Women engineers as territorial integrators: a conceptual framework of territorial articulation capacity for inclusive innovation and human development

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Abstract*– Women remain underrepresented in engineering, while responses emphasize access, retention, and numerical participation. Yet representation alone cannot explain the institutional and relational conditions through which women's professional expertise supports territorial transformation. This conceptual article develops an integrative framework linking women engineers situated agency to inclusive innovation and human development. Based on an integrative review of gender and engineering, regional innovation systems, territorial governance, inclusive innovation, knowledge co-production, and international cooperation, it introduces Territorial Articulation Capacity (TAC). TAC is an emergent relational capability that converts dispersed technical, institutional, community, and financial resources into coordinated action. It develops through five interdependent practices: territorial sensing and actor mapping, knowledge translation, network convening and coordination, resource and legitimacy mobilization, and institutionalization and collective learning. Structural, intersectional, and institutional conditions enable or constrain these practices. International cooperation acts as a conditional catalyst dependent on local ownership, equitable partnership governance, and mutual learning. TAC mediates between situated agency and territorial outcomes, including participatory problem definition, context-sensitive solutions, fairer benefit distribution, expanded capabilities, professional learning, and sustainable livelihoods. The BIOINTEGRA Scientific Lexicon illustrates the framework without empirically validating it. The article advances a relational, institutionally grounded explanation of women engineers' contributions to inclusive territorial transformation.

I. INTRODUCTION

Women's participation in science, technology, engineering, and mathematics (STEM) remains constrained by stereotypes, family expectations, limited access to role models, and educational environments that shape career choices from an early age. These barriers persist after entry into higher education through disciplinary segregation, stereotype threat, and attrition across educational and professional pathways. Women's participation remains below 30% in several engineering and technology fields, showing that expanded access to higher education has not eliminated inequalities among fields of knowledge [1]. The Colombian case reflects the same pattern. Between 2001 and 2018, the gender gap among engineering graduates remained relatively stable, and women represented only 36.3% of graduates in 2018. Participation also varied markedly by discipline: although environmental, biomedical, and chemical engineering showed comparatively higher female participation, women accounted for less than 20% of graduates in electrical, electronic, and mechanical engineering [2] .

Inequality becomes more pronounced in transitions from higher education to research, scientific leadership, and decision-making. In Colombia, women receive more than half of undergraduate degrees in the natural sciences but represent less than 40% of researchers, obtain less than 30% of research grants, and occupy approximately one quarter of senior academic positions [3] . Across Latin America, women participate actively in regional scholarly circuits and research locally relevant problems, yet their work tends to receive less recognition in global academic circuits [4] . Numerical participation is therefore necessary but insufficient for assessing gender equality or understanding women's contribution to engineering, innovation, and territorial development. Their recognition, authority, network access, and capacity to influence institutions must also be considered.

Moving from representation to agency requires examining women engineers as professionals who construct trajectories, mobilize knowledge, and respond to changing organizational conditions. Career persistence in engineering depends partly on concern, control, curiosity, and confidence, but the relevance of these resources' changes across educational, early-career, and leadership stages. Their exercise is also conditioned by institutional cultures, gender norms, professional opportunities, and access to positions of authority [5] . Agency should consequently be treated as situated and relational rather than as an exclusively individual attribute. Professional engineering organizations can strengthen this agency by providing expressive social capital—belonging, emotional support, role models—and instrumental social capital, including mentoring,

professional knowledge, networks, and career-related [6] territorial processes.

Latin American initiatives such as the Matilda Latin American Open Chair for Women in Engineering illustrate how agency can be supported through collective and interinstitutional structures. The initiative connects universities, professionals, researchers, mentors, and students through conferences, publications, mentoring, expert panels, and public communication to increase women's visibility, development, and retention throughout STEM careers [7]. This article extends that network-based perspective. It proposes that, under enabling institutional conditions, women engineers may contribute not only to professional advancement but also to connecting technical knowledge, organizations, communities, and development resources. Territorial articulation is treated as a contingent professional function, not as an inherent characteristic of women or an automatic consequence of gender.

