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**ARTICLE**

# A Triangulated Analysis of Scientific-Technological Park Necessity in Colombia's Sub-Regional Innovation Ecosystems

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## ABSTRACT

This research highlights a paradox in Colombia's Science, Technology, and Innovation (STI) system, which has adopted national policies such as *CONPES 4069 (2021–2031)*, continuing to face structural unproductivity, territorial disparities, and institutional fragility, which underscore the emergence of functional regional innovation ecosystems. Positioned within the theoretical frameworks of regional innovation systems, the quadruple helix, and institutional theory, the research explores how scientific-technological parks (STPs) can act as strategic actors for building regional STI capacity in Colombia's regions. An exploratory design is adopted, the study uses content analysis and data triangulation (literature, Minciencias' GrupLAC within the SNCTI databases, and the *National Competitiveness Report 2024–2025)*. The findings show a territorial concentration of STI capabilities, with over 60% of recognized research groups and researchers located in four departments (Bogotá-Cundinamarca, Antioquia, Valle del Cauca, and Santander). Only one officially consolidated STP (Parque Tecnológico Guatiguará) exists nationwide, reflecting the gap between policy design and territorial reality. An institutional instability, budgetary contraction, and weak governance mechanisms have undermined the policy coherence

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required to sustain innovation infrastructure and regional convergence. The analysis concludes that STPs represent not autonomous solutions but potential actors for rebuilding regional innovation. The study contributes to theoretical debates on innovation policy and institutional constraints in developing economies, offering empirical foundations and policy insights for reorienting Colombia's STI agenda toward regional inclusion and sustainable knowledge-based development.
***Keywords:*** Innovation; Scientific-Technological Parks; Colombia; Regional Innovation

# 1. Introduction

The contemporary discussion on economic development has positioned science, technology, and innovation (STI) as a variable for sustainable growth, productivity, and social transformation in knowledge-based economies [1, 2]. This paradigm shift has been emphasized in developing nations seeking to transcend the "middle-income trap" and establish competitive advantages in increasingly globalized markets [3]. Scientific-technological parks (STPs) have emerged as strategic territorial instruments designed to materialize the triple helix model of innovation [4], facilitating dynamic interactions among academia, industry, and government while catalyzing the construction of robust regional innovation cultures. However, the Colombian case presents a scenario that needs an academic observation., the formal adoption of ambitious policy frameworks, the National Science, Technology and Innovation Policy 2022–2031 (CONPES 4069, 2021), which established the goal of increasing investment in STI activities from 0.64% to 1.5% of GDP by 2031 [5], the reality shows a systematic dichotomy of the institutional architecture necessary for such transformation.

Colombia's position in global innovation rankings and its persistently low investment in R&D shows weaknesses in its STI system, situating the country below both OECD recommendations and different regional peers. According to the Global Innovation Index 2024, Colombia ranks 63rd among 133 economies, positioned significantly below regional counterparts such as Chile (52$^{nd}$), Mexico (58$^{th}$), and Costa Rica (54$^{th}$) [6]. More concerning, however, are the underlying indicators that reveal the depth of the country's innovation deficit. Investment in research and development (R&D) as a percentage of GDP, the fundamental metric of a nation's commitment to knowledge production, has remained stagnant in Colombia at approximately 0.28% during the period 2018–2023 [7], placing the country among the lowest performers within the Organization for Economic Cooperation and Development. This figure stands in stark contrast to the OECD average of 2.7% and to regional leaders such as Brazil (1.2%) and Argentina (0.49%) [8].

These disparities reflect not only historical patterns of uneven development but also the systematic failure of national policies to effectively promote regional convergence in innovation capabilities, a stated objective of CONPES 4069 that remains largely aspirational. The human capital dimension reveals equally concerning patterns. Colombia produces approximately 13 PhDs per million inhabitants annually, a rate substantially below the Latin American average of 23 and dramatically distant from OECD standards of 230 per million [9, 10]. Furthermore, the country's scientific production, while growing in absolute terms, remains modest in comparative perspective, with 0.29% of global scientific publications originating from Colombian institutions, a figure that has shown minimal growth over the past decade [11].

The post-pandemic period 2021–2024 has seen a deterioration in the institutional and financial conditions of Colombia's STI system, creating a critical conjuncture that threatens to reverse the modest gains achieved over previous decades. The most visible manifestation of this crisis is the dramatic fiscal compression experienced by Minciencias, the main entity formally charged with STI governance. The 2024 national budget allocated to the sector represented the lowest proportion of total government expenditure since the institution's elevation to ministerial status in 2019 [12]. In nominal terms, the ministry's operating budget declined by 18% in real terms between 2022 and 2024, even as inflation eroded the purchasing power of remaining allocations [13]. This contraction has occurred precisely when CONPES 4069 mandated increased investment trajectories, creating an insurmountable gap between policy commitments and fiscal realities.

The implications of this budgetary position extend far beyond ministerial operations. The Sistema General de Regalías (SGR), historically a complementary public source of STI financing derived from extractive industry revenues, has

experienced parallel contractions due to volatile commodity prices and shifting priorities in resource allocation [14], the aggregate national investment in STI activities has declined rather than advanced toward the CONPES 4069 targets, with preliminary estimates for 2023 indicating a decrease to 0.25% of GDP, the lowest level registered in the past fifteen years [7].

Beyond fiscal cuts, Minciencias has experienced institutional turbulence characterized by frequent leadership changes, internal restructuring processes, and public controversies that have undermined its technical capacity and political authority. The ministry has operated under four different transitions accompanied by strategic reorientations and administrative disruptions that have prevented the consolidation of coherent policy trajectories [15, 16]. This instability has generated what organizational theorists' term "institutional entropy", a progressive loss of organizational memory, strategic focus, and implementation capacity that cannot be remedied through budget increases alone. The governance established by previous administrations, including coordination mechanisms with regional governments, sectoral entities, and the private sector, has substantially deteriorated.

Perhaps the significant dimension of Colombia's current STI crisis is the disconnection between existing programmatic initiatives and the strategic framework established in CONPES 4069. Despite this comprehensive framework articulating seven strategic lines of action [5], empirical evidence suggests systematic implementation failures. The most recent evaluations indicate that fewer than 15% of the specific actions stipulated in CONPES 4069 have been initiated, and only 3% have achieved their intermediate milestones [17]. More problematically, current ministerial programs demonstrate limited alignment with CONPES priorities, instead reflecting reactive responses to emerging technologies without strategic integration into broader capacity-building efforts [18]. This disconnection extends to the territorial dimension. CONPES 4069 explicitly emphasized the need to strengthen regional innovation systems and reduce territorial disparities through coordinated interventions, including the development and consolidation of STPs. However, current programs lack systematic regional distribution mechanisms, continue to concentrate resources in already-developed urban centers, and have failed to establish the governance structures necessary for effective regional innovation policy [19]. The result is an abandonment of the territorial equity agenda, perpetuating rather than ameliorating Colombia's pronounced regional imbalances in innovation capacity.

