

Building Biodigital Clusters in Emerging Economies: A Conceptual Framework Integrating Technological Capabilities and Governance in the Pharmaceutical Sector

José Luis Meza de la Rosa and María del Rocío Soto Flores

Escuela Superior de Comercio y Administración, Unidad Santo Tomás, Instituto Politécnico Nacional, Ciudad de México, México

joseluis.mezad11@gmail.com

msotof@ipn.mx

Abstract: The emergence of artificial intelligence, biotechnology, advanced data analytics, and digital health technologies is transforming the pharmaceutical industry and reshaping the conditions under which innovation occurs. These developments are driving the formation of biodigital innovation ecosystems, where scientific knowledge, technological capabilities, governance arrangements, and institutional coordination become critical determinants of competitiveness and innovation performance. Despite the growing importance of biodigital convergence, existing literature has largely examined technological capabilities, innovation systems, cluster development, and governance as separate analytical domains. Limited attention has been devoted to understanding how these dimensions interact to support the emergence and consolidation of biodigital clusters, particularly in emerging economies characterized by institutional fragmentation, technological dependency, and uneven innovation capabilities. This paper presents the conceptual architecture of an ongoing doctoral research project that seeks to address this gap. The study proposes an integrative framework that combines three complementary perspectives: technological capabilities theory, governance theory, and innovation ecosystem approaches. The framework is designed to explain how technological capabilities and governance mechanisms jointly influence the development of biodigital clusters in the pharmaceutical sector. The proposed model conceptualizes technological capabilities as the ability of organizations and territories to acquire, absorb, adapt, generate, and reconfigure knowledge and technologies, while governance is understood as the set of coordination mechanisms that align actors, resources, institutions, and strategic objectives across multiple levels. The interaction between these dimensions is expected to facilitate knowledge flows, collaborative innovation, institutional learning, and ecosystem development. The research is particularly relevant in the context of emerging economies, where strengthening domestic innovation capabilities has become a strategic priority for technological sovereignty, industrial upgrading, and health resilience. Mexico provides a particularly interesting context due to recent efforts aimed at fostering innovation-driven industrial development and strengthening the pharmaceutical and biotechnology sectors.

Keywords: Industrial Clusters, Pharmaceutical Industry, Innovation Geography, Capabilities, Global Value Chains

1. Introduction

The pharmaceutical industry is undergoing a profound transformation driven by the convergence of artificial intelligence (AI), biotechnology, advanced data analytics and digital health technologies. Together, these advances are creating a biodigital paradigm in which biological knowledge and digital technologies reshape drug discovery, pharmaceutical research and industrial innovation, redefining the technological and institutional foundations of competitiveness.

This transformation reflects the broader dynamics of the Fourth Industrial Revolution, characterised by the integration of digital, biological and physical technologies into interconnected innovation processes. In pharmaceuticals, AI has become a strategic enabling technology for accelerating target identification, molecular design, toxicity prediction and clinical decision-making, while advances in genomics, synthetic biology, gene editing and precision medicine have expanded opportunities for therapeutic innovation. As a result, pharmaceutical innovation increasingly depends on the integration of diverse scientific and technological capabilities rather than on traditional research and development (R&D) activities alone.

Technological convergence is also reshaping the geography of innovation. Pharmaceutical innovation increasingly emerges within collaborative ecosystems involving universities, biotechnology firms, pharmaceutical companies, research institutes, regulatory agencies and digital technology providers. These interactions reinforce the strategic importance of industrial clusters as environments that facilitate knowledge exchange, collaborative learning and technological specialisation. However, in biodigital industries, geographical proximity alone is insufficient; effective innovation also depends on governance mechanisms, institutional coordination and strong technological capabilities.

For emerging economies, biodigital convergence offers opportunities for industrial upgrading, technological sovereignty and stronger health systems, while simultaneously exposing structural weaknesses associated with fragmented innovation systems and limited technological capabilities. Strengthening pharmaceutical competitiveness therefore requires integrated strategies that combine scientific investment with governance arrangements capable of coordinating multiple actors and supporting long-term capability development.

