

Examining the Challenges of Indian Deep-Tech Startups: Pathway for Sustainable Entrepreneurial Practices

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Abstract: Deep-tech startups are rooted in scientific and engineering innovations and hold transformative potential for addressing critical societal challenges in healthcare, clean energy, water treatment, and sustainable infrastructure. Unlike traditional digital startups, which scale swiftly via continuous innovation, deep-tech startups confront distinctive hurdles due to lengthy R&D periods, intensive capital investments, stringent regulatory compliance, and unpredictable market penetration. These conditions expose them to the Valley of Death (VoD), a critical phase in which promising innovations fail to reach commercial viability before funding is exhausted. This vulnerability stems from a fundamental misalignment between experimental outcomes and commercial viability, further compounded by systemic gaps in institutional support, including inadequate legal frameworks and limited market awareness in emerging market contexts. Despite growing scholarly interest in both the Valley of Death and the Technology–Organization–Environment (TOE) framework, there is limited research to explain how technological, organizational, and environmental conditions collectively produce specific commercialization barriers for deep-tech startups. This study addresses this gap through qualitative research with five deep-tech startups in India operating across agritech, healthcare technology, neurotechnology, nanotechnology, and cybersecurity. Thematic analysis of semi-structured interviews resulted in interrelated themes, each representing a different aspect of the TOE framework. The results reveal that technological, organizational, and environmental barriers are not isolated phenomena but dynamically reinforce one another, giving rise to three interrelated Valley of Death barriers: funding gaps, market translation failure, and legitimacy deficits. The proposed TOE–VoD framework therefore suggests that overcoming commercialization challenges in deep-tech startups requires an integrated perspective that simultaneously addresses technological, organizational, and environmental dimensions. The framework further provides founders with a diagnostic tool, policymakers with a rationale for multi-dimensional interventions, and researchers with a foundation for comparative and longitudinal inquiry into deep-tech commercialization across emerging market contexts.

Keywords: Deep-Tech Startup, Valley of Death, TOE Framework, Commercialization, Emerging Markets

1. Introduction

Deep technology, commonly referred to as deep tech refers to startups whose business models are founded on breakthrough scientific discoveries or advanced engineering innovations, rather than the incremental application of existing technologies (Mierzejewska, 2019). First coined in 2015, the term captures a category of startups operating across biotechnology, nanotechnology, artificial intelligence, quantum computing, advanced materials, healthcare technology, robotics, and autonomous systems (Thu et al., 2024). Unlike conventional technology startups that leverage existing platforms to build products and services, deep-tech startup develops the foundational scientific and engineering capabilities themselves, a distinction that fundamentally shapes their funding requirements, development timelines, and path to commercialization (Giones and Brem, 2017). Global investment in deep tech has grown substantially, with the sector attracting fifty billion dollars in venture capital investment in 2024 (Basilio et al., 2023). In India, deep-tech entrepreneurship has emerged as a strategic priority, with startups addressing critical societal challenges in agritech, healthcare, water treatment, neurotechnology, and cybersecurity attracting increasing attention from investors, incubators, and policymakers.

Despite this growth, deep-tech startups face a structural challenge that distinguishes them sharply from mainstream startups, the Valley of Death. The Valley of Death describes the critical phase between research-driven technological innovation and commercial viability. At this point, deep-tech startups have either developed a technology or written a business plan with a prototype ready to implement, but have not yet obtained enough financing to move their products to production (Markham et al., 2010). Deep-tech startups often struggle to transition beyond the Valley of Death because of inadequate capital, operational challenges, and a lack of credibility with prospective customers (Nedayvoda et al., 2020). Research shows that the majority of all start-ups experience the Valley of Death on several occasions during the commercialization process, and that the vast majority of corporate spin-outs and government-supported startups also experience these challenges (Gbadegeshin et al., 2022). Murray et al. (2023) identify the Valley of Death as a product of systemic entrepreneurial conditions rather than individual startup failings, arguing that overcoming it requires

simultaneously addressing networking and ecosystem conditions, value proposition and customer creation, strategic focus, and financing. However, what remains absent in literature is a structured account of the specific conditions that determine how deep a startup Valley of Death is and which mechanisms produce each distinct failure mode. Existing frameworks identify that a gap exists, but do not explain what causes it to be wider or narrower for different startups operating in different contexts.