STPs represent a transformative instrument for constructing regional innovation cultures and capabilities. International experience, such as IASP, demonstrates that well-designed and adequately supported STPs can serve as cores for clustering knowledge-intensive activities, facilitating university-industry collaboration, attracting high-quality human capital, and generating demonstration effects that progressively transform regional economic structures [20–22]. Yet Colombia's trajectory in developing this critical infrastructure reveals the depth of institutional challenges facing the national STI system. The first recognized STP was "TECNICAFÉ", which was a very important case for R&D projects and articulation for the coffee industry. At the moment, there is only one STP recognized by Minciencias, "Parque Tecnológico Guatiguará" in Santander, which has received technical assistance from international cooperation with KOICA, developing projects for its region [23]. This accomplishment contrasts with the infrastructure development goals articulated in CONPES 4069 and highlights the implementation gap between public policy and territorial implementations.

The case of Parque Tecnológico Guatiguará, while representing an important pioneering effort, underscores the complexities of establishing STPs in contexts characterized by institutional fragility and resource constraints. Located in the Santander department, a region with limited scientific capacity concentrated in its universities and research centers, the park emerged from sustained regional articulation efforts among academia, local government, and private sector actors [24]. Yet, even this successful case faces challenges related to financial sustainability, alignment with national policy frameworks, and effectiveness in catalyzing broader regional innovation culture transformation. The absence of additional recognized STPs across Colombia's remaining 32 departments, many of which possess comparable or greater scientific capacity than Santander, reveals systematic barriers to infrastructure development that transcend regional conditions and point to weaknesses in national STI governance and support mechanisms. The question emerges: Can sub-regions develop robust innovation ecosystems in the absence of STPs serving as physical and institutional anchors for university-industry-government collaboration for STI capabilities?

Specifically, this study aims to point out the territo-

rial distribution of scientific-technological capabilities and institutional infrastructure across Colombian departments, identifying patterns of concentration, articulation gaps, and potential opportunities for STP development. Through systematic documentary analysis triangulating official administrative databases with independent policy assessments, this research seeks to generate empirical evidence regarding regional disparities in innovation capacity and the structural necessity for territorial instruments capable of integrating dispersed actors into functional ecosystems.

This research addresses a gap in both academic literature and STI public policy regarding regional innovation in contexts characterized by institutional fragility and conjuncture [4, 9, 25]. While scholarship exists on STPs in developed economies and in emerging economies with sustained innovation policy commitments [26–28], less attention has been directed toward cases where infrastructure development itself becomes nearly impossible despite recognized necessity, such as the current Colombian situation. From an academic perspective, this investigation contributes to institutional theory's application to innovation studies by examining how national-level institutional failures constrain sub-national capacity to construct functional innovation ecosystems.

From a practical policy perspective, this research offers urgently needed empirical evidence for addressing Colombia's STI crisis. As the country approaches the mid-point of the CONPES 4069 implementation period, up to 2031, with minimal progress on stated objectives, rigorous assessment of what structural conditions actually exist becomes essential for the following years of implementation. By documenting territorial patterns of scientific capacity, institutional infrastructure presence and absence, and articulation gaps, this study informs more realistic policy designs that acknowledge where STPs could strategically contribute to regional innovation ecosystem development, which territories present priority opportunities and contexts of inequity [29], and what enabling conditions must be addressed for successful implementation.

The structure of this paper begins by presenting the problem and its relevance, followed by a description of the research methodology applied, and then, it develops the theoretical foundations that guide the study, including perspectives from regional innovation systems, territorial development, institutional theory, and the conceptualization of STPs. After the theoretical framework, the paper presents the research findings, which are subsequently analyzed in the discussion section. The conclusions summarize the key findings and implications for future research and practice.

## 2. Materials and Methods

This research employs an exploratory-descriptive design with a qualitative approach based on documentary analysis and data triangulation [30]. Given the nature of the research object and the absence of comprehensive primary data on regional STI infrastructure in Colombia, the study aims to provide a first systematic approximation to the territorial distribution of scientific-technological capabilities and their relationship with STPs. The research adopts a cross-sectional design using data from 2023–2025, with Colombian departments (n = 33) as the primary territorial unit of analysis.

Three documentary sources were utilized for data triangulation [31]. First, the current academic literature provides a scope for the analysis. Second, the institutional database of recognized actors in the National Science, Technology and Innovation System (SNCTI) from Minciencias, with a data cut-off of September 2025, identified STP, technological development centers, research centers, business incubators, corporate R&D units, and technology appropriation centers across the country. Third, the National Competitiveness Report 2024–2025 from the Private Competitiveness Council provided contextual information on regional innovation capabilities and policy recommendations [32]. The selection of these three sources responds to the triangulation principle of combining official administrative data (sources 2 and 3) with the academic review (source 3) to enhance the validity and credibility of findings [33–36].

Two analytical constructs were operationalized through documentary evidence. The first construct, territorial concentration of STI capabilities, examines the degree of geographic inequality in the distribution of scientific-technological institutional assets across Colombian departments through the interpretation of research group distribution patterns, concentration of scientific excellence in specific territories, and relative scientific density normalized by population. The second construct, institutional STI infrastructure, captures the presence and diversity of specialized organizations performing science, technology, and innovation activities in each territory, particularly those fulfilling intermediation

and ecosystem articulation functions, assessed through documentation of recognized STPs, diversity of STI actor types present, and institutional density per department.

Departments were categorized according to their relative positioning in terms of (i) concentration of scientific-technological capabilities and (ii) endowment of institutional STI infrastructure. This study employed a qualitative approach using data from triangulated documentary evidence. This allowed the identification of four territorial profiles (Tier) reflecting different configurations of scientific capacity and institutional infrastructure. The specific allocation of departments to each tier, as well as their empirical characteristics, is presented and discussed in the following sections.

