

Towards a Regenerative Theoretical-Methodological Framework: Bioeconomics

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Abstract: - This article critically examines the dominant paradigm of bioeconomics, arguing that its technocratic, linear, and growth-oriented rationale reflects the epistemological limitations of Western thought. Adopting a transdisciplinary approach that integrates political ecology, complexity science, philosophy of science, environmental justice, and decolonial perspectives, it shows how hegemonic bioeconomics reproduces extractivist dynamics, instrumentalizes nature, and marginalizes alternative knowledge systems, particularly in Latin America. In response, the study proposes reconfiguring bioeconomics as a theoretical and methodological framework oriented toward the systemic regeneration of life, integrating ecological, social, cultural, and symbolic dimensions. Grounded in thermodynamics and complexity, it conceptualizes sustainability as a contextual, regenerative, and community-based process, and introduces a systemic formalization approach to model dynamic interactions within a regenerative bioeconomic system from a Latin American perspective.

Key-Words: - Bioeconomy, Regenerative bioeconomy, Complexity science, Systems thinking, Environmental justice, Decoloniality, Socioecological systems, Regeneration.

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1 Introduction

Bioeconomy, a concept that has become a central theme in global development agendas over the past few decades, is often presented as a promise to reconcile economic growth with environmental sustainability, [1], [2]. However, far from being a neutral field, bioeconomy is permeated by profound epistemological, political, and civilizational tensions that situate it within the modern Western paradigm, [3], [4]. This paradigm, based on an instrumental rationality oriented toward control, accumulation, and productive optimization, has tended to fill knowledge gaps by assigning meaning to notions such as sustainability and ecological transition, frequently reducing them to adaptation strategies for the dominant economic model, [5]. In this scenario, bioeconomy has ultimately become a new expression of green capitalism, reinforcing extractive structures under the guise of innovation, sustainability, efficiency, and the market.

Faced with this reality, it is necessary to rethink the bioeconomy not only as an economic model or a resource management technique, but as a field of epistemological, political, and ethical dispute surrounding the ways of inhabiting, producing, and

coexisting in territories, [6]. Along these lines, this article takes up this challenge by questioning the ontological and epistemological foundations of conventional bioeconomy and proposing, from a critical and transdisciplinary approach, a reinterpretation oriented towards the systemic regeneration of Life, [7].

From this perspective, there is a need to incorporate disruptive approaches that allow us to abandon the dominant technocratic rationality and to develop tools that support living, pluralistic, and contextualized processes, [8], [9]. Rather than imposing homogeneous schemes, the aim is to generate frameworks of understanding that recognize the diversity of knowledge, practices, and worldviews that shape the socioecological dynamics of territories. In this sense, this work proposes a theoretical-methodological framework to contribute to the decolonization of measurement languages and to enable new ways of thinking about the relationship between economy, nature, and community, [10]. As a situated, dialogical, and open tool, this framework does not seek to establish universal standards, but rather to support regenerative dynamics and strengthen practices

oriented towards care, reciprocity, and socio-environmental justice, [11].

With this in mind, the article is structured in five interrelated sections. First, it examines the epistemic roots of the dominant bioeconomy, which seeks to objectify and operationalize technocratic logics to support economic and social development within a classical economic framework. Second, it analyzes the evolution of the concept of bioeconomy and the theoretical tensions that have shaped its development at the international level. Third, it highlights the applications of bioeconomy in Latin America, where the promises of sustainability are reaffirmed while coexisting with structures of power, dynamics of dependency, and institutional fragmentation. Fourth, it presents the central thesis that defines the article's core, proposing a theoretical and methodological framework for a regenerative bioeconomic system aimed at understanding the articulation among ecological, social, cultural, and symbolic dimensions from a complex perspective. Finally, the fifth section offers an initial approach to the mathematical formalization of regenerative bioeconomic dynamics within a systemic framework. The conclusions open a space for dialogue and reflection on bioeconomics beyond the development paradigm, grounded in the perspective of complexity sciences and founded on the primacy of Life.