The Technology–Organization–Environment framework, developed by Tornatzky and Fleischer (1990), provides a systematic way to analyze the factors impacting a firm's ability to implement and commercialize new technologies across three dimensions. The technological component of the TOE framework represents the nature of the foundational technology and its level of maturity and protection. The organization component reflects the organizational capacity, resources and processes the firm has to leverage new technologies or innovations. The Environment component consists of the external conditions in which the organization operates (e.g. institutions, markets and ecosystems), which may either facilitate or impede the firm's ability to commercialize innovative technologies. While the TOE framework has been widely applied to technology adoption decisions in established firms (Oliveira and Martins, 2011), it has not been studied in depth with respect to commercialization challenges faced by deep-tech startups. Furthermore, the TOE framework has not been integrated with the Valley of Death concept. Consequently, existing studies identify the contextual conditions surrounding a startup but fall short of explaining how these conditions translate into specific commercialization barriers. This integration represents the theoretical gap by addressing the following research questions:

RQ1: What mechanisms hinder deep-tech startups from overcoming the Valley of Death in the process of translating breakthrough innovations into scalable and commercially viable solutions?

RQ2: How do technological complexity, organizational capabilities, and environmental conditions influence a deep-tech startup's ability to navigate the Valley of Death?

Collectively, these research questions seek to examine both the barriers faced by deep-tech startups and the contextual conditions that give rise to the Valley of Death (VoD). Drawing on qualitative evidence from deep-tech startups in India, this study develops an integrated TOE–VoD conceptual framework that explains the underlying mechanisms of commercialization failure while offering practical guidance for enhancing commercialization success.

2. Methodology

A qualitative research design is appropriate because the study addresses how and why questions that require contextual depth rather than statistical breadth, specifically examining how founders commercialize breakthrough innovations and why certain conditions create commercialization barriers while others do not. (Denzin and Lincoln, 2011). The interpretive stance adopted in this study prioritizes founders' lived experiences over statistical generalization, consistent with its theory-building rather than theory-testing orientation.

Purposive sampling was employed to select participants who could provide real-time insights into the deep-tech commercialization process. Inclusion criteria required that each startup be engaged in research-intensive innovation in domains such as biotechnology, nanotechnology, artificial intelligence, healthcare technology, or advanced materials; that the startup had achieved at least a working prototype; and that the founder or senior executive had direct experience navigating funding and commercialization challenges. Five deep-tech startups based in India were selected as shown in Table 1. Semi-structured interviews were conducted with founders and co-founders between July 2025 and early 2026, lasting 60-80 minutes each. Interviews were conducted online, audio-recorded with consent, and transcribed verbatim. Data analysis followed Braun and Clarke's (2006) six-phase thematic analysis framework: familiarization, coding, generating themes, reviewing themes, naming themes, and writing up. The analysis began with repeated reading of transcripts to develop familiarity with the data, followed by manual open coding to generate first-order codes in the language of informants. Axial coding was then applied to identify connections across first-order codes, producing second-order codes that captured the underlying conceptual constructs. Second-order codes were iteratively reviewed and consolidated into aggregate themes aligned with the three TOE dimensions. Themes were discussed among researchers to validate interpretations and ensure that the conceptual categories accurately reflected their experiences.

Table 1: Case Overview

Company Name	Founding Year	Sector	Product / Service offered	Estimated TRL
Sputnik Brain	2023	Neural Interface	Neural interfaces for stress reduction and mental health	TRL 6–7 (clinical pilots, pre-launch)
Quekey	2024	Cybersecurity	AI-driven software and design solutions	TRL 5–6 (validated prototype)
Neer Shakti Systems	2022	Nanotechnology	Nanotechnology-based machines,	TRL 9 (commercially deployed)
Sense Health Technologies Pvt. Ltd.	2017	Deep Learning	AI-based sensing technologies	TRL 5–6 (validated prototype)
GreenPod Labs	2019	Agri-tech	Patented active packaging sachets	TRL 9 (commercially deployed)

Note: Technology Readiness Level (TRL) are estimated based on publicly available evidence and founder interviews, mapped against the NASA/ISO TRL scale (Mankins, 1995; NASA, 2023), as startups do not routinely self-report. There are 9 TRL levels: Basic principle observed, concept formulated, Experimental proof of concept, validation in laboratory, validation in relevant environment, prototype demonstration in relevant environment, demonstration in operational environment, complete and qualified system and actual system in use.

3. Findings and Discussion

The findings highlight technological, organizational, and environmental dimensions contributing to the Valley of Death barriers faced by deep-tech startups. The analysis moves from aggregate themes through second-order codes and first-order inductive coding, demonstrating the analytical trail from raw data to theoretical interpretation. Each dimension is interpreted in relation to its corresponding VoD barrier as the themes are presented with the systemically integrated TOE–VoD framework as shown in Table 2.