The analytical process included three sequential moments. First, national-level characterization established the overall panorama of STI capabilities through thematic analysis of documentary evidence and pattern identification across sources. Second, territorial comparative analysis identified concentration patterns and regional gaps through geographic interpretation of data distribution, departmental classification based on two dimensions (STI capability concentration and institutional infrastructure endowment), and construction of a typology with four territorial profiles. Third, gap identification determined departments with scientific critical mass and consolidated university research but lacking STPs, through triangulation of quantitative indicators from administrative databases with qualitative assessments from the Competitiveness Report regarding university-enterprise-state articulation weaknesses.

The triangulation process, while strengthening validity through multiple sources, remains limited to secondary documentary evidence without primary data generation [30–34]. Consequently, findings should be interpreted as exploratory, serving to identify patterns and generate hypotheses for future research rather than prescribing specific policies [35–37]. Data management employed Excel for systematization, and content analysis matrices for triangulation.

# 3. Theoretical Framework

## 3.1. Regional Innovation Systems and Territorial Development

The regional innovation system approach provides the primary conceptual lens for examining how STPs contribute to territorial development [38]. This perspective, originating in the broader national innovation literature [39], emphasizes that innovation emerges from interactive learning processes among heterogeneous actors embedded in specific geographic and institutional contexts [2]. Regional innovation systems comprise the productive structure (firms, sectors, industrial networks), the knowledge infrastructure (universities, research centers, technology transfer mechanisms), and the governance dimension (policy frameworks, support institutions, coordination mechanisms) operating within a bounded territory [40, 41].

STPs theoretically function as "nodes of interaction" within regional innovation systems, providing physical and institutional spaces where universities, research centers, innovative firms, and support organizations converge [42, 43]. The critical theoretical proposition is that geographic proximity facilitates knowledge spillovers, reduces transaction costs for collaboration, enables face-to-face interaction crucial for tacit knowledge transfer, and generates agglomeration economies that enhance innovative capacity [20, 27]. However, empirical evidence demonstrates that proximity alone proves insufficient; the conversion of spatial concentration into functional innovation ecosystems requires active intermediation, trust-building mechanisms, and institutional frameworks that incentivize collaboration [44, 45].

The regional context shapes STP effectiveness. Poonjan and Tanner [46] identify five critical contextual dimensions: a) the presence and quality of universities and research institutes; b) the structure and sophistication of regional industry; c) institutional environments, including intellectual property protection and regulatory frameworks; d) availability of financial resources and venture capital; d) and urbanization levels affecting access to skilled labor and infrastructure. Regions deficient in these foundational elements face substantially greater challenges in establishing functional STPs, suggesting that parks cannot simply be "parachuted" into unprepared territories [47, 48]. This contextual sensitivity becomes particular in developing country contexts where institutional voids, weak property rights enforcement, limited venture capital, and fragmented innovation actors characterize many regions [49].

## 3.2. Science and Technology Parks Conceptualization

STPs are specialized spatial concentrations of knowledge-intensive activities characterized by formal link-

ages with universities or research institutions, deliberate strategies to promote technology transfer and innovation, and provision of business support services to tenant firms [50]. The International Association of Science Parks and Areas of Innovation (IASP) defines STPs as organizations managed by specialized professionals whose fundamental mission is to increase the wealth of communities by promoting an innovation culture and the competitiveness of associated companies and knowledge-based institutions [51]. This definition emphasizes not merely physical infrastructure but active management functions and explicit development objectives.

The literature distinguishes several STP models reflecting different strategic orientations and evolutionary stages [52–55]. Research parks focus primarily on hosting R&D activities with strong university connections but with limited commercialization emphasis. Technology parks combine R&D facilities with manufacturing capabilities and business incubation services. Innovation districts represent more recent urban-integrated models emphasizing dense interaction, mixed-use development, and are embedded within broader metropolitan innovation ecosystems [55–59]. Despite typological variations, effective STPs share common functions:

a. Facilitating university-industry knowledge transfer;
b. Providing specialized infrastructure and services;
c. Attracting and retaining innovative firms;
d. Generating spin-offs from research institutions;
e. Serving as policy instruments for regional development [60–62].

The quadruple helix model provides crucial theoretical grounding for understanding STPs as instruments of innovation policy [4, 25, 63–65]. This framework conceptualizes innovation as emerging from overlapping relationships among the institutional spheres: universities generating knowledge and human capital, industry transforming knowledge into commercial products and services, and government establishing framework conditions and providing resources [4, 66–68]. The model postulates that economic development in knowledge-based economies requires not merely the presence of these actors but their active collaboration through shared spaces, hybrid organizations, and recursive interactions that blur traditional institutional boundaries, where STPs become important [63, 69–73].

The literature on STP economic impacts reveals complex and contested findings. Proponents argue that well-functioning parks generate multiple development benefits: stimulating regional GDP growth through knowledge-intensive firm clustering [28, 38, 74, 75], creating high-quality employment particularly for skilled workers [72], attracting foreign direct investment and venture capital [73], facilitating technology transfer and social appropriation of academic research [22], fostering entrepreneurship through incubation services and demonstration effects [74], and contributing to economic diversification away from traditional sectors [75]. Systematic reviews identify positive correlations between STP activity and various performance metrics, including firm innovation output, employment growth, and regional competitiveness indicators [76, 77].

However, critical scholarship challenges overly optimistic assessments and highlights substantial heterogeneity in outcomes [78, 79]. Luger and Goldstein's influential study of U.S. research parks found limited evidence of significant regional economic impacts, with older established parks capturing most benefits while newer initiatives showed minimal effects [80]. Subsequent research confirms that STP impacts vary dramatically based on: regional context and pre-existing innovation capacity [46], quality of park management and services provided [81], selectivity in tenant admission versus open access models [82], strength of university linkages and research quality [83], and broader policy environments and public investment levels [84, 85].

Particularly relevant for the Colombian context, Arauzo-Carod et al. [86] demonstrate that STPs may generate heterogeneous effects across firm types, benefiting high-growth companies while potentially harming low-growth firms through resource diversion or unrealistic growth pressures. This finding suggests that parks in regions with predominantly traditional or low-technology enterprises may not achieve anticipated development impacts. Moreover, Zhu et al. [61] document how institutional obstacles, including weak intellectual property protection, insufficient funding, and fragmented governance, undermine STP effectiveness in emerging markets, causing parks to adopt short-term survival strategies rather than long-term ecosystem building efforts.

