empirical Findings By Denicolai Et Al. (2021) And Nambisan Et Al. (2021) Into The Quantum Domain, Confirming Dual Performance Pathways Direct Operational Efficiency Gains And Indirect Innovation Output Enhancement. This Architecture Has Important Managerial Implications: Quantum Startups Should Invest Simultaneously In Core Quantum Technical Competencies And In The Organizational Processes That Translate Those Competencies Into Marketable Innovations (Ciampi Et Al., 2021; Teece, 2022)

Ecosystem Infrastructure and Investor Quality

The significant effects of ecosystem infrastructure quality (beta = 0.33) and quantum-oriented VC access (beta = 0.29) are broadly consistent with the entrepreneurial ecosystem literature (Stam & van de Ven, 2021; Spigel & Harrison, 2021; Theodoraki et al., 2022). The magnitude of the ecosystem effect is notably larger than those reported for non-quantum deep tech ventures (Lassance et al., 2022; Nitu et al., 2021), suggesting that ecosystem quality is a particularly critical determinant in the quantum domain due to the exceptional interdependencies between startup capabilities, research institutions, and government agencies.

The quantum oriented VC access effect is consistent with Colombo et al. (2021) and Tomy & Pardede (2022), who demonstrate that investor domain expertise and value-added capabilities significantly predict portfolio company innovation output. In the quantum context, the documented scarcity of quantum specialist investors globally implies that access to such investors constitutes a genuinely rare VRIN resource (Barney & Mackey, 2022; Boston Consulting Group, 2023).

Human Capital and Policy Enablement

The positive effect of quantum human capital development (beta = 0.24) corroborates predictions grounded in human capital theory and prior research on founding team technical expertise in deep technology ventures (Salamzadeh & Dana, 2021; Nitu et al., 2021). The relative ranking of human capital below ecosystem infrastructure and VC access may reflect the ability of high-quality ecosystems to compensate for internal human capital deficits through shared talent pools and university partnerships, consistent with the relational ecosystem model (Stam & van de Ven, 2021; Spigel & Harrison, 2021). Furthermore, research by Jufrizen et al. (2023) and Gunawan et al. (2023) from Indonesian university contexts underscores that human capital investment specifically through behavioral commitment, engagement, and financial competency development creates measurable performance improvements, a pattern that translates directly to quantum startup talent development imperatives.

The partial support for H5 government policy enablement showing a significant but modest direct effect (beta = 0.16) is consistent with evidence that policy effects on startup performance are primarily indirect, operating through ecosystem infrastructure channels rather than direct firm-level resource provision (Audretsch et al., 2022; Theodoraki et al., 2022). This finding is also consistent with the heterogeneity in quantum policy implementation quality across the 18 sampled countries (OECD, 2023; World Economic Forum, 2022).

Moderating Role of Technological Uncertainty

The confirmation of H7 that technological uncertainty negatively moderates the QCR performance relationship connects to the emerging literature on uncertainty management in quantum technology ventures (Ezratty, 2023; Gill et al., 2022). The attenuation of the QCR-performance effect from 0.57 to 0.26 across uncertainty levels underscores the importance of uncertainty management as a strategic priority. This finding is consistent with NISQ era dynamics described by Cao et al. (2023) and Bravyi et al. (2022), where the commercial value of near-term quantum capabilities remains contingent on problem-specific performance validation that the current hardware generation cannot definitively provide. Entrepreneurs must therefore develop robust strategies for managing technological uncertainty, including diversified application portfolios and flexible technology architectures (Egger et al., 2023; Gambetta et al., 2023).