Table 2: Coding Tree

Aggregate Theme	Second Order Codes	First-order Codes (Verbatim Informant Language)
Technology (T)	T1 Innovation readiness	"Upgrading and bringing change with time is the law — continuous year-on-year improvement is not a phase but an operating principle." "Writing research papers is five percent of the job — 95% is the struggle that you have to go through. If the technology is not taken to the market and from there you are not earning money, then it's not a sustainable model."
	T2 Technical uncertainty	"The chance of success is less than 0.10% — that means your chance of failure is 99.9% in this sector. Any company you start from scratch is bound to fail. That's how the odds are." "High risk and low probability of success in deep tech startups—failure is normalized in deep tech."
	T3 Knowledge protection	"The patent process in India is quite slow — in the US or Europe it takes a maximum of six months, but the waiting period in India is quite long." "We prioritized technology, patents, and teams over early revenue—building IP protection first before approaching investors."

Aggregate Theme	Second Order Codes	First-order Codes (Verbatim Informant Language)
Organization (O)	O1 Resource mobilization	"The biggest challenge any company has is funding, no matter if it is deep tech or any other company." "Mismanagement of funds and capital leads to loss of investor confidence and financial waste." "Many international suppliers from China, Taiwan, and South Korea were unwilling to ship to India, even after receiving full payment. Orders were sometimes cancelled after delays of 60 to 70 days."
	O2 Organizational learning	"Initially, we deployed product exterior packaging, which was harder to open in the field—we got the feedback that this had to be simplified. We did change this." "When you came up with this product, the product is already market fit. The only thing is how you enter the market. That is the challenge." "Most of the startups have a solution, but many do not know how to enter the market—that is the problem."
	O3 Commercial strategy	"Per month, the cost of pricking is about 4000 rupees—what we are offering is that per month you don't need to even pay 400 rupees." "Affordability as a key design and market driver—pay-less model—cost efficiency in India." "Partnerships provide visibility but not guaranteed revenue."
Environment (E)	E1 Policy & regulation	"We have validated it. Now the next step is the clinical trial—if we get the regulatory approval, then of course India will accept." "Many startups in this sector face the challenge of compliance. But we built this with compliance from the very first day." "Regulatory approval delays — certification challenges — heavy regulation as a structural feature of the market environment."
	E2 Ecosystem support	"I reached out to approximately 170 to 180 professors worldwide—only a small fraction responded, and just three agreed to meet." "These platforms are good for any startup, but they will not fill your stomach. You have to go and own that business yourself."
	E3 Market conditions	"Every technology has a phase—incubation, adaptability, then the market adopts it. It's just like how EVs were in the early 2000s—there was not much adoption. But now every third person has an EV." "Deep tech success depends on public acceptance and understanding of the technology behind the product."

3.1 Technological Dimension

Three second-order themes were identified within the technology dimension: innovation readiness (T1), technical uncertainty (T2), and knowledge protection (T3). Collectively, these themes reveal why deep-tech startups experience a structural funding gap that differs qualitatively from the financing constraints typically faced by conventional startups.

3.1.1 Innovation Readiness (T1)

Innovation readiness indicates how developed a startup main technology has progressed from basic research towards commercial viability. Across all five startups, founding decisions were driven by unmet societal problems. GreenPod Labs stated its mission directly: *"The company vision is to minimize the food waste and food losses in the developing countries,"* while Sense Health's motivation was rooted in the understanding of the magnitude of diabetes in India. Shane and Venkataraman (2000) argue that identifying solutions to customer problems forms the foundation of entrepreneurial opportunity creation. However, in deep-tech startups,

entrepreneurs often face a tension between prioritizing long-term societal or technological problems and responding to immediate market demand when setting development priorities.

Innovation processes were described as continuous rather than milestone-driven. Neer Shakti Systems articulated the operating principle: *"Upgrading and bringing change with time is the law—continuous year-on-year improvement is not a phase but an operating principle."* QueKey described the *"research to market gap—lab to market—commercialization challenges are the real barrier after research is done."* This extends Chesbrough's (2010) regarding the "lab to market" gap; but in the case of the Indian deep-tech context, it is not one significant transition but rather a continual source of challenges through many lengths of time that far exceed most investor horizons.

