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A Transformative Innovation Framework for Activating Regenerative Circular Niches in Vulnerable Territories of Panama

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Abstract*– Circular transition initiatives in Latin America often remain uncoordinated, technically limited, and insufficiently institutionalized, restricting their ability to transform socio-technical structures that perpetuate linear material flows, territorial inequality, and environmental degradation. This article presents a Transformative Innovation Framework to activate regenerative niches in vulnerable regions of Panama. Using a conceptual methodology, the study synthesizes recent literature on multi-level transitions, niche shielding, policy barriers, urban metabolism, exnovation, and transition learning. Results are structured in two layers: (i) synthesis of knowledge gaps and (ii) a coding matrix. Identified transition mechanisms are grouped into twelve categories (M1–M12) and mapped to framework levers (L1–L4) and implementation phases (P1–P3). The synthesis identifies six main findings: transition bottlenecks are largely institutional and coordination-related; early niche protection is essential; capability development is fundamental; scaling follows differentiated pathways; sustained transition requires both innovation support and targeted exnovation; and territorial metabolic intelligence is key for implementation. These findings inform a four-lever framework: territorial diagnostic intelligence (L1), niche orchestration and protective conditions (L2), policy alignment with targeted exnovation (L3), and educational transformation via a skills pipeline (L4). Implementation is structured into three phases: Activation (P1), Education and Demonstration (P2), and Scaling with Exnovation (P3). These phases are supported by three decision tools: Regenerative Niche Readiness Levels, a Circularity–Territorial Justice Matrix, and a Feasibility Decision Pathway. As a pre-implementation study, the focus is on framework development, operational mapping, and decision-support tool design, establishing a foundation for future field validation in Panama and similar Latin American contexts.

Keywords*-- socio-technical transitions, regenerative niche, circular economy, territorial vulnerability, transformative innovation.

I. Introduction

The transition from linear to circular systems now constitutes a primary challenge for climate action and development, superseding its previous status as a secondary sustainability concern [1]. Material production and use, encompassing both products and food systems, account for nearly half of all climate impacts [2], [3]. necessitating systemic transformation rather than incremental improvements.

This challenge is particularly acute in urban areas, where population growth, territorial expansion, and environmental pressures intersect. By 2050, nearly two-thirds of the global population is projected to reside in cities, which will continue to account for a significant share of greenhouse gas emissions [4], [5], [6]. The built environment remains among the largest contributors to global emissions [7], [8], while rapid urbanization intensifies demands on land, water, infrastructure, and ecosystem services [6], [9]. Consequently, effective decarbonization requires not only energy substitution but also the transformation of material flows, territorial planning, and institutional coordination [1], [10], [11]. Although circular economy (CE) agendas are receiving increased attention, many cities continue to operate under a predominantly linear paradigm, characterized by products and infrastructure with short life cycles, limited recirculation, and sustained resource throughput [12]. Current strategies frequently prioritize waste management efficiency and technological adoption, often neglecting institutional coordination, local capacity building, and socio-cultural legitimacy. Consequently, interventions may achieve success as pilot projects but fail to facilitate systemic transition [13], [14]. This implementation gap is especially evident in vulnerable territories, where fiscal, technical, and institutional capacities are constrained, and urban growth exacerbates ecological degradation and social inequalities [15].

Another significant limitation is that urban policies often remain sectoral and technocratic, addressing waste, water, energy, housing, and mobility as isolated domains. This fragmentation undermines adaptation to climate impacts, which are interconnected across environmental, economic, and social dimensions [16], and leads to spatial discontinuities and functional wastescapes, including abandoned lots, underutilized peri-urban lands, and disconnected infrastructure systems [17], [18]. From the perspective of urban metabolism, these patterns indicate inefficient circulation of materials, energy, water, and information, thereby reinforcing extractive rather than regenerative development trajectories [16], [19], [20]. Achieving a circular transition thus requires moving beyond project-level optimization toward territorial system design grounded in closed-loop flows and adaptive governance.

Socio-technical transition theory provides insight into the challenges of enabling these transformations. The Multi-Level

Perspective (MLP) highlights the co-evolution of niches, regimes, and landscapes, illustrating how incumbent regimes stabilize unsustainable practices and resist structural change [21], [22], [23]. Niche theory indicates that emerging alternatives require protection and institutional support before they can effectively challenge dominant systems [24]. Research on exnovation and policy mixes demonstrates that transformation involves introducing innovation, as well as deliberately destabilizing and phasing out harmful incumbent configurations [25], [26]. This is especially pertinent for CE transitions, where barriers are frequently organizational and institutional rather than solely technical [27].