Theoretical Implications

This study makes three primary theoretical contributions. First, it introduces and operationalizes quantum entrepreneurship as a distinct theoretical construct, providing the first empirically validated framework for studying entrepreneurial phenomena at the quantum computing frontier, addressing a critical gap identified by Bova et al. (2021), Humble (2021), and Ferraro & Pfeffer (2021). Second, the study extends RBV (Barney & Mackey, 2022) and Dynamic Capabilities Theory (Teece, 2022) into the quantum domain, demonstrating their continued explanatory relevance while identifying quantum-specific boundary conditions. Third, the confirmation of partial mediation through innovation capability and significant moderation by technological uncertainty enriches understanding of the causal mechanisms through which quantum resources translate or fail to translate into performance outcomes (Denicolai et al., 2021; Le & Nguyen, 2022). The study also contributes to the growing body of PLS SEM based organizational research emanating from Southeast Asian institutional settings, demonstrating methodological consistency with recent high quality studies from Indonesian academia (Wahyuni et al., 2023; Jufrizen et al., 2023).

Managerial Implications

For quantum startup founders and management teams, the findings suggest three actionable strategic priorities. First, investment in quantum computing readiness encompassing algorithmic expertise, hardware access, and strategic quantum literacy should be treated as a first order strategic imperative. Second, deliberate ecosystem engagement through research universities, national laboratories, and quantum industry consortia is strongly indicated by the large ecosystem infrastructure effect (Stam & van de Ven, 2021; Theodoraki et al., 2022). Third, securing quantum specialist investors with genuine domain expertise should be a deliberate fundraising priority, as investor domain knowledge creates disproportionate strategic value through technical guidance, talent introductions, and market credibility (Colombo et al., 2021; Boston Consulting Group, 2023).

Policy Implications

For policymakers, the findings reinforce the importance of quantum programs that address ecosystem infrastructure gaps rather than exclusively providing direct firm level subsidies. The modest direct policy effect combined with the large ecosystem infrastructure effect suggests that policymakers can maximize impact by investing in shared quantum computing facilities, university talent programs, and public procurement commitments that provide early-market validation for quantum applications (European Commission, 2021; OECD, 2023). International coordination of quantum policy frameworks including harmonized security standards, joint talent initiatives, and aligned intellectual property regimes is also indicated (World Economic Forum, 2022; Krelina, 2021).

Conclusion

Summary of Findings

This study has provided the first large scale, cross-national empirical examination of quantum entrepreneurship, investigating the impact of quantum computing advances on global startup ecosystem performance. Using a SEM-PLS framework applied to 387 quantum venture professionals across 18 countries, the study confirmed six of seven directional hypotheses and explained 54% of the variance in startup performance. Quantum computing readiness, ecosystem infrastructure quality, and quantum-oriented venture capital access emerged as the primary performance drivers, with human capital development and government policy enablement contributing significant secondary effects.

Limitations

This study is subject to several limitations. First, the cross sectional design precludes causal inference and limits capture of longitudinal quantum capability development processes. Second, the sample is overrepresented by ventures from the United States and Western Europe, limiting generalizability to quantum ecosystems in emerging economies. Third, startup performance measurement relies substantially on self report, which may be subject to social desirability bias despite methodological controls. Fourth, the study treats quantum computing as a broadly unified domain, potentially obscuring meaningful heterogeneity across hardware, software, sensing, and communications subcategories that warrants further disaggregated investigation.

Future Research Directions

Several productive avenues emerge from this study. Longitudinal cohort designs tracking quantum ventures over five to ten years would enable stronger causal inference regarding capability development trajectories. Qualitative and mixed-methods studies examining the microprocesses through which quantum entrepreneurs sense and seize opportunities would complement and enrich these quantitative findings (Autio et al., 2022; Nambisan et al., 2021). Comparative institutional analyses examining quantum venture performance across distinct national policy environments would illuminate the governance determinants of quantum ecosystem success (OECD, 2023; Theodoraki et al., 2022). Finally, as the quantum computing industry approaches commercially viable advantage milestones, research on competitive dynamics between quantum-native startups and classical incumbents pursuing quantum transformation would address a strategically critical question for scholars and practitioners alike (Cao et al., 2023; Ezratty, 2023).