Although the literature has generated important contributions on technological capabilities, governance, industrial clusters and innovation ecosystems, these perspectives have largely evolved independently. Existing studies provide only partial explanations of biodigital transformation and offer limited understanding of how governance and technological capabilities jointly shape the emergence of biodigital pharmaceutical clusters, particularly in emerging economies. To address this gap, this paper proposes the Biodigital Cluster Framework (BCF), an integrative conceptual model combining technological capabilities theory, governance theory and innovation ecosystem perspectives. The framework conceptualises technological capabilities as dynamic processes through which organisations and territories acquire, integrate and reconfigure knowledge, while governance is understood as the multi-level coordination mechanisms that align institutions, actors and strategic objectives across pharmaceutical innovation ecosystems.

2. Literature Review

The transformation of the pharmaceutical industry reflects the convergence of artificial intelligence (AI), biotechnology, computational sciences and digital technologies into a new biodigital paradigm that is redefining innovation processes, industrial organisation and value creation. This transformation is consistent with Schumpeter's (1934) view of innovation as the engine of economic change and with Dosi's (1982) concept of technological paradigms, which explains how technological trajectories shape future innovation opportunities. Arthur (2009) further argues that technological evolution occurs through the recombination of existing technologies, providing a useful explanation for the integration of AI, biotechnology and computational biology in pharmaceutical innovation. Similarly, Perez (2002) interprets technological revolutions as systemic transformations that reshape production systems, institutions and industrial organisation. Recent OECD reports (2023; 2024) identify AI, synthetic biology and precision medicine as enabling technologies driving competitiveness, productivity and resilience. Nevertheless, current research continues to examine these technologies largely in isolation, providing only limited understanding of how their convergence reshapes territorial innovation dynamics.

The literature on technological capabilities explains why organisations differ in their ability to innovate by emphasising cumulative learning and knowledge accumulation. Lall (1992) defines technological capabilities as the competencies required to acquire, adapt and improve technologies, while Bell and Pavitt (1995) distinguish technological capabilities from production capabilities, arguing that innovation depends upon continuous learning rather than operational efficiency alone. Kim (1997), Figueiredo (2002; 2010) and Dutrénit (2004) demonstrate that these capabilities evolve progressively through learning, experimentation and interaction with external knowledge sources. Castellacci (2008) further conceptualises technological capabilities as multidimensional constructs integrating organisational learning, knowledge creation and innovation performance. More recently, Dynamic Capabilities theory (Teece, 2007; 2018) has extended this perspective by highlighting firms' ability to sense opportunities, seize emerging technologies and continuously reconfigure organisational resources. However, this literature remains largely focused on individual organisations and provides limited explanation of how capabilities are collectively developed within territorial innovation ecosystems.

Complementing this perspective, cluster and innovation ecosystem theories emphasise that innovation increasingly emerges through interactions among interconnected organisations rather than isolated firms. Porter (1998) highlights the competitive advantages of geographical agglomeration, while Regional Innovation Systems stress the importance of institutional interaction and regional learning (Cooke, 1998; Asheim and Gertler, 2005). Boschma (2005) further argues that innovation depends on multiple forms of proximity beyond geographical location, including cognitive, institutional and organisational proximity. More recent ecosystem approaches describe innovation as a dynamic process of value co-creation among interdependent actors (Autio and Thomas, 2014; Jacobides, Cennamo and Gawer, 2018), whereas Mazzucato (2018) emphasises the strategic role of governments in shaping innovation ecosystems through mission-oriented policies. Despite these advances, existing approaches provide only partial explanations of how AI, biotechnology and digital technologies jointly transform pharmaceutical innovation and territorial development.