Research on socio-technical transitions demonstrates that substantial change relies on the interplay among niche innovation, regime structures, and landscape pressures [14], [28], [29]. Within this framework, niches serve as protected socio-technical spaces where new practices, knowledge, relationships, and values can emerge, challenging prevailing models of production, consumption, and governance [24]. In vulnerable territories, however, the development of niches depends not only on technical experimentation but also on sustained governance, public legitimacy, and the strengthening of local capabilities [30], [31].

Transition routes in Latin American and middle-income contexts are less thoroughly theorized and institutionalized compared to the Global North [32], [33]. There, circular initiatives often provide local benefits but remain disconnected, with limited integration into long-term public policy, financing mechanisms, and educational systems [34]. In many cities, policymakers still lack clear operational definitions and implementation roadmaps for circular urban transformation [34], [35], [36], [37]. As a result, initiatives that improve specific processes may not generate regime-level changes.

This paper seeks to address the implementation gap by presenting a Transformative Innovation Framework to support regenerative niche activation in Panama. The framework is tailored for contexts characterized by ecological pressures, territorial inequality, and institutional fragmentation. By integrating territorial diagnosis, collaborative design, institutional shielding, and scaling logic within context-sensitive governance conditions, the framework provides a structured pathway for advancing from isolated pilot projects to a systemic transition. The remainder of this paper is organized as follows: Section II outlines the theoretical foundation and identifies the knowledge gap. Section III details the methodological approach. Section IV introduces the proposed framework, including its dimensions, phases, and decision tools. Section V discusses implications for engineering, education, and policy. Section VI concludes with the paper's contributions and future research directions.

II. Theoretical Foundation and Knowledge Gap

Sustainability transitions within the CE are best understood not as isolated technical substitutions but as systemic reconfigurations spanning multiple levels of socio-technical organization. Niche experiments interact with incumbent regimes amid broader landscape pressures, and the MLP is especially useful for explaining why circular innovations often remain localized. Lasting change requires that governance, market rules, infrastructure, and cultural norms co-evolve in a coordinated way [32], [33]. Thus, developing niches goes beyond simply piloting technology; it involves deliberate expectation-building, actor-network formation, and iterative learning. Strategic niche management (SNM) emphasizes another crucial element: providing protection from immediate selection pressures, which allows alternatives time to mature before facing dominant linear systems [22], [24], [31]. Here, shielding, nurturing, and empowerment function as complementary, overlapping mechanisms rather than as sequential steps, jointly explaining how fragile innovations either consolidate or disappear [29], [33].

Recent studies also demonstrate that transition frameworks developed in the Global North are not directly transferable to the Global South [32], [37], [38]. Outcomes are shaped by institutional path dependencies, fragmented governance, and place-specific political economies. As a result, place-sensitive and polycentric designs become essential, especially where circular initiatives intersect with informality, uneven state capacity, and vulnerable ecosystems [39].

A second key shift in the literature is the territorialization of circular transitions [40]. Rather than viewing circularity as merely a firm-level efficiency strategy, recent research frames cities and regions as living metabolic systems in which resource flows, social inequities, and ecological stress collectively shape outcomes [16], [20], [41]. In this context, “wastescapes” are not simply residual spaces excluded from planning, but symptoms of systemic mismatches among metabolism, infrastructure, and governance [17], [18]. This territorial perspective also supports arguments for mission-oriented policy approaches, in which circular transition is conceptualized as a directional, collective process that coordinates public purpose, innovation portfolios, and institutional reform across sectors and levels of government [32], [42], [43], [44]. This orientation is particularly relevant in Panama, where urban growth, waste systems, ecosystem pressures, and social vulnerability are deeply interconnected.

Another significant body of research addresses policy design. Studies on transition policy interventions suggest that circular change depends on a dual strategy: nurturing emergent alternatives upstream, while simultaneously destabilizing unsustainable lock-ins downstream [45], [46]. Yet, the literature still under-specifies how exnovation should be operationalized [47], [48], [49]. This gap is critical for implementation, as transformative projects often falter when they develop niches without addressing entrenched linear routines.

Recent studies focusing on small and medium-sized enterprises (SMEs) provide practical insights into the implementation of transitions [50], [51]. Government-backed programs that combine training, coaching, and ecosystem collaboration have proven effective in supporting the development of niche circular business models. Nonetheless, firms continue to face capability, financial, and regulatory barriers. These findings reinforce that transition is as much about building capabilities as it is about technological advancement [50]. The regenerative turn is gaining prominence, yet its conceptual boundaries remain ambiguous within CE research. Recent studies distinguish restoration, returning to a previous state, from regeneration, which aims to create net-positive social and ecological outcomes. Nevertheless, operational frameworks are still lacking, particularly for SMEs and context-specific applications. This ambiguity highlights the need for a structured, territorially grounded framework rather than another generic narrative of circularity [52].