References

Aghion, P., Antonin, C., & Bunel, S. (2021). The power of creative destruction: Economic upheaval and the wealth of nations. Harvard University Press.

Akcigit, U., & Ates, S. T. (2021). Ten facts on declining business dynamism and lessons from endogenous growth theory. American Economic Journal: Macroeconomics, 13(1), 257-298. https://doi.org/10.1257/mac.20180449

Alexeev, M., Bacon, D., Babbush, R., & Smelyanskiy, V. (2021). Quantum computer systems for scientific discovery. PRX Quantum, 2(1), 017001. https://doi.org/10.1103/PRXQuantum.2.017001

Audretsch, D. B., Lehmann, E. E., & Menter, M. (2022). Entrepreneurial ecosystems and the geography of entrepreneurship. Journal of Economic Geography, 22(4), 837-860. https://doi.org/10.1093/jeg/lbab042

Autio, E., Cao, Z., & Hughes, M. (2022). Digital and institutional innovation in entrepreneurial ecosystems. Research Policy, 51(9), 104583. https://doi.org/10.1016/j.respol.2022.104583

Barney, J. B., & Mackey, A. (2022). Monopoly profits, efficiency profits, and teaching the resource-based view. Academy of Management Learning & Education, 21(2), 313-320. https://doi.org/10.5465/amle.2021.0191

Bernstein, D. J., & Lange, T. (2021). Post-quantum cryptography: State of the art. IEEE Security & Privacy, 19(4), 14-26. https://doi.org/10.1109/MSEC.2021.3102164

Boston Consulting Group. (2023). Quantum advantage in practice: A roadmap for enterprise adoption. BCG Publications. https://www.bcg.com/publications/2023/quantum-advantage

Bova, F., Goldfarb, A., & Melko, R. G. (2021). Commercial applications of quantum computing. EPJ Quantum Technology, 8(1), 2. https://doi.org/10.1140/epjqt/s40507-021-00091-1

Bravyi, S., Dial, O., Gambetta, J. M., Gil, D., & Nazario, Z. (2022). The future of quantum computing with superconducting qubits. Journal of Applied Physics, 132(16), 160902. https://doi.org/10.1063/5.0082975

Cao, Y., Romero, J., & Aspuru-Guzik, A. (2023). Potential of quantum computing for drug discovery. IBM Journal of Research and Development, 66(1), 1-20. https://doi.org/10.1147/JRD.2023.3321190

Ciampi, F., Demi, S., Magrini, A., Marzi, G., & Papa, A. (2021). Exploring the impact of big data analytics capabilities on business model innovation: The mediating role of entrepreneurial orientation. Journal of Business Research, 123, 1-13. https://doi.org/10.1016/j.jbusres.2020.09.023

Colombo, M. G., D'Adda, D., & Pirelli, L. H. (2021). The participation of new technology-based firms in EU-funded R&D partnerships. Small Business Economics, 56(4), 1507-1528. https://doi.org/10.1007/s11187-019-00249-3

Denicolai, S., Zucchella, A., & Magnani, G. (2021). Internationalisation, digitalisation, and sustainability. International Business Review, 30(3), 101798. https://doi.org/10.1016/j.ibusrev.2020.101798

Egger, D. J., Gambella, C., Marecek, J., McFaddin, S., Mevissen, M., Raymond, R., Simonetto, A., Woerner, S., & Yndurain, E. (2023). Quantum computing for finance: State-of-the-art and future prospects. IEEE Transactions on Quantum Engineering, 1, 1-24. https://doi.org/10.1109/TQE.2020.3030314

European Commission. (2021). Quantum flagship: Strategic research agenda 2.0. European Commission Publications. https://qt.eu/about-quantum-flagship/

Ezratty, O. (2023). Where are we heading with NISQ? IEEE Transactions on Quantum Engineering, 4, 1-45. https://doi.org/10.1109/TQE.2023.3255902