Governance has consequently become a key concept for understanding how complex innovation systems coordinate heterogeneous actors operating across multiple institutional levels. Unlike hierarchical government, governance emphasises collaborative networks, institutional interaction and strategic coordination (Rhodes, 1997). Jessop (2002) further argues that governance evolves through the continuous interaction between institutional structures and strategic actors, enabling innovation systems to adapt to technological change. Importantly, governance extends beyond institutional coordination by encompassing the broader arrangements that shape collaboration, trust, decision-making and long-term ecosystem development. Although governance is widely recognised within innovation policy research, relatively few studies have explicitly examined how governance interacts with technological capability accumulation to explain the emergence of biodigital pharmaceutical clusters. This unresolved relationship constitutes the principal theoretical gap addressed by the conceptual framework proposed in this paper.

3. Conceptual Research Gap

The preceding literature review demonstrates that substantial theoretical progress has been achieved in understanding technological capabilities, governance, industrial clusters and innovation ecosystems. However, these research traditions have largely evolved as independent streams, each explaining a specific dimension of innovation while providing only limited insight into their interactions under conditions of biodigital technological convergence. The technological capabilities literature has generated robust explanations regarding how organisations accumulate knowledge, develop learning routines and strengthen innovation performance. Nevertheless, most capability-based studies focus primarily on firm-level learning processes and pay relatively little attention to the governance arrangements that enable capability accumulation across multiple organisations and institutions. Consequently, the broader ecosystem conditions supporting collective technological learning remain insufficiently theorised.

Conversely, governance literature has significantly advanced our understanding of institutional coordination, collaborative networks and public policy mechanisms. Yet governance studies generally conceptualise technological change as an external context rather than as a dynamic process that co-evolves with governance structures. As a result, the reciprocal relationship between governance and technological capability development has received comparatively limited theoretical attention. Research on industrial clusters and regional innovation systems has consistently demonstrated the importance of geographical agglomeration, knowledge spillovers and collaborative interaction in fostering regional competitiveness. However, much of this literature was developed before the emergence of artificial intelligence, computational biology and digital biotechnology as enabling technologies. Consequently, existing cluster theories only partially explain how technological convergence is reshaping spatial patterns of pharmaceutical innovation and creating new forms of biodigital ecosystems.

Finally, innovation ecosystem approaches have broadened the analysis beyond geographical proximity by emphasising value co-creation, complementarities and interdependence among heterogeneous actors. Nevertheless, current ecosystem frameworks frequently remain descriptive and provide limited analytical explanation regarding how technological capabilities, governance mechanisms and territorial conditions interact to produce sustained innovation performance within emerging biodigital industries. To synthesise the preceding discussion, Table 1 presents the principal theoretical contributions and limitations identified across the existing literature, thereby illustrating the conceptual fragmentation that underpins the need for an integrative biodigital cluster framework.

Table 1: Principal conceptual limitations in the existing literature

Literature Stream	Principal Contribution	Main Limitation for Biodigital Cluster Research
Technological capabilities	Explains organisational learning, knowledge accumulation and innovation capabilities	Primarily focuses on firms and pays limited attention to governance and ecosystem coordination.
Governance	Explains institutional coordination, collaborative networks and public policy	Does not explicitly incorporate technological capability accumulation or technological convergence.
Industrial clusters	Explains geographical agglomeration, knowledge spillovers and regional competitiveness	Developed largely before AI-driven pharmaceutical innovation and provides limited explanation of biodigital convergence.

Literature Stream	Principal Contribution	Main Limitation for Biodigital Cluster Research
Innovation ecosystems	Explains value co-creation, inter-organisational collaboration and ecosystem dynamics	Provides limited integration of territorial capabilities, governance and technological transformation within a unified analytical model.

Source: Authors' own elaboration based on the literature reviewed in this study.

4. Proposed Conceptual Framework

Building upon the conceptual gaps identified in the previous section, this paper proposes the Biodigital Cluster Framework (BCF) as an integrative conceptual model explaining how technological capabilities and multi-level governance interact to facilitate the emergence and evolution of biodigital pharmaceutical clusters in emerging economies. Rather than considering innovation as the outcome of isolated organisational efforts, the framework conceptualises biodigital clusters as complex adaptive systems in which organisations, institutions, technologies and territorial resources continuously co-evolve through collaborative learning and knowledge exchange. The proposed framework integrates four complementary theoretical perspectives. First, technological capabilities explain how organisations and territories accumulate, absorb and generate scientific knowledge. Second, governance theory explains how heterogeneous actors coordinate collective action through institutions, policies and collaborative arrangements. Third, innovation ecosystem theory provides the systemic perspective required to understand inter-organisational interactions. Finally, cluster theory contributes the territorial dimension through which geographical concentration facilitates knowledge spillovers and innovation dynamics.