Critics further warn against viewing STPs as solutions to regional development challenges [87, 88]. Amirahmadi and Saff [89] emphasize that successful parks require

substantial state support, proximity to research universities, adequate infrastructure, and cultural conditions favoring entrepreneurship—prerequisites that are absent in many regions where parks are promoted. Goldstein and Luger[47] argue that park impacts depend fundamentally on "input elements" including quality of anchor institutions, human capital availability, and regional economic structure, cautioning against unrealistic expectations in less favorable contexts. These critical perspectives suggest that the Colombian government's limited capacity to establish even a single recognized STP beyond Guatiguará may reflect not merely policy failures but rather fundamental challenges in assembling the contextual preconditions for functional parks.

The territorial dimension of innovation policy provides essential framing for understanding STPs within broader regional development strategies[90, 91]. Place-based approaches recognize that innovation capabilities are unevenly distributed across territories and that generic "one-size-fits-all" policies often fail to account for local specificities, path dependencies, and contextual constraints[92–95]. This perspective emphasizes the need for territorially differentiated interventions that build on regional assets, address specific bottlenecks, and adapt to local absorptive capacities[96–100]. STPs, from this viewpoint, represent place-based instruments potentially tailored to regional characteristics, though their design and implementation must reflect territorial realities[101, 102].

### 3.3. Institutional Theory and Policy Implementation

Institutional theory provides analytical tools for understanding why ambitious policy frameworks like CONPES 4069 fail to translate into effective implementation[103, 104]. This emphasizes that organizational behavior and policy outcomes depend on formal rules, resource availability, informal norms, taken-for-granted assumptions, cognitive frameworks, and power relationships that structure action[105]. Policy implementation constitutes an institutionally embedded process where formal policy intentions encounter existing institutional arrangements, actor interests, and path-dependent practices that enable, constrain, or transform intended outcomes[106].

The concept of "institutional voids" proves particularly relevant for understanding STP development challenges in emerging economies[107]. These voids—gaps in institutional infrastructure, including weak property rights enforcement, underdeveloped capital markets, limited managerial capacity, and fragmented regulatory frameworks—create coordination problems and increase transaction costs for innovation activities[108]. STPs theoretically help fill institutional voids by providing localized governance structures, specialized services compensating for market failures, and trusted intermediaries reducing information asymmetries[20]. However, parks themselves depend on broader institutional contexts for effectiveness; severe institutional deficiencies may prevent parks from fulfilling gap-filling functions[109].

Colombia's current STI crisis exemplifies profound institutional challenges. Frequent ministerial turnover generates "institutional entropy"—loss of organizational memory, strategic coherence, and implementation capacity[110]. Disconnection between CONPES 4069 strategic framework and actual programs reflects what implementation scholars term "symbolic adoption," where policies are formally endorsed but lack genuine commitment or capacity for execution[111]. Governance fragmentation, with uncoordinated initiatives across governmental levels and weak public-private collaboration mechanisms, undermines the systemic coherence essential for innovation ecosystem development[112]. These institutional problems suggest that establishing effective STPs requires specific interventions but comprehensive strengthening of the broader governance architecture for innovation policy[80, 113, 114], a prerequisite currently absent in Colombia.

## 4. Research Findings: The Necessity of STP for Sub-Regional Innovation Ecosystem

The analytical process reveals a call for STPs as infrastructure for Colombia's regional innovation development. This necessity emerges not from theoretical postulates but from concrete structural conditions documented in this investigation: acute territorial concentration of STI capabilities, profound institutional infrastructure deficits in most departments, and systematic articulation gaps preventing the emergence of functional innovation ecosystems outside established urban centers. The findings establish that STPs represent policy instruments but critical missing components whose absence fundamentally constrains regional capacity

development across Colombian departments.

The literature on regional innovation systems consistently emphasizes that innovation capabilities cannot be uniformly distributed across territories but rather tend toward spatial concentration driven by agglomeration economies, knowledge spillovers, and cumulative causation processes[115, 116]. However, the degree of concentration documented in Colombia's case substantially exceeds patterns observed even in other Latin American contexts characterized by territorial inequality[117]. This polarization creates what economic geographers' term "capability deserts"—extensive territories lacking the minimum threshold of scientific-technological assets necessary for autonomous innovation ecosystem emergence[118].

## 4.1. Territorial Disparities of STI Capabilities

The convergence of evidence across the three documentary sources—Minciencias' administrative databases, SNCTI institutional records, and independent policy analysis—establishes an unambiguous pattern of extreme territorial concentration in Colombia's scientific-technological capabilities. This triangulated analysis reveals not merely quantitative disparities in resource distribution but also qualitative differences in the nature and depth of innovation ecosystems across Colombian departments, with profound implications for regional development policy and the strategic necessity of place-based infrastructure interventions.

Analysis of Minciencias' GrupLAC database for the 2023 national call demonstrates that 60.5% of Colombia's 7842 recognized research groups are concentrated in four departments: Bogotá-Cundinamarca (38.2%, representing 2996 groups), Antioquia (12.4%, 972 groups), Valle del Cauca (6.3%, 494 groups), and Santander (3.6%, 282 groups) (see **Figure 1**). This pattern of concentration becomes more pronounced when examining research excellence indicators. Groups classified at the highest tier (A1) exhibit 71.3% concentration in these four territories, while A-level groups show 67.8% concentration in the same regions. The remaining 28 Colombian departments collectively account for only 39.5% of recognized research groups, with 14 departments possessing fewer than 100 groups each and five departments (Guainía, Vaupés, Vichada, Guaviare, and Amazonas) registering fewer than 25 groups—figures that place these territories below the critical mass thresholds identified in comparative research on emerging innovation systems[119–121].

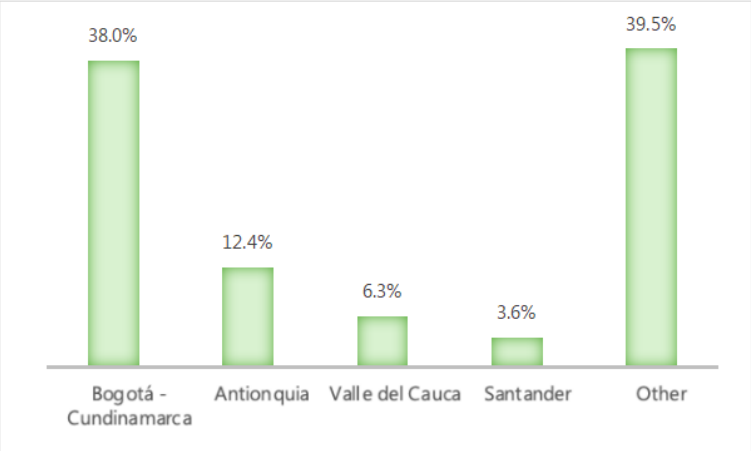


**Figure 1.** Research group concentration.

Source: Author's own elaboration with data from Minciencias, 2023.