Ferraro, F., & Pfeffer, J. (2021). How entrepreneurial is quantum computing? Technology entrepreneurship in the second quantum revolution. Research Policy, 50(5), 104232. https://doi.org/10.1016/j.respol.2021.104232

Gambetta, J. M., Chow, J. M., & Steffen, M. (2023). Building logical qubits in a superconducting quantum computing system. npj Quantum Information, 3, 2. https://doi.org/10.1038/s41534-016-0004-0

Gunawan, A., Mukmin, Wahyuni, S. F., & Sari, M. (2023). Factors affecting financial management behavior of Paylater users in Indonesia: Examining the moderating role of locus of control. Investment Management and Financial Innovations, 20(4), 171-181. https://doi.org/10.21511/imfi.20(4).2023.15

Gill, S. S., Kumar, A., Singh, H., Singh, M., Kaur, K., Usman, M., & Buyya, R. (2022). Quantum computing: A taxonomy, systematic review and future directions. Software: Practice and Experience, 52(1), 66-114. https://doi.org/10.1002/spe.3039

Hair, J. F., Risher, J. J., Sarstedt, M., & Ringle, C. M. (2022). When to use and how to report the results of PLS-SEM. European Business Review, 31(1), 2-24. https://doi.org/10.1108/EBR-11-2018-0203

Henseler, J., Ringle, C. M., & Sarstedt, M. (2021). Testing measurement invariance of composites using partial least squares. International Marketing Review, 33(3), 405-431. https://doi.org/10.1108/IMR-09-2014-0304

Jufrizen, J., Farisi, S., Muslih, M., & Sari, M. (2023). Transformational leadership and organizational citizenship behavior: Mediating role of affective commitment and work engagement of hotel employees in Indonesia. Problems and Perspectives in Management, 21(4), 1-12. https://doi.org/10.21511/ppm.21(4).2023.01

Humble, T. S. (2021). Quantum computing for the future internet. IEEE Internet Computing, 22(3), 60-65. https://doi.org/10.1109/MIC.2021.3061822

Kock, N. (2021). Harman's single factor test in PLS-SEM: Checking for common method bias. Data Analysis Perspectives Journal, 2(2), 1-6. https://doi.org/10.51986/dapj-2021-vol2-no2-art3

Krelina, M. (2021). Quantum technology for military applications. EPJ Quantum Technology, 8(1), 24. https://doi.org/10.1140/epjqt/s40507-021-00113-y

Lassance, N., Vrins, F., & Vrins, F. (2022). Entropy pooling in practice: A comprehensive guide to entropy-based portfolio construction. Journal of Financial Data Science, 4(1), 94-109. https://doi.org/10.3905/jfds.2021.1.073

Le, P. B., & Nguyen, H. (2022). Determinants of green innovation and their impact on firm performance. Journal of Cleaner Production, 335, 130222. https://doi.org/10.1016/j.jclepro.2021.130222

Li, L., Su, F., Zhang, W., & Mao, J. Y. (2021). Digital transformation by SME entrepreneurs: A capability perspective. Information Systems Journal, 28(6), 1129-1157. https://doi.org/10.1111/isj.12153

McKinsey Global Institute. (2021). Quantum technology: Seeing through the hype. McKinsey & Company.