3.1.2 Technical Uncertainty (T2)

Technical uncertainty refers to the unpredictability associated with R&D in deep technology. Neer Shakti Systems stated, *"The chance of success is less than 0.10%—that means your chance of failure is 99.9% in this sector. Any company you start from scratch is bound to fail. That's how the odds are."* QueKey also elaborated on the development experience: *"There were many hiccups, long sleepless nights—we kept trying and trying, and then finally it worked."* While T1 refers to where on this developmental trajectory a startup is currently located, T2 is a broader measure of the unpredictability of that trajectory, irrespective of the company's current stage. Ghosh and Nanda (2010) demonstrate that this uncertainty generates investor risk perceptions categorically different from software ventures, where technical risks are lower and feedback loops substantially faster. Investor reluctance is therefore rational rather than uninformed, and overcoming the funding gap requires better mechanisms for communicating risk rather than simply better technology.

3.1.3 Knowledge Protection (T3)

Knowledge protection captures the challenge of securing a competitive advantage through intellectual property (IP) mechanisms in weak, slow, or costly formal systems. QueKey described the structural problem: *"In our universities it is not that much talked about how a patent could be filed—only researchers who do PhDs get to know about all these things."* Teece (1986) identifies the appropriability regime as a key determinant of whether innovators can capture returns from their innovations. In weak IP environments, founders face a disclosure dilemma that further widens the funding gap. Revealing sufficient technical detail to attract investors increases the risk of knowledge appropriation in settings with weak IP enforcement (Khanna & Palepu, 1997), while the absence of supportive policy signals limits the institutional assurances that investors rely on when direct assessment of technological potential is difficult (North, 1990).

Altogether, T1, T2, and T3 intensify the funding gap by making the startup proposition illegible, unpredictable, and indefensible to investors simultaneously. Innovation immaturity means investors cannot assess commercial viability. Technical uncertainty means the risk profile cannot be quantified using standard frameworks. Weak IP protection means a competitive advantage cannot be guaranteed even if the technology succeeds.

3.2 Organisational Dimension

The organizational dimension encompasses the internal capabilities, resources, and strategic processes that shape a startup's ability to transform technological innovation into commercial traction. Three sub-themes emerged: resource mobilization (O1), organizational learning (O2), and commercial strategy (O3).

3.2.1 Resource Mobilization (O1)

Resource mobilization captures the startup capacity to secure, manage, and deploy financial and operational resources. Neer Shakti Systems stated, *"The biggest challenge any company has is funding—no matter whether it is deep tech or any other company,"* adding that *"mismanagement of funds and capital leads to loss of investor confidence and financial waste."* Sense Health talked about how sustained grant-based bootstrapping could be used to help fund an organization until they could produce something from their pre-clinical stage. Brush, et al., (2001) indicated that when making investment decisions, potential investors consider resource mobilization capability in conjunction with technology development maturity. O2 is an organizational dimension of resource mobilization since it is an internal capability of a company, but O2 also exists in the funding gap, which refutes the notion that the funding gap is a technology-based issue in VoD literature (Auerswald and Branscomb, 2003). Thus, organizational inefficiency in resource management adds an additional barrier to technology-driven barriers.

3.2.2 Organizational Learning (O2)

Organizational learning captures how startups develop an understanding of target customers and the behavioral factors shaping adoption. GreenPod Labs described the approach: *"Before any product development, we spend more than 15 days with the customer to understand their pain points."* The consequence of insufficient market learning was illustrated concretely: *"Initially, we deployed product exterior packaging that was harder to open in the field—we got the feedback that this had to be simplified. We did change this."* Sense Health described the mismatch between research assumptions and commercial reality: *"When you came up with this product, the product was already market fit. The only thing is how you enter the market. That is the challenge."* According to Eisenmann et al. (2012), the primary reason for startup failures is the effect of premature scaling, which occurs when a startup invests in its product before achieving product-market fit; this risk is augmented in deep tech by the long lead times between Development and the opportunity to make a correction.

3.2.3 Commercial Strategy (O3)

Commercial strategy captures the startup approach to market positioning and revenue design. Affordability is a dominant factor in commercial strategy in the Indian context. Sense Health framed the affordability logic: *"Per month, the cost of pricking is about 4000 rupees—what we are offering is that per month you don't even need to pay 400 rupees."* Neer Shakti Systems reinforced this: *"Affordability as a key design and market driver—pay-less model—cost efficiency in India."* Strategic positioning and legitimacy signaling emerged as a second mechanism within this theme. GreenPod Labs described a deliberate 60-40 focus between long-term and short-term goals as a commercial discipline, Prahalad (2004) argues that emerging market commercialization requires fundamental business model redesign rather than price adaptation. Chesbrough and Rosenbloom (2002) identify the value creation versus value capture distinction: the activities that build credibility and those that generate revenue require different organizational logics, and technically-oriented founding teams consistently conflate them.