The territorial concentration extends across multiple disciplinary domains, though with varying intensities. Analysis by OECD knowledge area classification reveals that engineering and technology research groups concentrate 64.2% in the four leading departments, while natural sciences groups show 58.7% concentration, and medical and health sciences 69.4% concentration in these same territories[9]. Social sciences and humanities exhibit somewhat lower but still substantial concentration at 53.1%, suggesting that territorial inequality affects all dimensions of knowledge production, not

merely technology-oriented fields. This pattern contradicts the territorial differentiation principle articulated in smart specialization literature[122, 123], which posits that regions should develop distinctive profiles based on local assets; instead, Colombia's leading departments dominate across virtually all knowledge domains while peripheral territories remain marginalized across the full spectrum of scientific activities.

Geographic visualization of research group density (groups per 100,000 inhabitants) accentuates territorial disparities. Bogotá exhibits a density of 36.8 research groups per 100,000 inhabitants, followed by Antioquia (14.7), Santander (13.2), and Valle del Cauca (10.8). In contrast, departments such as Córdoba (2.1), Sucre (1.8), Chocó (1.4), and the Amazonian territories collectively (0.9) demonstrate densities more than 20-fold lower than the capital region[124]. These disparities substantially exceed those documented in other Latin American countries with pronounced regional inequalities; Brazil's coefficient of variation for research density across states registers 0.68 compared to Colombia's 0.94, while Mexico's reaches 0.71[125, 126]. This suggests that Colombia's territorial concentration represents an extreme case even within the Latin American context characterized by persistent spatial inequalities.

The SNCTI institutional database corroborates and extends the concentration patterns identified in research group data by documenting parallel disparities in qualified human capital and institutional infrastructure. The database identifies 63.5% of individual researchers recognized under Minciencias' measurement systems as operating within Bogotá-Cundinamarca (42.1%), Antioquia (11.8%), Valle del Cauca (6.4%), and Santander (3.2%). When restricting analysis to researchers with doctoral degrees—the qualification level most strongly associated with frontier research capacity and international collaboration potential[127, 128]—concentration intensifies to 68.7% in these four departments, with Bogotá-Cundinamarca alone accounting for 47.3% of the national doctoral workforce in STI activities.

This human capital concentration reflects and perpetuates institutional capacity disparities. The four leading departments host 71.2% of universities classified as high or very high research institutions under the Colombian higher education quality assurance system, 78.4% of university programs accredited at the doctoral level, and 74.6% of postgraduate programs in STEM fields[108]. Moreover, these territories concentrate 82.1% of university research centers formally recognized by Minciencias and 76.8% of specialized laboratories equipped with advanced scientific instrumentation—infrastructure prerequisites for competitive research in fields such as biotechnology, materials science, and advanced manufacturing[129, 130].

The concentration extends beyond universities to encompass the broader ecosystem of knowledge-producing and intermediating organizations. Analysis of specialized STI actors recognized in the SNCTI database reveals that Bogotá-Cundinamarca, Antioquia, Valle del Cauca, and Santander collectively host most of the consolidated actors in the STI ecosystem.

These institutional infrastructure deficits create what Chaminade and Edquist term "incomplete innovation systems"[93]—territorial contexts where certain critical functions (knowledge production, entrepreneurship support, financing, and intermediation) remain underdeveloped or entirely absent, preventing regions from generating the interactive learning and recombinant innovation that characterize functional ecosystems. The absence of complementary organizations means that whatever research capacity exists in peripheral departments operates in relative isolation, unable to connect with industrial applications, entrepreneurial initiatives, or policy mechanisms that could translate knowledge production into economic and social impact[131–133].

The National Competitiveness Report 2024–2025 provides independent corroboration and contextual interpretation of the concentration patterns documented in administrative databases, while identifying the structural mechanisms perpetuating territorial inequality[32]. The report emphasizes that Colombia's STI ecosystem exhibits a "centro-periferia" dynamic where leading urban centers function as integrated innovation hubs characterized by dense inter-organizational networks, multiple knowledge sources, sophisticated demand, and supportive institutional environments, while peripheral territories remain trapped in low-innovation equilibria characterized by fragmented capabilities, limited absorptive capacity, and weak governance mechanisms.

Particularly significant for the present analysis, the Competitiveness Report documents systematic articulation gaps in regions outside the four leading departments. Through surveys of university researchers, firm managers,

and government officials across Colombian territories, the report identifies that 67% of researchers in peripheral regions report minimal or no collaboration with private sector actors, compared to 31% in Bogotá and 38% in Antioquia [32]. Similarly, 72% of innovative firms in peripheral territories report difficulty accessing relevant university research or technical expertise, versus 43% in leading regions. These articulation deficits reflect not merely geographic distance but institutional voids—the absence of intermediary organizations, trusted brokers, shared spaces, and governance mechanisms that facilitate university-industry-government interaction in more developed innovation systems [58, 107].

The report further documents that those peripheral territories face compounded disadvantages beyond research capacity deficits. These regions typically exhibit:

- Average firm R&D intensity in peripheral departments registers 0.12% of sales compared to 0.47% in leading departments, constraining demand for advanced research and technology services [134].
- New firm formation rates in knowledge-intensive sectors average 2.3 per 100,000 inhabitants in peripheral regions versus 8.7 in leading departments, limiting the spin-off and startup dynamics that animate successful innovation districts [135].
- Venture capital and angel investment concentrate 91% in Bogotá, Medellín, Cali, and Barranquilla, creating financing deserts that prevent promising innovations from scaling even when generated in peripheral territories [136].
- Peripheral regions experience net outmigration of STEM-qualified graduates to leading urban centers at rates exceeding 40% within five years of degree completion, progressively depleting human capital stocks [137].

These contextual constraints underscore the challenge of establishing functional STPs in less-developed territories. However, they also highlight the strategic necessity of place-based interventions specifically designed to address regional deficits. As Tödtling and Trippl argue in their differentiated regional innovation policy framework, "organizationally thin" regions require different policy instruments than "thick" metropolitan innovation systems [91]. While leading regions benefit from policies supporting network densification and internationalization, peripheral territories require foundational interventions that build basic capabilities, create missing linkages, and attract complementary actors—precisely the functions that well-designed STPs can potentially fulfill, provided they receive sustained support and operate within coherent governance frameworks [138, 139].