Unlike previous conceptual models, the BCF assumes that technological capabilities and governance are mutually reinforcing rather than independent variables. Governance influences the development of technological capabilities by creating institutional conditions that facilitate collaboration, investment and knowledge exchange, while accumulated technological capabilities strengthen governance by increasing organisational maturity, collaborative capacity and strategic coordination. Consequently, biodigital clusters emerge through continuous feedback processes rather than through sequential stages of development. Figure 1 illustrates the proposed conceptual framework.

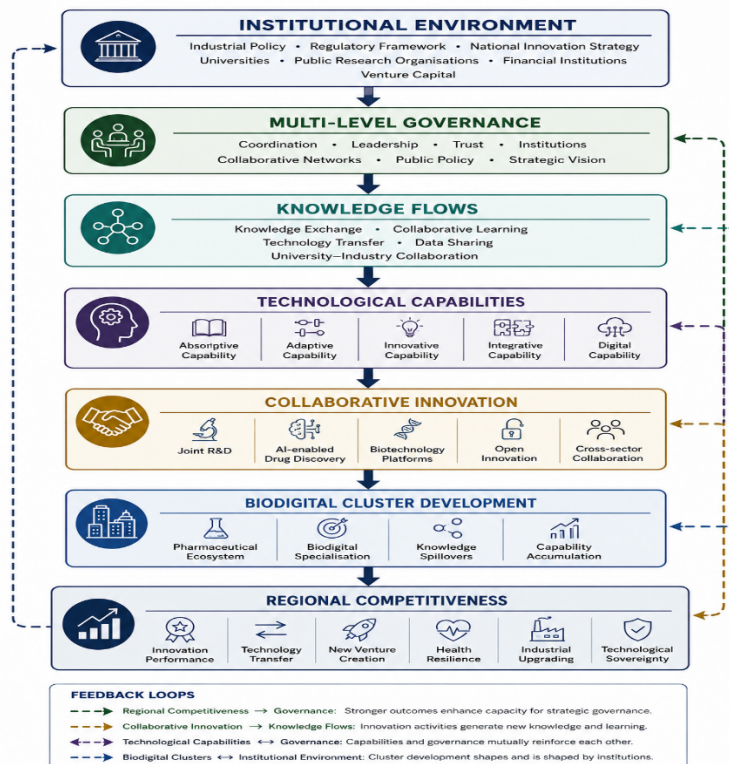


Figure 1: The Biodigital Cluster Framework (BCF): an integrative conceptual model for pharmaceutical innovation ecosystems in emerging economies.

Source: Authors' own elaboration using generative AI-assisted graphic design.

The framework assumes that biodigital innovation begins within a broader institutional environment composed of industrial policies, regulatory systems, universities, research organisations, financial institutions and public innovation agencies. These contextual conditions shape the opportunities available for collaboration, investment and technological learning. Rather than acting as passive background conditions, institutions actively influence the configuration and evolution of pharmaceutical innovation ecosystems.

4.1 Multi-Level Governance

Governance represents the central coordinating mechanism of the proposed framework. It is conceptualised as the set of formal and informal arrangements through which heterogeneous actors collectively organise strategic activities, allocate resources and coordinate innovation processes. Unlike traditional hierarchical governance models, biodigital governance is distributed across multiple organisational and territorial levels involving governments, universities, pharmaceutical companies, biotechnology firms, investors and regulatory agencies.

Five complementary dimensions characterise governance within biodigital clusters.