Synthesis of the knowledge gap from the reviewed corpus: While current literature offers (i) robust transition theory, (ii) emerging territorial and regenerative perspectives, and (iii) practical insights on capability-building, there remains a lack of an integrated framework that connects urban metabolism diagnostics, niche governance, exnovation logic, and educational transformation for vulnerable territories in developing-country contexts [32], [33], [39]. Table I synthesizes these gaps, specifying what the literature offers, what remains missing, and how the proposed Transformative Innovation Framework responds to each gap.

TABLE I
KNOWLEDGE GAP SYNTHESIS: FROM LITERATURE TO FRAMEWORK RESPONSE

Gap Dimension	What the Literature Offers	What is Missing	How This Framework Responds
1. Socio-technical integration in vulnerable territories	Robust MLP and SNM theories explaining niche-regime dynamics [21], [22], [24]	Limited application and contextualization to Global South contexts, particularly vulnerable territories with fragmented governance [32], [33], [46]	Contextualizes MLP/SNM for Panamanian conditions by integrating territorial diagnostic intelligence as the first framework lever, enabling place-based niche activation
2. Territorial metabolism operationalization	Emerging frameworks on urban metabolism, material flows, and wastescapes [16], [19], [20]	Lack of operational tools to link metabolism diagnostics to niche governance and transition pathway design	Introduces territorial metabolic intelligence (Lever 1) with specific diagnostic outputs: resource-flow mapping, actor network analysis, and wastescape identification
3. Exnovation and dual policy instrumentation	Recognition that transitions require both niche support and destabilization of linear lock-ins [25], [45]	Under-specified operationalization of exnovation; limited guidance on how to phase out persistent linear practices [47], [48]	Integrates selective exnovation in Phase III (Scaling with Exnovation), supported by decision tools (Feasibility Decision Tree, RNRL) to identify phase-out priorities
4. Capability formation and educational integration	Evidence on SME programs, learning networks, and competency-building for CE [50], [51]	Weak integration between CE initiatives and formal education systems; skills pipelines remain disconnected from territorial needs [39]	Embeds educational transformation as the fourth structural lever (Lever 4), linking curricula, technical training, and territorial problem-solving through phased implementation

This paper addresses the identified gaps by proposing a Transformative Innovation Framework that operationalizes these four dimensions into a coherent, phased implementation pathway, supported by decision-making tools.

III. Methodological Approach

A theory-integrative conceptual design approach is adopted. The objective is to construct an implementable framework that can subsequently inform pilot projects, comparative case studies, and policy experimentation, rather than empirically testing a single intervention at this stage. The procedure consists of four sequential steps. First, a targeted literature corpus is defined by combining foundational transition theory with recent studies on circularity and regeneration, with particular emphasis on post-2020 contributions and their relevance to the Global South. Second, structured thematic coding is conducted across four analytical dimensions: socio-technical dynamics, including niche, regime, landscape, and lock-in; territorial metabolism and spatial inequality; policy instrumentation, including exnovation; capability formation and education.

Third, cross-dimensional synthesis is employed to construct an actionable architecture that links diagnosis, intervention design, governance alignment, and learning loops. Fourth, this architecture is translated into implementation components and decision criteria suitable for use by governments, universities, and local coalitions. This methodology aligns with evidence indicating that effective transition pathways require integration of multi-level governance, niche support, and institutional alignment, rather than reliance on isolated technical pilots.

IV. Results

This section presents the results of the conceptual synthesis that underpins the proposed Transformative Innovation Framework. The analysis consolidates recent evidence on socio-technical transitions, CE governance, niche development, and constraints to territorial implementation in vulnerable contexts. The results are organized in three layers: (i) evidence-to-framework traceability, (ii) core synthesis findings, and (iii) operational framework design.

A. Evidence-to-Framework Traceability Matrix

Table II synthesizes the literature into an evidence-to-framework matrix that connects documented transition dynamics with the architecture proposed in this study. Each source is mapped to specific mechanisms, levers, phases, and functions in the model-building process, allowing the framework design to be traced to explicit analytical inputs. The synthesis shows that circular transitions in vulnerable territories are shaped by socio-technical and institutional constraints, including fragmented governance, weak capability formation, limited policy coherence, and insufficient niche protection. This consolidated evidence directly informs the four-lever structure and clarifies how the framework organizes a transition pathway from dispersed initiatives to coordinated, phase-based implementation.

B. Core synthesis findings

The evidence synthesis identifies six convergent findings:

B.1. Transition bottlenecks are primarily institutional and coordination-based

Implementation gaps are consistently associated with fragmented governance structures, discontinuous institutional support, and misalignment between policy objectives and execution capacity, as reported across studies. These findings indicate that transition design should prioritize institutional architecture and coordination mechanisms from the outset.