Triangulation across the three documentary sources enables the construction of a territorial typology classifying Colombian departments according to two dimensions: (1) concentration of STI capabilities (research groups, qualified researchers, institutional infrastructure), and (2) presence of specialized innovation intermediaries (particularly STPs, but also CDTs, incubators, and technology transfer mechanisms). This typology, summarized in **Table 1**, identifies four distinct territorial profiles with differentiated implications for science park strategy:

**Table 1.** Territorial Typology of Colombian Departments: STI Capabilities and Infrastructure.

| Territorial Profile | Departments | STI Capability Characteristics | Infrastructure Endowment | Strategic Implications for STPs |
|---|---|---|---|---|
| Tier 1: Consolidated Innovation Hubs | Bogotá-Cundinamarca, Antioquia | Very high research group density (>2000 groups); doctoral workforce exceeds 1500; multiple research-intensive universities; strong industrial R&D presence. | Multiple CDTs, incubators, technology transfer offices; Guatiguará STP (Santander only); dense intermediary networks. | Limited additional STP necessity; focus on network optimization and internationalization [84, 87]. |
| Tier 2: Emerging Innovation Centers | Valle del Cauca, Santander, Atlántico | Moderate research capacity (200–500 groups); growing doctoral workforce; established research universities; emerging technology sectors. | Some CDTs and incubators; fragmented intermediary ecosystem; weak university-industry linkages. | High STP strategic priority: regions possess minimum critical mass but lack integrative infrastructure; STPs could catalyze ecosystem articulation [134, 140]. |
| Tier 3: Latent Capability Regions | Bolívar, Boyacá, Caldas, Cauca, Córdoba, Magdalena, Meta, Nariño, Norte de Santander, Quindío, Risaralda, Tolima | Limited research capacity (50–150 groups); small doctoral workforce; regional universities with modest research profiles; traditional economic structures. | Minimal or absent specialized infrastructure; few intermediaries; isolated capabilities. | Moderate STP potential: requires substantial complementary investments in research capacity, absorptive capacity building, and governance strengthening before STPs viable [136]. |

**Table 1.** *Cont.*

| Territorial Profile | Departments | STI Capability Characteristics | Infrastructure Endowment | Strategic Implications for STPs |
|---|---|---|---|---|
| Tier 4: Capability Deserts | Amazonas, Arauca, Caquetá, Casanare, Cesar, Chocó, Guainía, Guaviare, Huila, La Guajira, Putumayo, San Andrés, Sucre, Vaupés, Vichada | Very limited research capacity (<50 groups); minimal doctoral presence; weak or absent university research infrastructure; extractive or subsistence economies. | No specialized STI infrastructure; no intermediaries; institutional voids. | Low immediate STP viability: foundational capacity building required before infrastructure interventions; alternative territorial development strategies may prove more appropriate [133, 137]. |

Source: Author's elaboration based on triangulation of Minciencias GrupLAC database (2023), Sncti Institutional Database (2025), and *National Competitiveness Report 2024–2025.*

This typology reveals that strategic opportunities for STP interventions concentrate particularly in Tier 2 territories—departments possessing sufficient research capacity, institutional presence, and economic sophistication to support functional parks but lacking the integrative infrastructure necessary to convert fragmented capabilities into coherent ecosystems. Valle del Cauca, with its 494 research groups, three research-intensive universities (Universidad del Valle, Universidad Icesi, Pontificia Universidad Javeriana Cali), emerging clusters in biotechnology and ICT, and regional government commitment to innovation policy, represents the most compelling case for strategic STP development outside the Bogotá-Antioquia axis [135, 136]. Santander's successful establishment of Parque Tecnológico Guatiguará despite possessing lower absolute research capacity than Valle (282 versus 494 groups) demonstrates that sustained regional articulation and governance can overcome initial disadvantages [24].

The Atlántico department, centered on Barranquilla, presents a similarly promising profile with 167 research groups, strong logistics and port-related industry clusters, regional leadership aspirations evident in its 2032 development plan, and explicit commitment to innovation infrastructure development [137]. However, this department currently lacks any recognized STP or substantial innovation intermediary presence, suggesting significant unrealized potential for place-based intervention. The contrast between Atlántico's capabilities and infrastructure deficit exemplifies the broader pattern documented throughout this analysis: Colombia possesses dispersed territorial capabilities that remain unproductive due to systematic failures in developing the connective tissue—particularly STPs—that functional innovation ecosystems require.

## 4.2. Institutional STI Infrastructure, Deficits and Articulation Gaps

While the previous section established the pronounced territorial concentration of research capabilities, the SNCTI institutional database reveals an equally problematic pattern: profound deficits in specialized infrastructure designed specifically to facilitate university-industry-government collaboration and innovation commercialization. This infrastructure gap manifests most dramatically in the near-complete absence of recognized STPs but extends to multiple categories of intermediary organizations whose presence correlates strongly with regional innovation performance in comparative international research [130, 131, 138].

The most important finding concerns STPs themselves. Despite CONPES 4069's explicit emphasis on developing science and technology parks as strategic instruments for regional innovation system strengthening [5]. The consolidation of the policy instruments or such infrastructure remains limited. There are some initiatives for STP in different regions of Colombia: Parque Tecnológico Guatiguará (Guatiguará Technology Park), Biopacífico (BioPacífico Innovation Hub), Risvalley (Regional Innovation System (RIS) Valley), Parque Tecnológico de Antioquia (Antioquia Technology Park), Parque Tecnológico del Caribe (Caribbean Technology Park), Parque Tecnológico de la Sabana (Sabana Technology Park), Parque Tecnológico de la Umbría (Umbría Technology Park), Tecnoparque SENA (SENA Technology Park), Tecnicafé (Tecnicafé Technology Center) [138–141], but at the moment, only one park has been consolidated and recognized by the National system: Parque Tecnológico Guatiguará in the Santander department (see **Table 2**). This accomplishment stands in stark contrast to the infrastructure densities observed in regional innovation systems that

Colombia ostensibly seeks to emulate. Comparative data from the International Association of Science Parks and Areas of Innovation indicates that countries with populations and GDP levels comparable to Colombia's typically operate between 15 and 35 recognized STPs distributed across multiple regions[132]. Throughout neighboring Latin American territories, Brazil maintains 98 operational science and technology parks across 24 states, with explicit policies promoting geographic distribution to address regional disparities[93, 131, 140]. Mexico operates 52 recognized parks across 28 states, while Chile maintains 11 parks serving a population one-third Colombia's size[140].