1. Coordination facilitates the alignment of strategic priorities among organisations with different objectives and capabilities.
2. Institutions provide stable formal and informal rules that reduce uncertainty, promote collaboration and support long-term investments.
3. Trust reduces transaction costs, facilitates knowledge sharing and strengthens collaborative relationships among ecosystem participants.
4. Public policy establishes strategic incentives, regulatory certainty and long-term industrial priorities that encourage technological investment.
5. Leadership enables collective vision-building, mobilises strategic resources and promotes ecosystem coordination around shared development objectives.

Together, these governance mechanisms create institutional conditions that support sustained innovation rather than isolated technological projects.

4.2 Knowledge Flows

Knowledge flows constitute the principal mechanism through which governance influences capability accumulation. Pharmaceutical innovation increasingly depends upon continuous exchanges of scientific knowledge among universities, biotechnology firms, pharmaceutical manufacturers, hospitals, regulatory agencies and digital technology providers. These interactions include collaborative research, data sharing, technology transfer, researcher mobility, open innovation initiatives and multidisciplinary learning processes. Within biodigital ecosystems, knowledge is simultaneously codified and tacit, requiring organisational capabilities capable of integrating biological sciences, computational methods, engineering, regulatory science and clinical expertise. Consequently, effective governance enhances both the quantity and quality of knowledge circulation throughout the ecosystem.

4.3 Technological Capabilities

Technological capabilities represent the endogenous innovation potential of organisations and territories. Consistent with capability theory, the framework conceptualises these capabilities as cumulative, dynamic and path-dependent processes that evolve through continuous learning and interaction.

Five complementary capability dimensions are incorporated into the model.

1. Absorptive capability refers to the ability to identify, acquire and assimilate external scientific and technological knowledge.
2. Adaptive capability reflects the capacity to modify existing technologies in response to changing scientific, regulatory and market conditions.
3. Innovative capability represents the ability to generate original products, technologies and scientific solutions through internal research and collaborative development.
4. Integrative capability refers to the ability to combine heterogeneous knowledge originating from biology, artificial intelligence, engineering, medicine and data science into coherent innovation processes.

5. Digital capability encompasses organisational competencies related to artificial intelligence, advanced analytics, cloud computing, digital infrastructures and computational modelling.

Collectively, these technological capabilities determine the capacity of organisations and regions to participate successfully in biodigital innovation ecosystems.

4.4 Territorial Conditions

The framework explicitly recognises that technological capabilities develop within specific territorial contexts. Biodigital clusters emerge where complementary actors coexist and interact through dense institutional networks.

Four territorial components are particularly important:

- **Universities and public research organisations** generate scientific knowledge and highly specialised human capital.
- **Pharmaceutical and biotechnology firms** transform scientific discoveries into commercial innovations while investing in technological development.
- **Government agencies** establish industrial policies, regulatory frameworks and public investment programmes that reduce uncertainty and encourage innovation.
- **Financial institutions** and venture capital organisations provide long-term funding required to commercialise emerging technologies and support high-risk innovation projects.

The interaction among these territorial actors generates cumulative knowledge spillovers that strengthen regional innovation performance over time.

4.5 Expected Outcomes

The final stage of the framework describes the expected outcomes associated with biodigital cluster development. These outcomes extend beyond firm-level innovation and encompass broader regional and societal impacts.

- **At the innovation level**, biodigital clusters increase collaborative research, interdisciplinary knowledge production and technological diversification.
- **At the industrial level**, stronger ecosystems facilitate technology transfer, accelerate AI-enabled drug discovery, stimulate the creation of biotechnology start-ups and strengthen participation in global pharmaceutical value chains.
- **At the territorial level**, biodigital clusters contribute to regional competitiveness through capability accumulation, employment generation, industrial upgrading and enhanced attractiveness for international investment.
- **At the societal level**, stronger biodigital ecosystems improve health resilience, accelerate responses to emerging public health challenges and reinforce technological sovereignty by reducing dependence on imported knowledge and critical technologies.

Taken together, the Biodigital Cluster Framework proposes that governance and technological capabilities should not be interpreted as separate determinants of innovation. Instead, they constitute interdependent and co-evolving processes embedded within territorial ecosystems that collectively shape the emergence, consolidation and long-term competitiveness of biodigital pharmaceutical clusters in emerging economies.