Inclusive innovation provides a basis for conceptualizing this broader contribution. It redirects attention from generating technological solutions to the processes through which historically excluded actors participate in problem definition, knowledge production, decision-making, and benefit distribution. Studies of agricultural innovation systems in the Global South show that social learning, social capital, collective cognition, and consensus formation can produce technical, organizational, and institutional change [8] . Such processes are territorially embedded because opportunities for participation and knowledge mobilization depend on regional institutions, socioeconomic hierarchies, and power relations. The hierarchical regional innovation system perspective demonstrates that these conditions may either enable or constrain inclusive eco-innovation [9]. Territorial development therefore depends not only on available technology or expertise but also on the capacity of universities, firms, public institutions, communities, and other actors to coordinate resources and negotiate collective priorities.

Despite these connections, the relevant literature remains analytically fragmented. Gender and STEM research mainly examines educational choices, stereotypes, segregation, professional trajectories, and institutional interventions addressing underrepresentation [10]. In parallel, regional innovation scholarship examines how structures, networks, and policies can be reoriented or transformed to address grand societal challenges [11]. Read together, these streams do not adequately explain how women engineers exercise relational agency within territorial innovation systems, which practices enable them to connect dispersed capabilities, or under which conditions such connections become coordinated collective action. This unresolved relationship constitutes the article's scientific gap.

Accordingly, this study asks: How and under what conditions do women engineers contribute to transforming dispersed technical, institutional, community-based, financial, and international-cooperation resources into Territorial Articulation Capacity for inclusive innovation and human development? It develops an integrative conceptual framework positioning women engineers situated agency as the starting point, Territorial Articulation Capacity as the mediating mechanism, and structural, institutional, intersectional, and cooperation conditions as enabling or constraining factors. The framework contributes a relational explanation of women engineers as potential territorial integrators without attributing to them an inherent capacity for cooperation or making their participation solely responsible for institutional transformation.

II. METHODOLOGY

Research Design

This study adopted a qualitative conceptual design supported by a critical integrative literature review. A review can operate as a research methodology when it uses an explicit procedure to identify, organize, evaluate, and synthesize knowledge [12] . An integrative approach was appropriate because the research question connects fields that are usually examined separately: gender and engineering, professional agency, regional innovation systems, territorial governance, inclusive innovation, international cooperation, and human development. Rather than estimating an aggregate effect or mapping publication trends, the review sought to generate a new conceptual explanation by comparing theoretical perspectives, empirical findings, and analytical categories [13]; [14]. The review was also critical: it examined the assumptions, explanatory mechanisms, omissions, and boundaries of each literature stream instead of merely summarizing its findings [15] .

Search Strategy and Evidence Selection

The search covered English- and Spanish-language publications issued from 2015 through 2026. Peer-reviewed studies were identified through Scopus, Web of Science, SciELO, Dimensions, and Redalyc, combining international coverage with the visibility of Latin American scholarship. The search proceeded in two stages. The first combined terms such as "women engineers," "women in engineering," "women in STEM," and "gender gap in engineering" with agency, leadership, professional identity, mentoring, and networks. The second addressed the mechanisms and contexts of the proposed framework through terms including "inclusive innovation," "inclusive bioeconomy," "territorial development," "regional innovation systems," "quadruple helix," "innovation governance," "territorial articulation," "international cooperation," "capacity building," and "human development." Multiple databases, explicit search boundaries, and complementary search clusters were used to improve coverage and transparency [16], [17].

Sources were eligible when they: (a) fell within the specified period; (b) provided peer-reviewed or otherwise authoritative scholarly evidence; (c) directly informed at least one component of the research question; and (d) addressed relevant actors, practices, mechanisms, conditions, barriers, or

development outcomes. Duplicate records, non-academic opinion pieces, tangential mentions of women or innovation, and documents lacking sufficient methodological or bibliographic information were excluded. The reviewed literature was organized into five domains: structural gender gaps and professional trajectories; agency, leadership, and networks; inclusive bioeconomy and territorial transformation; innovation governance and territorial capabilities; and international cooperation, capacity building, and human development. This thematic organization maintained the interdisciplinary scope while connecting evidence selection to the intended conceptual contribution [18] .

Following peer review, a targeted supplementary literature search was conducted to clarify the relationship between TAC and established concepts of boundary spanning, knowledge brokering, and innovation intermediation, and to strengthen the framework's grounding in Latin American innovation systems. The supplementary sources were selected for their conceptual relevance, geographical context, and contribution to explaining the institutional and relational mechanisms proposed in the framework. These additions informed the revised theoretical discussion and contextual interpretation without constituting empirical validation of TAC.