**Table 2.** Colombia STP's Initiatives.

| Colombia STPs Initiatives | Current Status |
|---|---|
| Parque Tecnológico Guatiguará (Guatiguará Technology Park) | Accredited by SNCTI |
| Biopacífico (BioPacífico Innovation Hub) | Active (Not accredited) |
| Risvalley (Regional Innovation System (RIS) Valley) | Active (Not accredited) |
| Parque Tecnológico de Antioquia (Antioquia Technology Park) | Not active since 2012 |
| Parque Tecnológico del Caribe (Caribbean Technology Park) | Not active |
| Parque Tecnológico de la Sabana (Sabana Technology Park) | Not active |
| Parque Tecnológico de la Umbría (Umbría Technology Park) | Not active |
| Tecnoparque SENA (SENA Technology Park) | Active (Not accredited) |
| Tecnicafé (Tecnicafé Technology Center) | Active (Not accredited) |

Source: Author's own elaboration.

International evidence demonstrates that functional innovation systems in countries at similar development stages typically maintain STP densities of 0.8 to 1.5 parks per 10 million inhabitants[139, 141]. Applied to Colombia's population of approximately 52 million, this benchmark suggests the country should operate between 4 and 8 strategically distributed STPs to provide adequate territorial coverage and catalyze regional ecosystem development. The reality of a single recognized park represents an infrastructure shortfall of 75–87% relative to international patterns, indicating systematic underinvestment in this critical innovation infrastructure category.

The absence of STPs in territories beyond Santander cannot be attributed solely to insufficient demand or capability prerequisites. Departments such as Valle del Cauca (494 research groups, three research-intensive universities, emerging technology clusters), Atlántico (167 research groups, strong logistics sector, explicit innovation policy commitments), and even Tier 3 territories like Caldas and Risaralda (coffee technology clusters, established regional universities) possess sufficient foundational capabilities to potentially support functional parks[135, 136, 142]. The infrastructure gap thus reflects not natural capability constraints but systematic policy implementation failures and institutional weaknesses that prevent the translation of regional potential into concrete infrastructure development—a pattern consistent with the broader CONPES 4069 implementation crisis documented in Section 1.

The infrastructure deficit extends beyond STPs to encompass the broader ecosystem of specialized organizations performing innovation intermediation functions. The SNCTI database identifies 47 Technological Development Centers (CDTs) nationwide, with 68% (32 institutions) located in the four leading departments, leaving 24 departments without any such institution and only four departments outside the top tier possessing more than two CDTs[135]. CDTs perform critical intermediation functions that markets alone do not adequately provide: applied research services for small and medium enterprises lacking internal R&D capacity, technical assistance and problem-solving support, quality testing and certification services, technology scanning and adaptation, and specialized training programs[143, 144]. Their absence in most Colombian territories creates what Howells terms "intermediation voids"[141, 145]—situations where firms with innovation intentions cannot access the technical expertise and specialized facilities necessary to transform ideas into commercial applications.

Business incubators exhibit similar concentration patterns, with 71% (45 of 63 institutions) operating in the four leading departments[136]. These leave 18 departments entirely without incubation infrastructure and limit most peripheral territories to a single institution—inadequate to serve diverse sectoral needs or generate competitive selection effects that enhance incubation quality. Technology transfer

offices demonstrate even more extreme concentration, with 79% (29 of 37 formally recognized offices) located in institutions within leading departments, directly constraining the ability of peripheral universities to engage productively with regional industry. Corporate R&D centers exhibit 84% concentration in the four leading departments, indicating that industrial research concentrates even more intensely than academic research, reflecting firms' rational location decisions to situate R&D activities proximate to complementary innovation assets disproportionately available in leading urban centers.

The National Competitiveness Report 2024–2025 provides crucial triangulating evidence extending beyond infrastructure deficits to analyze their functional consequences—specifically, systematic articulation gaps preventing productive university-industry-government collaboration even where some capabilities exist[32]. Through surveys of 847 university researchers, 623 firm managers, and 156 government officials across Colombian territories, the report documents that collaboration intensity varies dramatically by region in ways that cannot be explained by capability differences alone.

Colombia's institutional architecture for STI governance includes Departmental Councils of Science, Technology and Innovation (CODECTIs)—collegial bodies established in each of the country's 33 departments to coordinate regional STI policy, facilitate inter-institutional dialogue, and align national STI frameworks with territorial development priorities[146–149]. The SNCTI database documents that 31 departments have formally constituted CODECTIs, with representation typically including departmental government officials, university rectors, business association leaders, and occasionally civil society representatives. These councils theoretically provide governance mechanisms for regional innovation system articulation, addressing coordination failures through regular dialogue, joint priority-setting, and collaborative program design.

However, triangulation with the National Competitiveness Report reveals that CODECTIs face severe operational limitations that constrain their effectiveness as ecosystem orchestrators[32]. First, meeting frequency remains insufficient for sustained coordination: 64% of CODECTIs convene only once or twice annually, with several departments reporting no meetings during 2023–2024 due to leadership transitions or budgetary constraints. Second, CODECTIs lack dedicated budgets or implementing authority, functioning primarily as advisory bodies whose recommendations require separate implementation through member institutions—a structural weakness that transforms potentially strategic platforms into forums for information exchange without decision-making capacity. Third, technical secretariats supporting CODECTI operations remain understaffed or entirely absent in 23 departments, limiting councils' capacity to conduct regional diagnostics, develop evidence-based strategies, or monitor implementation progress[32, 150–153].

Most critically for the present analysis, CODECTIs operate without the physical infrastructure and specialized intermediary organizations necessary to translate coordination agreements into concrete collaborative actions. Regional government officials surveyed in the Competitiveness Report express frustration that CODECTI discussions frequently identify collaboration opportunities—joint research projects, industry problem-solving initiatives, technology demonstration programs—but lack mechanisms for implementation[32]. Universities and firms may agree in principle to collaborate but require neutral spaces for interaction, professional facilitation, shared equipment access, intellectual property negotiation support, and co-financing mechanisms that CODECTIs cannot provide through coordination alone. As one interviewee articulated: "We have excellent dialogue in the CODECTI, but when researchers and companies leave the meeting room, they return to their separate institutions with no bridge connecting them"[32].