B.2. Niche protection is necessary for early-stage stability

The synthesis demonstrates that emerging circular-regenerative initiatives require deliberate protective conditions to withstand early selection pressures. Such protection encompasses not only funding but also institutional recognition, stakeholder alignment, and mechanisms for building legitimacy. These elements facilitate learning and refinement before exposure to full regime competition.

B.3. Capability formation is a core transition mechanism

Learning processes, technical competencies, and knowledge-bridging actors are essential for ensuring continuity and enabling scaling. Where capability development pipelines are weak, pilot projects remain isolated and fail to generate system-level impact. This finding highlights the necessity of integrating educational and skills infrastructure as a structural element of the framework.

B.4. Scaling follows differentiated pathways

The evidence demonstrates that scaling occurs through multiple pathways. Some initiatives expand by conforming to existing systems, while others exert transformative pressure on institutional routines. This duality requires the design of explicit pathways and context-sensitive sequencing.

B.5. Transition requires both innovation support and selective exnovation

Supporting new alternatives is necessary but not sufficient for a durable transition. Effective transition also requires the targeted phase-out of persistent linear practices that perpetuate lock-in effects. This finding supports the inclusion of selective exnovation as a policy and governance lever within the framework.

B.6. Territorial intelligence is indispensable for implementation relevance

Circular-regenerative strategies are effective only when grounded in place-based diagnostics of material, energy, water, land-use, and waste-flow interactions, as well as socio-spatial inequities. Generic policy templates are inadequate for vulnerable territories. Instead, territorial metabolism should inform intervention priorities.

C. Operational Framework Design

The six convergent findings translate directly into the framework's operational architecture, comprising four interconnected levers, a three-phase pathway, shielding mechanisms, and decision tools (see Figure 1). Each lever responds to specific constraints identified in the evidence synthesis.

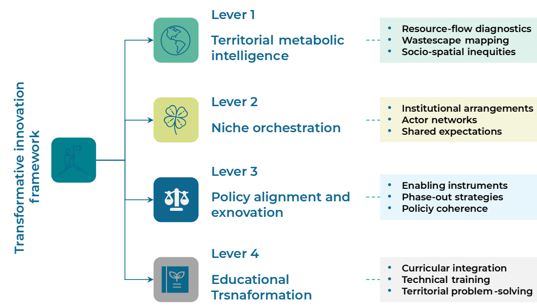

Fig. 1 Four-Lever Architecture of the Transformative Innovation Framework.

The four levers are operationalized through three sequential phases. Table III summarizes the objective, core actions, primary outputs, and dominant levers for each phase.

D. Multi-Dimensional Shielding Architecture

Finding B.2 demonstrates that effective niche protection extends beyond financial support. Table III delineates shielding across four complementary dimensions: institutional shielding through agreements and policy recognition to reduce uncertainty; pedagogical shielding, implemented via curricular integration and facilitator networks to enhance local competency; symbolic and narrative shielding, fostered through shared narratives and public events to build collective identity and social legitimacy; and technical-community shielding, facilitated by accessible prototyping and community co-validation to ensure usability and local maintainability. These dimensions establish a protective environment that is formal, cognitive, cultural, and practical, thereby enabling niches to develop into viable regime-challenging alternatives.

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TABLE II
EVIDENCE-TO-FRAMEWORK SYNTHESIS SUPPORTING THE PROPOSED TRANSFORMATIVE INNOVATION FRAMEWORK.

ID	Source	Evidence type	Mechanism code	Lever mapped	Phase mapped	Function in model building
E1	[21], [22]	Theoretical	M1: Multi-level transition dynamics	L2, L3	P1-P3	Structural transition logic
E2	[24]	Theoretical	M2: Shielding, nurturing, empowerment	L2	P1-P2	Niche protection design
E3	[39]	Empirical-conceptual	M3: Learning networks and connectors	L4, L2	P2	Capability and learning architecture
E4	[29]	Methodological	M4: Niche maturity dimensions	L2	P1-P3	Readiness/progression criteria
E5	[27]	Empirical	M5: Incumbent transformation mechanisms	L3, L2	P2-P3	Regime engagement strategy
E6	[33]	Empirical	M6: Upscaling pathways	L3, L2	P3	Scaling route design
E7	[38]	Policy analysis	M7: Context-dependent policy performance	L3	P1-P3	Contextual policy alignment
E8	[34]	Policy-empirical	M8: Governance fragmentation and capability gaps	L3, L4	P1-P2	Institutional and capability constraints
E9	[53]	Conceptual	M9: Regime-niche bridge actors	L2, L3	P1-P3	Coalition/intermediary design
E10	[39]	Conceptual-empirical	M10: Competency networks and brokers	L4	P2	Educational system integration
E11	Proposed by this study	Design input	M11: Three-phase architecture and KPIs	L1-L4	P1-P3	Operationalization backbone
E12	Proposed by this study	Design input	M12: Multi-dimensional shielding	L2, L4	P1-P2	Implementation scaffold