5. Implications and Conclusions

The Biodigital Cluster Framework (BCF) proposed in this paper contributes to the literature on pharmaceutical innovation by integrating theoretical perspectives that have traditionally evolved independently. While previous studies have examined technological capabilities, governance, industrial clusters and innovation ecosystems as separate analytical domains, the proposed framework conceptualises these dimensions as mutually reinforcing processes that collectively explain the emergence of biodigital pharmaceutical clusters in emerging economies. This integrative perspective responds to the increasing complexity of pharmaceutical innovation, where artificial intelligence, biotechnology and digital technologies are transforming not only research and development processes but also the institutional and territorial conditions under which innovation occurs.

From a theoretical perspective, the framework extends several established approaches. Unlike Porter's cluster theory, which primarily emphasises geographical concentration and competitive advantage, the Biodigital Cluster Framework highlights governance quality and technological capability accumulation as complementary determinants of cluster development. Likewise, although Regional Innovation Systems and Triple Helix models recognise the importance of institutional interaction, they provide only limited explanation of how emerging digital technologies reshape ecosystem dynamics. The proposed framework explicitly incorporates technological convergence and multi-level governance as endogenous mechanisms driving ecosystem evolution. Furthermore, it complements Dynamic Capabilities theory by extending the analytical focus from firm-level adaptation towards capability accumulation occurring across territorially embedded innovation ecosystems.

The framework also generates important implications for industrial and innovation policy. For emerging economies, strengthening pharmaceutical competitiveness requires moving beyond policies focused exclusively on research funding or scientific infrastructure. Instead, governments should promote integrated strategies that simultaneously reinforce technological capabilities, collaborative governance, regulatory quality and knowledge exchange among universities, firms, research organisations, financial actors and public institutions. Such systemic approaches may contribute to industrial upgrading, technological sovereignty and more resilient health systems.

From a managerial perspective, the framework suggests that pharmaceutical firms should increasingly regard innovation as an ecosystem-based process rather than an organisational activity undertaken in isolation. Developing absorptive and digital capabilities, participating in collaborative research networks and establishing strategic partnerships across scientific and institutional boundaries will become essential sources of long-term competitiveness within biodigital industries. As a conceptual study, this paper has inherent limitations. The Biodigital Cluster Framework has not yet been empirically validated and should therefore be interpreted as a theoretical architecture designed to guide future research rather than as a predictive model. Future studies should operationalise the proposed constructs and examine their relationships through structural equation modelling, comparative case studies and longitudinal analyses across pharmaceutical innovation ecosystems in different institutional contexts.

In conclusion, the Biodigital Cluster Framework provides a novel conceptual contribution to understanding pharmaceutical innovation by demonstrating that governance and technological capabilities should be interpreted as co-evolving processes embedded within territorial innovation ecosystems. By integrating these dimensions into a single analytical model, the framework offers a comprehensive perspective for explaining biodigital transformation and establishes a conceptual foundation for future empirical research on innovation policy, regional development and pharmaceutical competitiveness in emerging economies. Beyond its application to the pharmaceutical industry, the Biodigital Cluster Framework contributes to the broader field of Innovation Studies by proposing a conceptual lens through which technological convergence, governance and territorial capability accumulation can be understood as interdependent processes shaping industrial transformation. As artificial intelligence and biotechnology continue to redefine innovation across multiple sectors, the framework offers a transferable analytical foundation for future comparative research on biodigital ecosystems, industrial policy and regional development in emerging economies.

Ethics Declaration

This study is conceptual in nature and does not involve human participants, personal data, animal experimentation, or any procedures requiring ethical approval. Therefore, formal ethical clearance was not required.

AI Declaration

Artificial intelligence tools were used exclusively to support language refinement, structural organisation, editorial revision, and the graphical development of Figure 1 (Biodigital Cluster Framework) during manuscript preparation. The conceptual design of the framework, the theoretical integration, the interpretation of the literature, and all scientific arguments presented in this paper were entirely developed, critically reviewed, and validated by the authors.

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