Evidence Analysis Model Construction

Each source was incorporated into a conceptual evidence matrix containing bibliographic information and DOI, geographical and institutional context, phenomenon and unit of analysis, research design, main findings, mechanisms, enabling or constraining conditions, limitations, research gaps, and relevance to the research question. Such matrices support comparison among heterogeneous studies while making the extraction process visible [19] . Evidence was analyzed through hybrid deductive–abductive coding. Deductive coding assigned sources to the five domains, while additional codes captured recurring practices, relational roles, resources, barriers, institutional conditions, and outcomes. Cross-domain comparison then identified convergence, contradiction, overlap, and boundary conditions. Abductive reasoning was used when recurrent patterns could not be adequately explained within a single literature stream, enabling alternative theoretical connections grounded in the reviewed evidence [20] .

Model construction progressively connected four components: antecedent resources and enabling or constraining conditions; women engineers situated agency; Territorial Articulation Capacity as an emergent mediating mechanism; and inclusive innovation and human development outcomes. International cooperation was positioned as a conditional catalyst that may expand knowledge, networks, financing, legitimacy, and institutional opportunities, but not as an independent guarantee of development. Every proposed relationship had to integrate concepts from previously disconnected research streams and explain how and under what conditions an expected outcome could occur, consistent with theory-synthesis and model-building principles [21]. BIOINTEGRA was used only to illustrate the framework's analytical applicability, not to validate causal relationships. Finally, gender was never coded as an intrinsic source of collaborative or articulating ability; contributions were attributed to identifiable knowledge, experience, network position, resources, authority, and institutional arrangements to avoid essentialist assumptions.

III. Conceptual Synthesis and Discussion

From Structural Barriers to Situated Agency

The synthesis indicates that women's underrepresentation in engineering is reproduced through cumulative and intersecting mechanisms rather than a single barrier at entry. Stereotyping, differential treatment, exclusion from teamwork, restricted access to influential relationships, and organizational cultures structured around masculine norms affect belonging, recognition, and professional confidence. These effects vary because gender interacts with race, ethnicity, socioeconomic position, and other social locations; women's professional and leadership agency must therefore be examined intersectionally and across career stages [22],[23]. STEM inequalities are consequently constitutive of situated agency rather than external background variables

Agency nevertheless develops relationally. Families, teachers, mentors, colleagues, and professional organizations can validate technical abilities and provide knowledge, institutional guidance, contacts, and strategies for navigating discriminatory environments. Networks thus operate as infrastructures through which individual capabilities become recognized and actionable [24]. Cross-domain comparison reveals a transition from protective networks, which support persistence and belonging, to generative networks, which additionally foster engineering identity, leadership, collaboration, and resource mobilization. Student organizations can provide spaces in which women consolidate their engineering identities [25]. but this literature rarely examines whether such resources enable system-level coordination. The unresolved transition from professional support to territorial action provides the starting point for conceptualizing women engineers situated agency.

Situated agency does not imply that all women engineers encounter identical constraints or possess equivalent opportunities. Women may enter engineering institutions while informal networks, evaluation criteria, leadership structures, and decision-making practices continue to distribute influence unequally [26]. Professional success may also coexist with racialized and gender pressures, restricted recognition, stereotype management, and substantial emotional and professional costs [27]. Because gender bias persists even where diversity initiatives expand participation [28], numerical inclusion cannot be equated with effective authority. The analytically relevant question is whether women engineers can mobilize knowledge and relationships to influence collective territorial decisions

Territorial Articulation Capacity as a Relational Mechanism

Territorial innovation constraints arise not only from resource scarcity but also from the fragmentation of existing assets. In remote, rural, and less-favoured regions, dispersed firms, limited knowledge-intensive organizations, weak public capabilities, and the importance of community actors make Quadruple Helix arrangements more suitable than models restricted to university–industry–government relations [29] . Yet the coexistence of multiple actors does not produce coordination automatically. Living labs show that intermediaries can orchestrate experimentation and stakeholder engagement, but their integration into regional ecosystems depends on policy support, funding, strategic alignment, and formal collaboration [30]. The key distinction is therefore between possessing a network and being able to activate it around a shared territorial problem.