Note: To help readers quickly grasp how the 12 transition mechanisms align with the four levers and three phases, they are summarised below by primary phase: Phase P1–P3: M1, M4, M7, M9, M11 (L2/L3; M11 also involves L1 and L4), Phase P1–P2: M2, M8, M12 (L2/L4; M8 also involves L3), Phase P2: M3, M10 (L4/L2 for M3; L4 only for M10), Phase P2–P3: M5 (L3/L2), Phase P3: M6 (L3/L2).

TABLE III
THREE-PHASE IMPLEMENTATION PATHWAY

Phase	Objective	Core Actions	Primary Outputs	Dominant Lever(s)
I: Activation	Establish a territorial baseline and a coalition.	Waste stream mapping; actor identification; spatial analysis of high-potential areas	Resource-flow inventory; actor network map; prioritized intervention spaces	Lever 1 Territorial Intelligence
II: Education & Demonstration	Develop and test contextualized solutions.	Participatory co-design workshops; prototyping; educational module development	Co-designed solution portfolio; validated educational materials; prototype set	Levers 2 and 4 Niche Orchestration and Education
III: Scaling with Exnovation	Embed and replicate solutions; phase out linear practices	Acceptance testing, regenerative indicator definition, and scaling roadmap development	Validated solution package; scaling roadmap; exnovation targets	Lever 3 Policy and Exnovation

TABLE IV
MULTI-DIMENSIONAL SHIELDING ARCHITECTURE

Shielding dimension	Concrete mechanism	Short-term expected effect	Medium-term transition effect	Suggested indicator
Institutional shielding	Agreements with education authorities, municipalities, and technical partners; policy recognition	Reduced institutional uncertainty; stronger legitimacy	Early embedding of regenerative practices in local governance instruments	Number of formal agreements, policy references, or endorsements
Pedagogical shielding	Progressive curricular integration; active learning networks; facilitator training	Faster competency formation; local autonomy	Diffusion of regenerative practices through education channels	Number of trained educators, competency gain score, and facilitator retention
Symbolic and narrative shielding	Shared narrative devices (e.g., "Casa Viva"); visual campaigns; public events	Stronger collective identity; social cohesion around the niche	Increased social durability; political support for scaling	Narrative adoption score, participation intensity, and communication reach
Technical-community shielding	Accessible prototyping workflows; community co-validation	Higher usability; local maintainability	Greater replication potential; reduced external dependence	Prototype usability rating; local replication readiness score

Collectively, these dimensions establish a protective environment that is formal, cognitive, cultural, and practical, thereby enabling niches to develop into viable regime-challenging alternatives.

E. Decision-Support Instruments

To connect strategic framing with practical implementation, the framework incorporates three decision-support instruments, each grounded in specific convergent findings. The Regenerative Niche Readiness Levels (RNRL) offer a four-stage maturity scale: Latent, Emerging, Stabilized, and Scaling, to assess transition progress and inform resource allocation. This instrument operationalizes Findings B.4 (differentiated scaling) and B.2 (niche protection) by enabling practitioners to evaluate niche maturity and adapt shielding mechanisms as needed.

The Circularity-Territorial Justice Matrix categorizes potential interventions along two axes: circular depth, which ranges from shallow recycling to deep regenerative systems, and territorial justice impact, spanning from negative displacement to positive livelihood enhancement. Interventions located in the high-depth and high-justice quadrant receive priority. This tool directly addresses Finding B.6 (territorial intelligence) and Finding B.3 (capability formation), ensuring that solutions are ecologically effective and socially equitable.

The Feasibility Decision Tree uses four sequential filters, territorial data availability, coalition commitment, capability access, and exnovation potential, to evaluate go/no-go decisions before major implementation commitments. This instrument synthesizes Findings B.1 (institutional bottlenecks), B.5 (innovation with exnovation), and B.6 (territorial intelligence), offering a structured approach to managing complexity and uncertainty in vulnerable territories. Thus, these instruments seek to transform the conceptual framework into actionable guidance for governments, universities, and local coalitions.