Collectively, O1, O2, and O3 produce the market translation barrier by limiting the startup capacity to convert technical capability into commercial traction. Insufficient organizational learning results in product development decisions that are guided by assumptions rather than evidence of actual customer needs. An inadequate commercial strategy means there is no viable pathway from innovation to sustainable revenue in an emerging market context. These failures are mutually reinforcing; with weak resource mobilization it is less likely to invest in learning, and a startup without market learning is unlikely to develop a viable commercial strategy.

3.3 Environmental Dimension

The environmental dimension encompasses the external policy, ecosystem, market, and institutional conditions that shape a startup's operating context but remain largely beyond its direct control. This theme includes policy and regulation (E1), ecosystem support (E2), and market conditions (E3). These themes collectively produce the legitimacy deficit, the most structurally intractable VoD barrier because it cannot be resolved through startup internal action alone.

3.3.1 Policy and Regulation (E1)

Policy and regulation capture the institutional and regulatory environment. QueKey said, *"Many startups in this sector face the challenge of compliance. But we built this with compliance from the very first day,"* Sputnik Brain said that data privacy restrictions in neurotechnology are typically a barrier to R&D, as they can delay go-to-market activities regardless of the readiness of the technology. Neer Shakti Systems said that the number of regulations involved is an impediment to getting to market quickly, even after completing testing and evaluations. North (1990) states that the institutional model defines the rules of the game, while Aldrich and Fiol (1994) demonstrate that emerging technologies need to develop their legitimacy through a combination of cognitive beliefs and social-political factors to gain acceptance; therefore, delays in approval will delay that process. Regulatory approval serves as an institutional signal of credibility, and its absence creates a trust deficit regardless of the underlying technical quality of the innovation.

3.3.2 Ecosystem Support (E2)

Ecosystem support captures the role of the broader innovation infrastructure. Sense Health described institutional affiliation as a primary legitimacy signal: Sputnik Brain described the challenge of accessing ecosystem actors from outside established networks: *"I reached out to approximately 170 to 180 professors*

worldwide — only a small fraction responded, and just three agreed to meet." Neer Shakti Systems offered a grounding counter-perspective: "These platforms are good for any startup, but they will not fill your stomach. You have to go and own that business yourself." Etzkowitz and Leydesdorff (2000) argue that the university-industry-government triple helix is the structural foundation of innovation legitimacy, while Stinchcombe's (1965) liability of newness captures the compounding difficulty for startups outside strong ecosystems; every relationship must be built independently without the warm introductions that institutional affiliation provides.

3.3.3 Market Conditions (E3)

Market conditions capture the external demand for deep-tech innovations. Neer Shakti Systems framed adoption in lifecycle terms: "Every technology has a phase—incubation, adaptability, and then the market adopts it. It's just like how EVs were in the early 2000s—there was not much adoption. But now every third person has an EV." As Sputnik Brain notes, "Deep tech success depends on public acceptance and understanding of the technology behind the product." QueKey stated that the lack of elite institutional history for their founding team led to investors viewing as a non-viable start-up, and, therefore, legitimacy deficits can exist via social proxies (external factors) rather than just via technical merit. Rogers (2003) identified that the main factor that determines the diffusion rate for a given product is the compatibility of the new product with existing business processes, while Sarasvathy (2001), in explaining effectuation theory, stated that entrepreneurs create product opportunities where there were previously none, using effectual reasoning methods. In emerging markets, demand for new technologies often needs to be built rather than assumed, resulting in substantially longer commercialization and sales cycles.

Taken together, E1, E2, and E3 contribute to the emergence of a legitimacy deficit through distinct but complementary mechanisms. The absence of regulatory approval weakens institutional validation, limited ecosystem maturity restricts borrowed credibility, low market awareness slows technology adoption, and social proxies increasingly shape investor and customer judgments in place of direct technical evaluation. Critically, the legitimacy deficit is the most persistent of the three Valley of Death barriers because it is the least susceptible to actions undertaken solely within the startup.