Professionals may influence regional transformation when they extend their activities beyond conventional knowledge-production roles. Scientists involved in Lower Austria's transition toward a biomass bioeconomy modified, mobilized, and recombined regional assets, shaping the direction of the emerging development path [31]. Engineering academics working toward sustainable human development similarly combine interdisciplinary profiles, sustainability principles, social outreach, and connector roles across university boundaries [32]. Without assuming equivalence among professions or territories, these findings support the inference that women engineers may exercise system-level agency when technical credibility is combined with boundary-spanning positions, institutional legitimacy, heterogeneous networks, resources, and decision-making authority.

From these mechanisms, this study defines Territorial Articulation Capacity (TAC) as an emergent, higher-order relational capability through which territorial actors convert dispersed technical, institutional, community-based, and financial resources into coordinated collective action. TAC develops through five interdependent practices: (1) territorial sensing and actor mapping; (2) knowledge translation across technical, institutional, productive, and community vocabularies; (3) network convening and coordination; (4) resource and legitimacy mobilization; and (5) institutionalization and collective learning. It is neither an individual competence nor a synonym for networking. It emerges collectively when repeated articulation practices become embedded in territorial relationships and institutions.

TAC therefore provides a micro–meso bridge between professional agency and territorial innovation-system transformation. Inclusive innovation research emphasizes context-sensitive processes connecting knowledge, needs, actors, and institutions [8], whereas economic-geography research highlights how territorial hierarchies and power relations condition inclusion and sustainability [9]. Regional innovation scholarship also calls for explanations that move beyond firm-centred models and incorporate heterogeneous actors, institutional change, and collective directionality [11]. TAC advances these perspectives by specifying the relational mechanism through which available resources become jointly usable, without assuming that professional participation directly produces territorial transformation.

Latin American Evidence and Territorial Context

Evidence from Latin America provides a context-sensitive basis for examining the institutional and relational conditions under which TAC may emerge. Research on the regional innovation system of Risaralda, Colombia, identifies governance and institutional failures alongside dispersed stakeholder networks, illustrating how the availability of innovation actors does not necessarily translate into effective collective coordination [33]. An exploratory study conducted in Cumbal, Nariño, further examines institutional entrepreneurship as a mechanism for fostering inclusive innovation and locally situated transformation processes [34]. These findings provide regional evidence of the relevance of institutional arrangements, locally situated agency, and the coordination of heterogeneous resources.

The relationship between participation, knowledge circulation, and territorial innovation is further illustrated by research on a rural innovation laboratory in Nocaima, Colombia, which examines the social appropriation of knowledge and efforts to address gender inequalities in rural settings [35]. In Costa Rica, an analysis of the pineapple value network identifies weak network cohesion, limited information flows, and concentrated power as barriers to collective innovation within the circular bioeconomy [36]. Together, these studies reinforce the relevance of examining how institutional recognition, relational access, knowledge mobilization, and decision-making authority condition territorial innovation processes. They do not provide direct empirical validation of TAC or demonstrate that women engineers have already enacted the proposed territorial-integrator role. Rather, they establish a regional foundation for investigating the conditions under which situated professional agency may contribute to coordinated collective action and inclusive territorial transformation.

Conceptual Distinction from Boundary Spanning and Knowledge Brokering

TAC builds on, rather than replaces, established perspectives on boundary spanning, knowledge brokering, and innovation intermediation. Boundary spanners connect organizational and institutional domains, whereas knowledge brokers facilitate the acquisition, circulation, translation, and integration of knowledge across professional and organizational boundaries [37]. Innovation intermediaries may also perform knowledge-transfer, orchestration, and value-generation functions at different levels of innovation systems [38]. These constructs therefore share important mechanisms

with TAC, particularly the connection of heterogeneous actors, knowledge mobilization, and network coordination.

The proposed contribution of TAC does not lie in claiming novelty for these individual practices. Rather, TAC conceptualizes their sustained and interdependent enactment as an emergent territorial capability. Its five practices integrate territorial sensing, knowledge translation, network coordination, resource and legitimacy mobilization, and institutionalization of collective learning. Unlike an analysis restricted to the activities of an individual intermediary, TAC examines how these practices may become embedded in collective relationships and institutional arrangements that enable coordinated responses to territorially defined problems. Its analytical focus also incorporates the structural and intersectional conditions affecting women engineers' situated agency and the contingent relationship between collective articulation, inclusive innovation, and human development. Whether TAC constitutes an empirically distinguishable capability remains a question for future research.