Each decision instrument has defined inputs, outputs, and phase coupling. The RNRL inputs niche maturity across four dimensions (actor cohesion, resource stability, institutional recognition, learning capacity) and outputs a classification (Latent, Emerging, Stabilised, Scaling). It establishes a baseline in Phase I, calibrates shielding in Phase II, and determines exnovation readiness in Phase III. The Circularity–Territorial Justice Matrix inputs circular depth and territorial justice scores (from participatory mapping) and outputs a quadrant assignment, prioritising high-depth high-justice interventions. It is populated in Phase I, used for co-design in Phase II, and applied to scaling trade-offs in Phase III. The Feasibility Decision Tree inputs binary responses to four filters (data availability, coalition commitment, capability access, exnovation potential) and outputs a go/no-go recommendation. It is applied at the end of Phase I and reapplied at the Phase II–III transition.

F. Illustrative Scenarios for Pilot Implementation in Panama

To demonstrate how the framework's decision tools and implementation phases would operate prior to empirical validation, this section presents two theory-based hypothetical scenarios. From a methodological standpoint, illustrative scenarios of this type are a recognized strategy in socio-technical transition research for testing the internal logic and plausibility of a conceptual framework before costly implementation such as scenarios used as proof-of-concept in transition studies. They allow researchers and practitioners to explore "what would happen if" the framework was applied, identify potential coordination gaps, and refine operational criteria without requiring primary field data at this pre-implementation stage. Each scenario specifies: (i) territorial context and vulnerability profile, (ii) prioritization criteria using the Circularity–Territorial Justice Matrix, (iii) actor mapping and niche governance structure, and (iv) a phased pathway (P1–P3) with explicit shielding mechanisms and exnovation targets.

Scenario 1: Plastic Waste Management in the Las Perlas Archipelago (Panamá Province)

The Las Perlas Archipelago faces seasonal surges of plastic waste from tourism, limited final disposal via maritime transfer to the mainland, and impacts on marine-coastal ecosystems. Vulnerability includes high external dependency, institutional fragmentation between the municipality and the Tourism Authority, and low technical capacity for local recycling. Applying the Circularity–Territorial Justice Matrix, the intervention scores high circular depth due to the potential for on-island recycling and eco-design for tourism products, combined with high territorial justice, measured by local employment generation and the reduction of externalities in protected areas, placing it in the high-high priority quadrant. The orchestration core comprises the Municipality of San Miguel, an artisanal fishers' community organization, and a small existing recycling cooperative classified as Latent on the Regenerative Niche Readiness Levels scale. Supporting actors include the Technological University of Panama for eco-design training, the Tourism Authority for regulatory recognition of circular practices, and a maritime transport company for reverse logistics. Niche governance follows a polycentric committee model with representatives from the orchestration core plus a technical facilitator from the university; decisions are made by validated consensus with semi-annual accountability. The phased pathway unfolds as follows. In Phase I (months one to six), Lever 1 (territorial metabolic intelligence) is activated through mapping of coastal wastescapes and tourist-driven plastic flows. During Phase II (months seven to eighteen), Levers 2 and 4 (niche orchestration and education) guide participatory co-design of a community collection center and an eco-design school module. Shielding mechanisms include an institutional agreement for institutional shielding, a "Circular Beach" certification for symbolic and narrative shielding, and accessible prototyping workshops for technical-community shielding. In Phase III (months nineteen to thirty), Lever 3 (policy alignment and exnovation) drives replication to neighboring islands combined with phasing out open burning of plastics, as exnovation potential is confirmed by documented negative impacts on health and mangroves.

Scenario 2: Construction Materials for Informal Housing in Arraiján (Panamá Oeste)

Arraiján is a fast-growing peri-urban area with a housing deficit, unplanned expansion, construction and demolition waste (concrete, metals, plastics) dumped in degraded wetlands, and weak municipal technical capacity. Prioritisation using the Circularity–Territorial Justice Matrix yields medium-high circular depth through soil-cement blocks with recycled aggregates, and high territorial justice by improving self-built housing and reducing extraction from nearby quarries, again placing the intervention in the high-high priority quadrant. The orchestration core includes the Nueva Arraiján communal board, a construction and demolition waste recycling cooperative classified as Emergent on the Regenerative Niche Readiness Levels scale, and the Ministry of Housing's self-help housing programme. Supporting actors are the Faculty of Civil Engineering for technical assistance on mix design, the Panamanian Chamber of Construction for demand intermediation, and youth environmental brigades. A polycentric committee with equal representation from the communal board, the cooperative, and a technical facilitator from the university governs the niche; decisions are made by consensus with six-month reviews. The phased pathway begins with Phase I (months

one to four), where Lever 1 guides characterisation of construction waste flows, identification of wetland "wastescapes", and baseline mapping of self-built housing units. In Phase II (months five to fourteen), Levers 2 and 4 support participatory prototyping of recycled-aggregate blocks and the development of a short technical training module for local builders. Shielding mechanisms include a local procurement preference clause for institutional shielding, integration into the municipal training curriculum for pedagogical shielding, and a public campaign titled "My home, my circular neighbourhood" for symbolic and narrative shielding. During Phase III (months fifteen to twenty-four), Lever 3 drives scaling to three adjacent neighbourhoods paired with exnovation of illegal wetland dumping through citizen-monitored phase-out; the Feasibility Decision Tree is reapplied at the transition from Phase II to Phase III.