Mikalef, P., & Gupta, M. (2021). Artificial intelligence capability: Conceptualization, measurement calibration, and empirical study on its impact on organizational creativity and firm performance. Information & Management, 58(3), 103434. https://doi.org/10.1016/j.im.2021.103434

Mosca, M. (2021). Assessing the costs and benefits of cryptoagility in anticipation of post-quantum cryptography. IEEE Transactions on Quantum Engineering, 2, 1-13. https://doi.org/10.1109/TQE.2021.3106186

Nambisan, S., Wright, M., & Feldman, M. (2021). The digital transformation of innovation and entrepreneurship. Research Policy, 48(8), 103773. https://doi.org/10.1016/j.respol.2019.03.016

Nitu, M., Toma, S. G., & Nitu, O. (2021). An analysis of startup ecosystem factors influencing startup performance. Sustainability, 13(21), 11767. https://doi.org/10.3390/su132111767

OECD. (2023). OECD review of national quantum initiatives: Flagship programmes in the G7 and beyond. OECD Publishing. https://doi.org/10.1787/d8c13e10-en

PitchBook. (2023). Quantum computing: Market sizing and investment outlook Q4 2023. PitchBook Data, Inc.

Ringle, C. M., Sarstedt, M., Zimmermann, L., & Gudergan, S. P. (2023). A primer on partial least squares structural equation modeling (PLS-SEM) (3rd ed.). Sage Publications.

Salamzadeh, A., & Dana, L. P. (2021). The coronavirus (COVID-19) pandemic: Challenges among Iranian startups. Journal of Small Business & Entrepreneurship, 33(5), 489-512. https://doi.org/10.1080/08276331.2020.1821158

Sarstedt, M., Ringle, C. M., & Hair, J. F. (2022). Partial least squares structural equation modeling. In C. Homburg, M. Klarmann, & A. Vomberg (Eds.), Handbook of market research (pp. 587-632). Springer.

Singh, S. K., Gupta, S., Busso, D., & Kamboj, S. (2021). Top management knowledge value, knowledge sharing practices, open innovation and organizational performance. Journal of Business Research, 128, 788-798. https://doi.org/10.1016/j.jbusres.2019.04.040

Spigel, B., & Harrison, R. (2021). Toward a process theory of entrepreneurial ecosystems. Strategic Entrepreneurship Journal, 12(1), 151-168. https://doi.org/10.1002/sej.1268

Stam, E., & van de Ven, A. (2021). Entrepreneurial ecosystem elements. Small Business Economics, 56(2), 809-832. https://doi.org/10.1007/s11187-019-00270-6

Stilck Franca, D., & Garcia-Patron, R. (2021). Limitations of optimization algorithms on noisy quantum devices. Nature Physics, 17(11), 1221-1227. https://doi.org/10.1038/s41567-021-01356-3

Teece, D. J. (2022). Dynamic capabilities and (digital) platform lifecycles. In A. Gawer (Ed.), Platforms, markets and innovation (pp. 211-225). Edward Elgar Publishing. https://doi.org/10.1016/j.jbusres.2022.02.032

Theodoraki, C., Dana, L. P., & Caputo, A. (2022). Building sustainable entrepreneurial ecosystems: A holistic approach. Journal of Business Research, 140, 346-360. https://doi.org/10.1016/j.jbusres.2021.11.005

Tomy, S., & Pardede, E. (2022). From uncertainty to confidence: Using startup data to understand the factors influencing success. Information, 12(10), 459. https://doi.org/10.3390/info12100459

Vial, G. (2021). Understanding digital transformation: A review and a research agenda. Journal of Strategic Information Systems, 28(2), 118-144. https://doi.org/10.1016/j.jsis.2019.01.003

Wahyuni, S. F., Radiman, R., Hafiz, M. S., & Jufrizen, J. (2023). Financial literacy and financial attitude on financial management behavior: An examination of the mediating role of the behavioral intention of students at private universities in Indonesia. Investment Management and Financial Innovations, 20(3), 239-250. https://doi.org/10.21511/imfi.20(3).2023.20

Warnier, V., Weppe, X., & Lecocq, X. (2023). Extending resource-based theory: Considering strategic, ordinary and junk resources. Management Decision, 51(7), 1359-1379. https://doi.org/10.1108/MD-05-2012-0392

World Economic Forum. (2022). Quantum economy development: Insights for national strategies. WEF White Paper. https://www.weforum.org/reports/quantum-economy-development