Gendered, Institutional, and International-Cooperation Conditions

Research connecting gender and bioeconomy remains fragmented but increasingly recognizes women as actors in bioeconomic transitions and identifies gender equality, social impacts, territorial inequalities, and gender-sensitive frameworks as central concerns [39]. Evidence from circular-bioeconomy firms further shows that women managers' influence on sustainable and gender-inclusive practices depends on organizational position, value alignment, available resources, and the capacity to challenge established constraints. Transformative perspectives are neither exclusive to nor automatically held by women [40].

Accordingly, describing women engineers as territorial integrators neither essentializes women as naturally collaborative nor transfers responsibility for institutional transformation onto them. This role becomes possible when institutional conditions allow situated agency to activate the five articulation practices. Innovation should then be assessed not only through novelty and economic performance but also through participation, inequality reduction, and expanded individual and collective capabilities [41]. Recognition must therefore involve more than visibility: it must provide the legitimacy and authority required to convene heterogeneous actors, negotiate priorities, mobilize resources, and influence decisions.

International cooperation enters this relationship as a conditional catalyst. It may expand access to specialized knowledge, financing, technological infrastructure, international networks, and legitimacy, but conventional technology-transfer models often fail to respond to locally defined needs. Innovation cooperation offers a more suitable approach because it emphasizes equitable partnerships, interaction between domestic and international actors, and local capability development rather than one-directional donor–recipient relationships [42]. Cooperation thus contributes to TAC only when external resources are connected to territorial problems, relationships, and priorities.

Partnership governance determines whether this contribution strengthens autonomy or reproduces dependency. International collaborations may develop individual, organizational, and systemic capabilities while reinforcing inequalities when external partners retain control over agendas, resources, evaluation, and decisions. Locally led agenda setting, transparent responsibilities, institutional capacity assessment, mutual learning, and formal agreements on authority and benefit distribution are therefore necessary [43] . Access is also gendered: women engineers face unequal opportunities for mobility, funding, recognition, international networks, and leadership, with barriers varying across career stages and regions [44]. Formal openness does not by itself make cooperation inclusive.

These conditions reflect broader principles of knowledge co-production. Effective sustainability collaboration is context-based, pluralistic, goal-oriented, and interactive rather than a unidirectional transfer of solutions [45] . However, asymmetries in funding, prestige, infrastructure, and institutional position continue to shape the production and circulation of knowledge [46]. Shared ownership, sustained commitment, reflexivity, knowledge integration, and practitioner participation are therefore necessary throughout problem definition, implementation, and evaluation [47].

Research on transdisciplinary knowledge co-production identifies three mechanisms through which collaborative processes may generate sustainability-related impacts: knowledge production for informed and equitable decision-making, social learning for collective action, and the development of competencies for reflexive leadership [48]. These mechanisms suggest that the contribution of international cooperation should not be assessed solely through the transfer of technical knowledge or financial resources, but also through its capacity to strengthen shared learning, collective decision-making, and durable territorial capabilities.

Inclusive Innovation, Human Development, and the Integrated Model

The integrated model begins with structural and intersectional conditions—gendered career barriers, intersecting inequalities, unequal network access, and constrained trajectories—and institutional conditions, including recognition, legitimacy, organizational support, resources, heterogeneous networks, and effective authority. These conditions enable or constrain women engineers situated agency. Situated agency becomes territorially consequential when enacted through the five articulation practices, whose sustained interaction generates TAC. TAC then mediates the conversion of dispersed resources into coordinated collective action, while international cooperation may reinforce the sequence under equitable governance and local ownership.

TAC connects collective action with two contingent outcome pathways. Inclusive innovation involves participatory problem definition, context-sensitive technological and organizational solutions, broader access to knowledge, and fairer distribution of benefits and risks. Networks, agreements, and knowledge exchanges are relevant outputs, but they do not by themselves establish inclusion. Evaluation must examine who defines problems, whose knowledge shapes responses, who participates in decisions, and who benefits or bears risks. Human development expands the assessment beyond technology, growth, or employment toward substantive freedoms and opportunities that people have reason to value [49]. It includes individual and collective agency, participation, learning, and sustainable livelihoods. Connecting transformative innovation with capabilities further directs attention to justice, agency, and technological directionality [50].