Cross-cutting selection criteria for first pilot implementation.

To guide the initial choice of a regenerative niche in any Panamanian territory, the framework applies three explicit criteria derived from the convergent findings in Section IV.B (institutional bottlenecks, territorial intelligence, and capability formation). First, territorial criticality is assessed through documented environmental pressure (such as a wastescape or degraded ecosystem) combined with social exclusion indicators (including unmet basic needs or informality). Second, social capital maturity requires the existence of at least one pre-existing local organisation (a cooperative, communal board, or grassroots group) with demonstrated minimal capacity for collective action. Third, leverage potential demands demonstrable ability to articulate at least two external institutional actors (a university, municipality, or technical agency) that can provide shielding or capability support. These criteria are applied sequentially, and a potential niche is considered ready for Phase I only if all three are satisfied. Regarding niche governance principles, following the literature on polycentric governance of sustainability transitions, the framework adopts a polycentric committee model for each regenerative niche. The committee comprises representatives of the orchestration core (community, cooperative, local government), a technical facilitator (university or NGO), and observers from supporting actors. Decisions are made by validated consensus, as simple majority is insufficient, and accountability includes semi-annual public reporting to the community.

V. DISCUSSION

This section interprets the findings presented in Section IV, discusses their implications for theory and practice, acknowledges limitations, and identifies directions for future research.

A. Contributions to Transition Theory in Latin American Contexts

The six convergent findings identified in Section IV.B serve as the evidence-informed conceptual foundation for the framework's architecture and theoretical contributions.

Finding B.6, which asserts that territorial intelligence is indispensable for implementation relevance, directly informs the first theoretical contribution: the territorialization of transition theory. Although previous studies have emphasized the importance of spatial dimensions in circularity [17], [18], [40], few studies have operationalized the integration of territorial intelligence into niche design. Lever 1 (Territorial Metabolic Intelligence) addresses this gap by prioritizing place-based diagnostics of material flows, wastescapes, and socio-spatial inequities in niche activation [16], [20], [41]. This approach responds to critiques that transition frameworks often remain abstract and decontextualized [38], [41].

Findings B.2 (niche protection is necessary) and B.5 (transition requires both innovation support and selective exnovation) jointly inform the second contribution: the integration of exnovation as a design principle. While the dual imperative of niche support and regime destabilization is recognized in policy mix literature [25], [45], operational guidance for exnovation remains under-specified [47], [48], [49]. Finding B.5 confirms that supporting new alternatives is insufficient without the targeted phase-out of linear practices that reproduce lock-in. By embedding selective exnovation in Phase III and linking it to decision tools (the Feasibility Decision Tree and RNRL), the framework provides practical pathways to operationalize this duality.

Finding B.3, which identifies capability formation as a core transition mechanism, underpins the third contribution: positioning educational transformation as a structural lever. This responds to evidence that capability pipelines are essential for transition continuity [39], [50], [51], yet are insufficiently integrated into circular economy initiatives. Lever 4 (Educational Transformation) connects curricula, technical training, and territorial problem-solving, thereby establishing a skills pipeline that supports both niche development and long-term institutionalization. Finding B.1 (transition bottlenecks are primarily institutional) and Finding B.4 (scaling follows differentiated pathways) cut across all contributions, reinforcing the need for institutional architecture and context-sensitive sequencing to be designed from the outset rather than addressed reactively. Fig. 2 shows the three-phase implementation route, showing how each phase operationalizes specific convergent findings from Section IV.B. The diagram shows the progression from territorial diagnosis (Phase I, informed by B.6), through co-design and capability-building (Phase II, informed by B.3 and B.2), to scaling with explicit exnovation targets (Phase III, informed by B.4, B.5, and B.1).