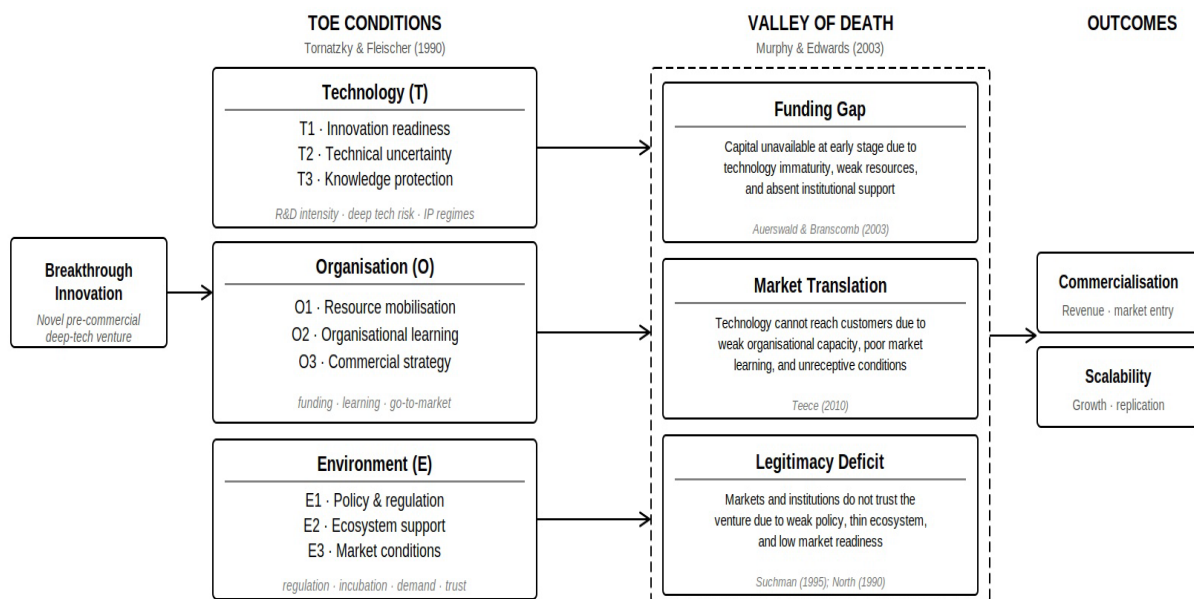


Figure 1: TOE and VoD framework

The critical theoretical insight this study offers, represented in Figure 1 by the convergence of all three TOE dimensions into the Valley of Death zone, is that the three barriers are simultaneous and, are mutually reinforcing rather than sequential. The funding gap is produced by the interaction of unproven technology, dysfunctional resource management, and a lack of institutional risk reduction in the environment. The market translation barrier is exacerbated when the technology is immature, and the marketplace is not receptive. Additionally, when a technology is socially unfamiliar, the legitimacy deficit is deepened by the failure to communicate a trustworthy position commercially.

This holistic view of the intersection of the three TOE dimensions builds upon the original conception of

Tornatzky & Fleischer (1990) that the TOE framework constitutes three independent categories of analysis for deep-technology commercialization; a weakness in one TOE dimension creates barriers for other dimensions. As illustrated through QueKey, Sputnik Brain, and Neer Shakti Systems, poor management of organizational resources exacerbates the funding gap when coupled with immaturity of technology. Poor commercial positioning exacerbates the legitimacy deficit when coupled with institutional weaknesses as illustrated through Sense Health and GreenPod Labs. Therefore, it is not adequate to only address one dimension, but all three must be addressed at the same time. Therefore, the integrated TOE-VoD framework is different from previous independent applications of either the TOE Framework (Oliveira & Martins, 2011) or the VoD concept.

4. Conclusion

This study develops an integrated TOE–VoD framework to explain why deep-tech startups in India struggle to cross the Valley of Death. The findings demonstrate that technological conditions, organizational capabilities, and environmental factors do not operate independently; instead, they collectively intensify three interconnected barriers: the funding gap, market translation failure, and legitimacy deficit. Addressing any single barrier in isolation is insufficient; all three must be navigated concurrently. The framework offers founders a diagnostic tool, policymakers a case for multidimensional intervention, and researchers a foundation for longitudinal and comparative inquiry into deep-tech commercialization across emerging market contexts.

Ethics Declaration

This study did not need formal ethical clearance but the researchers have obtained informed consent from all the respondents.

AI Declaration

AI applications like ChatGPT and Grammarly helped with formatting references, minor spelling, grammar, and clarity of language. The tools were not applied to create original research content or interpret findings.

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