These outcomes are recursive rather than final. Inclusive innovation and expanded capabilities may strengthen legitimacy, networks, resources, professional agency, and future cooperation, thereby supporting subsequent TAC. Conversely, unequal benefit distribution or weak institutionalization may erode trust and articulation capacity. Figure 1 represents this central explanatory sequence and its enabling, moderating, and feedback relationships.

Figure 1. Integrated model of women engineers as territorial integrators. Solid arrows represent the central explanatory sequence; dashed arrows indicate enabling, moderating, and feedback relationships. International cooperation is a conditional catalyst, and TAC mediates the conversion of situated agencies and dispersed resources into inclusive innovation and human development outcomes.

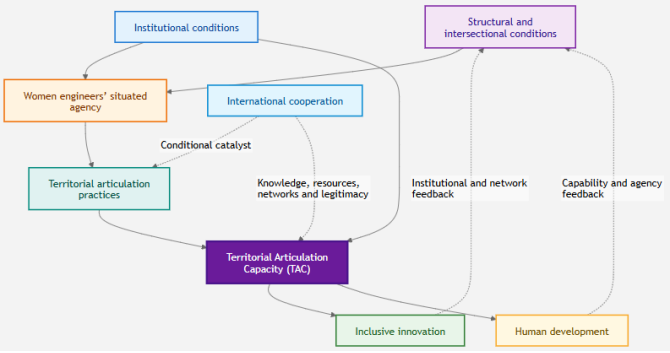


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Propositions and the Illustrative Role of BIOINTEGRA

The integrated synthesis yields four propositions:

P1—Contextual activation: Women engineers situated agency contributes to territorial transformation when structural and institutional conditions provide recognition, relational access, resources, and effective decision-making authority.

P2—Articulation and mediation: Situated agency contributes to inclusive territorial outcomes through the five articulation practices, with TAC mediating their conversion into coordinated collective action.

P3—Conditional cooperation: International cooperation strengthens TAC when it supports equitable partnership governance, mutual learning, local ownership, women's decision-making authority, and durable capability formation.

P4—Recursive transformation: Inclusive innovation and human development outcomes generate feedback effects on territorial institutions, networks, professional agency, and future cooperation processes.

BIOINTEGRA provides an illustrative application rather than empirical validation. Its Scientific Lexicon may support the identification of territorial problems, mapping of actors and resources, development of shared vocabularies, recognition of articulation practices, and specification of expected outcomes. Within this setting, women engineers may connect scientific and technological knowledge with community experience, productive organizations, public institutions, and international-cooperation mechanisms. The application demonstrates the framework's analytical usability but does not establish that TAC or the proposed outcomes have occurred. Empirical research must test how TAC emerges, changes, or deteriorates across territorial, institutional, and intersectional settings and whether it contributes to durable inclusive innovation and human development.

IV. CONCLUSION

This article developed a conceptual framework explaining how women engineers may contribute to inclusive territorial transformation. Its central contribution is Territorial Articulation Capacity (TAC), an emergent, higher-order relational capability that converts dispersed technical, institutional, community-based, and financial resources into coordinated collective action. TAC develops through five practices: territorial sensing and actor mapping, knowledge translation, network convening and coordination, resource and legitimacy mobilization, and institutionalization and collective learning. Women engineers situated agency becomes territorially consequential when these practices are supported by recognition, heterogeneous networks, resources, legitimacy, and effective decision-making authority.

The framework demonstrates that gender equality in engineering cannot be assessed solely through numerical participation in education, employment, or technical projects. Describing women engineers as territorial integrators does not imply an inherent female disposition toward cooperation or social innovation. It identifies a contingent professional role that emerges when structural, intersectional, and institutional conditions allow technical knowledge to relate to community priorities, productive actors, public institutions, and collective objectives. International cooperation may reinforce this

process, but only when partnerships ensure local ownership, equitable governance, shared authority, and reciprocal learning.

The study is limited by its conceptual and integrative design. It neither measures TAC nor establishes causal effects, and BIOINTEGRA is used exclusively as an illustrative application. Future research should operationalize the five articulation practices, develop TAC indicators, and test its mediating role through comparative cases, longitudinal designs, social-network analysis, process tracing, and participatory evaluation. This research should establish how TAC emerges, changes, or deteriorates across territorial and institutional contexts and whether it contributes to durable inclusive innovation and human development.

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