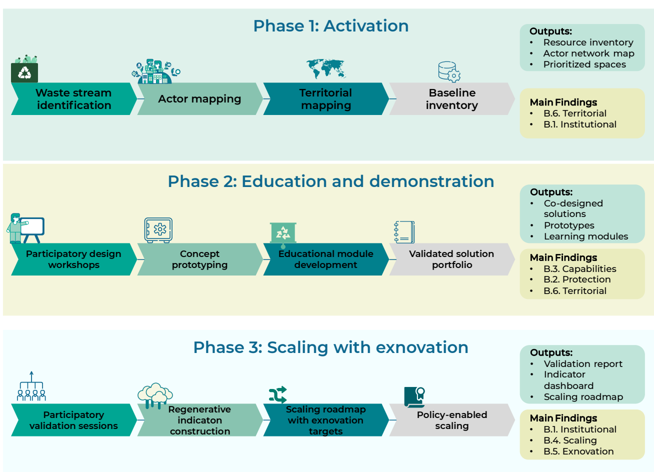

Fig. 2 Three-Phase Implementation Pathway with Links to Convergent Findings.

B. Implications for Engineering, Education, and Policy

The framework presents direct implications for three distinct audiences, each linked to specific findings outlined in Section IV.B. In engineering practice, as informed by Findings B.6 and B.4, the framework redirects attention from isolated technical solutions toward the design of systemic interventions. The finding in B.6 (territorial intelligence) indicates that engineering teams should cultivate competencies in place-based diagnostics and community engagement. Finding B.4 (differentiated scaling) requires developing solutions that are adaptable to either the fit-and-conform or the stretch-and-transform pathways, depending on contextual factors.

In the context of education, as informed by Findings B.3 and B.2, the framework advocates integrating CE principles into technical curricula through problem-based learning grounded in territorial challenges. Finding B.3 (capability formation) affirms the necessity of competency pipelines for ensuring transition continuity. The finding in B.2 (niche protection) suggests that educational institutions can serve as protective environments for the incubation of new practices.

Regarding policy, as informed by Findings B.1, B.4, and B.5, the framework provides a mission-oriented roadmap for coordinating interventions across various governance levels. Finding B.1 (institutional bottlenecks) underscores the importance of prioritizing coordination mechanisms. Finding B.4 (differentiated scaling) calls for policy mixes that support multiple transition pathways. Finding B.5 (innovation with exnovation) addresses the political economy associated with phasing out linear practices.

C. Limitations and Future Research

While the framework is grounded in the six convergent findings, several limitations should be acknowledged (see Table V).

TABLE V
LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Limitation	Linked Finding	Future Research Direction
Conceptual scope (no empirical validation)	All findings	Pilot the framework in Panama
Geographic specificity	B.6 (territorial)	Comparative case studies across Latin America
Exnovation mechanisms under-specified	B.5 (exnovation)	Develop exnovation instruments with policymakers
Educational models needed	B.3 (capabilities)	Co-design modules with universities
Decision tools untested	B.4 (scaling)	Apply and refine tools in pilot settings
Institutional mechanisms untested	B.1 (institutional)	Study institutional evolution during implementation

VI. CONCLUSIONS

This study introduces a Transformative Innovation Framework designed to activate regenerative niches in vulnerable territories of Panama. The framework is developed through a theory-integrative conceptual synthesis of recent literature on socio-technical transitions, circular economy governance, urban metabolism, and educational transformation.

A. Summary of Contributions

Six convergent findings from the literature (Section IV.B) establish that circular transitions in vulnerable territories: (i) face institutional bottlenecks; (ii) require niche protection; (iii) depend on capability formation; (iv) follow differentiated scaling pathways; (v) demand both innovation and exnovation; and (vi) must be grounded in territorial intelligence. The framework translates these findings into four levers and three phases. Territorial intelligence (B.6) informs Lever 1 and Phase I diagnostics. Niche protection (B.2) shapes Lever 2 and associated shielding mechanisms. Capability formation (B.3) underpins Lever 4 and Phase II competency-building. Scaling (B.4) and exnovation (B.5) are addressed in Phase III, using decision tools such as the Regenerative Niche Readiness Levels (RNRL) and the Feasibility Decision Tree. Institutional bottlenecks (B.1) function as a cross-cutting principle that informs all framework components. Three decision-support instruments connect strategic framing with practical decision-making: Regenerative Niche Readiness Levels (RNRL), a Circularity–Performance Trade-off Matrix, and a Feasibility Decision Tree.

B. Practical Recommendations

Phase I should start with participatory metabolic diagnostics (B.6). During Phase II, solutions should be co-designed while building competencies, using educational institutions as protective environments (B.3, B.2). In Phase III, scaling roadmaps should be developed with explicit exnovation targets and designed for multiple implementation pathways (B.4, B.5, B.1).

C. Closing Reflection

The six findings demonstrate that circular transitions in vulnerable territories necessitate institutional, territorial, and educational transformation, rather than solely technical solutions. The proposed framework offers a roadmap for advancing from isolated pilot projects to systemic change and now requires empirical validation through pilot implementation in Panama and similar Latin American contexts. This framework makes a substantive contribution to the development of alliances and knowledge systems essential for enabling circular transitions throughout the Americas.

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