This implementation gap underscores the critical distinction between governance mechanisms (CODECTIs) and operational infrastructure (STPs, CDTs, incubators). Governance bodies can identify priorities, convene actors, and legitimate collaboration, but they cannot substitute for the physical platforms, professional intermediation services, and sustained support structures that functional innovation ecosystems require[153, 154]. International evidence demonstrates that effective regional innovation governance combines strategic coordination mechanisms with specialized infrastructure capable of implementing collaborative initiatives—precisely the model exemplified by regions where STPs operate in tandem with regional innovation councils to translate strategic dialogue into operational programs[155, 156].

# 5. Discussion

The convergence of evidence across documentary sources establishes that Colombia's regional innovation challenge stems from capability deficits or governance weaknesses, but from the absence of integrative infrastructure capable of connecting fragmented actors into functional ecosystems. This finding aligns with theoretical perspectives emphasizing that innovation emerges not from individual organizational capabilities but from interactive learning processes among heterogeneous actors embedded in supportive institutional environments.

STPs represent the category of integrative infrastructure that Colombia's regions systematically lack. Drawing on the theoretical frameworks articulated in section 3, STPs perform multiple intermediation functions that isolated universities, firms, or government agencies cannot adequately provide: they reduce physical distance among potential collaborators, enabling the face-to-face interactions that trust-building and tacit knowledge transfer require; they provide institutional platforms where organizations with different logics can engage without favoring one sector's interests; they employ professional managers who translate between academic and business contexts, identify collaboration opportunities, and navigate intellectual property negotiations; and they create shared identities and communities of practice that transform isolated organizations into networks characterized by reciprocity norms and collective problem-solving.

The contrast between Santander's success in establishing Parque Tecnológico Guatiguará and other departments' experiences proves important insights for articulation between public policies and policy instruments. Documentary analysis of Guatiguará's development trajectory reveals sustained regional articulation among Universidad Industrial de Santander, local government, and private sector actors over a 15-year period, supported by leadership, funding from regional, national and international initiatives, and explicit alignment with regional development strategies centered on energy and petrochemical sectors. Critically, Guatiguará's governance structure integrates the departmental CODECTI with the park's operational management, creating institutional mechanisms that translate strategic dialogue into concrete programs, university-industry research projects, startup incubation services, specialized training, and technology demonstration facilities.

This integration distinguishes Guatiguará from territories where CODECTIs operate in isolation from implementation infrastructure. Valle del Cauca, despite possessing superior research capacity to Santander (494 versus 282 groups), has failed to establish a recognized STP, and its CODECTI remains disconnected from the region's universities and technology clusters, a fragmentation reflected in collaboration rates substantially below regional potential. The absence of an integrative platform means that Valle del Cauca's considerable capabilities remain dispersed across institutions that interact episodically rather than systematically, preventing the density of relationships that characterize functional innovation ecosystems.

The findings of this study show implications for international cooperation and global innovation policy learning. Colombia has engaged in international policy articulation processes, including collaboration with the OECD's Committee for Scientific and Technological Policy (CSTP), the International Mission of Experts (Misión Internacional de Sabios), and multiple cooperation agencies that have directly financed actors within the SNCTI. These articulations have contributed to the formulation of STI policy aligned with international standards. However, the evidence presented in this study suggests that policy convergence at the national level has not matched in the development of territorial innovation infrastructure capable of translating global policy learning into glocalized dynamics.

The triangulated evidence establishes that while CODECTIs represent necessary governance mechanisms for regional STI coordination, they prove insufficient without complementary operational infrastructure. STPs fulfill the critical integrative function that governance coordination alone cannot achieve, providing the physical spaces, professional intermediation services, shared resources, and sustained interaction platforms that convert fragmented capabilities into collaborative ecosystems. This finding carries significant implications for Colombia's innovation policy: addressing the country's profound territorial disparities requires not merely activating CODECTIs or exhorting actors to collaborate, but rather investing strategically in the intermediary infrastructure, particularly STPs, that makes collaboration operationally feasible.

# 6. Conclusions

This paper documents the paradox in Colombia's STI system. The triangulated analysis across academic literature, Minciencias databases, and the National Competitiveness Report establishes that Colombia's regional innovation challenge stems from the absence of integrative infrastructure—particularly STPs—capable of connecting fragmented capabilities into functional ecosystems, as evidenced by 67% of peripheral researchers reporting minimal industry collaboration and 72% of firms unable to access university expertise despite CODECTIs' governance efforts.

The findings demonstrate that STPs represent not autonomous solutions but critical missing components whose strategic development in territories possessing latent capabilities (particularly Tier 2 departments like Valle del Cauca, Atlántico, and the consolidated portions of Santander beyond Guatiguará) could catalyze ecosystem articulation, provided such interventions receive sustained policy support, coherent governance frameworks, and alignment with regional specialization strategies.

The research contributes to theoretical debates on regional innovation policy and institutional constraints in developing economies while offering empirical foundations for reorienting Colombia's STI agenda toward addressing the intermediation voids and governance weaknesses that perpetuate territorial inequality, suggesting that effective regional innovation development requires not merely activating coordination mechanisms but investing in the physical platforms, professional intermediation services, and sustained support structures that transform policy aspirations into operational reality across Colombian territories.

Several limitations should be pointed out. The analysis is based exclusively on secondary data sources, reflecting the current absence of primary data on regional STI infrastructure in Colombia; accordingly, the findings should be interpreted as exploratory and analytical rather than prescriptive. In addition, the territorial classification relies on qualitative comparative assessment using relative, theory-informed triangulation, which is suitable for identifying structural patterns and asymmetries but does not permit statistical generalization. Finally, the cross-sectional design captures a specific institutional and policy conjuncture (2023–2025) and therefore does not account for temporal dynamics or longitudinal conclusions. Future research can focus on incorporating primary data collection, longitudinal designs, and interviews to validate the territorial innovation profiles identified.

# Author Contributions

Conceptualization, M.D.H.M. and N.A.L.C.; methodology, M.D.H.M. and M.G.L.M.; validation, N.A.L.C.; formal analysis, M.D.H.M. and M.G.L.M.; investigation, M.D.H.M.; data curation, M.G.L.M. and Y.P.P.Q.; writing—original draft preparation, M.D.H.M.; writing—review and editing, M.G.L.M. and M.D.H.M.; visualization, Y.P.P.Q.; supervision, M.D.H.M.; project administration, M.D.H.M. All authors have read and agreed to the published version of the manuscript.

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# Conflicts of Interest

The authors declare no conflict of interest.

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