2 Evolution of the Concept of Bioeconomy and the Theoretical Tensions It Faces

The conception of the bioeconomy has gone through various narratives or academic approaches, reflecting the plurality of interpretations that have attempted to give it a connotation based on the still-emerging field [12], from the perspectives centered on economic science that address two conflicting models: on the one hand, a vision oriented towards growth and technological innovation, biotechnology, and bioindustry. These models address the economic model's perpetuity, giving it a green and/or sustainable twist, [13]. In contrast, perspectives advocating for sufficiency, equity, and ecological sustainability are presented from a polarized viewpoint, not only expressing different political priorities but also profound divergences in social values and mentalities, [14], [15]. Finally, there are proposals from disruptive scenarios oriented towards sustainable territorial development and, more recently, from the sciences of complexity.

These demand a new integrative theoretical and practical framework that provides an interconnection between systemic components. It is then that each discourse today functions as a device that mobilizes capital and legitimacy, even though they often fail to meet expectations. These findings reinforce the need to propose alternative imaginaries that transcend the logic of growth and are oriented towards regenerative social contracts, [5].

However, despite theoretical diversity, in contemporary practice, the bioeconomy has largely consolidated itself as a fundamental strategy of so-called green capitalism. This approach, serving as an economic policy to link the logic of growth and capital accumulation with sustainability discourses, promotes transformations through technological innovation, efficient resource management, and knowledge production, without questioning the structural foundations of the dominant economic model, [3], [11]. One of its most promoted developments has been the circular economy model, presented as a solution to extend production cycles, reduce environmental impacts through the reuse of production waste, and promote economic efficiency, under the assumption of sustainability compatible with growth, [16].

This vision, widely supported by multilateral organizations and adopted by numerous countries in response to their multiple crises or problematic situations that exceed their installed capacities, is based on a technocratic and economistic narrative that, despite its innovative rhetoric, continues to reproduce the extractivist logic of fossil capitalism, [3], [17]. In contexts marked by deep structural inequalities, technological dependence, and institutional fragility, as is the case in much of Latin America, this dominant circular bioeconomic approach is not only unfeasible in practical terms but also dangerous from an ecological-political perspective.

Far from representing a paradigm shift, the bioeconomy promoted by green capitalism has become a central focus of global agendas and institutional policies, keeping intact the logic of development under sustainable principles and objectives. Instead of promoting systemic transformation, it promotes a technocratic transition focused on market structures and linear logics, even as complex problems require integrative, critical, and deeply transformative approaches, [18].

It is therefore urgent to critically question the dominant bioeconomy and move towards a paradigmatic deconstruction that recognizes the complexity of Life and treats nature not as an object of exploitation, but as a subject of rights. This

transition requires an ontological, epistemological, and ethical shift that articulates social justice, ecological justice, and plurality of knowledge, [19]. In this sense, the problem with the bioeconomy lies not only in its technical implementation but also in its epistemological genesis. From a critical biophysical perspective, it has been pointed out how modern economics has systematically ignored the principles of physics and biology, especially the laws of thermodynamics, in particular the second law, which warns about entropy, which has led to a reduced reading of the very origin of the concept of bioeconomy, [7].

This omission is not circumstantial but structural, because the neoclassical economic model, from which the conventional bioeconomy derives, assumes that natural resources are always replaceable or substitutable and that the market is the ultimate arbiter. As a result, most studies prioritize productive efficiency and technological innovation, while the distributive impacts and biological, ecological, and social implications of bioeconomic transitions remain largely unexplored, [6]. On this basis, nature is no longer recognized as an evolutionary system (the biosphere) and is reduced to a mere resource.

From this perspective, the bioeconomy fails to capture the multiscale complexity of socioecological systems, [18]. Thus, biomass, like nature, is conceived as an exclusively extractable and productive resource, reinforcing a logic of efficiency, marginal production, and increasing returns that obscures the regenerative dynamics of life-nature, [16].

This reductionist view is anchored in modern thinking. The philosophy of science has shown how certain forms of knowledge, when institutionalized, become rigid frameworks that impose a single way of understanding reality, excluding other perspectives. In this way, it becomes evident that when an approach to knowledge becomes absolute, it ceases to be a tool for understanding science, as well as for its development and evolution, [8]. It becomes an instrument of power that blocks criticism and marginalizes other forms of thought. Along the same lines, the hegemonic bioeconomy operates as "normal science," as described in [9], unquestioningly reproducing the dominant paradigm. This epistemic rigidity limits the possibility of recognizing Life, rather than capital or productivity, as the true complex phenomenon capable of generating, energizing, and reconfiguring systems. Thus, the need for a profound change in the vision of civilization, grounded in an

understanding of complexity, systemic networks, and regeneration [20], is postponed.

At this point, it becomes imperative to question the reductionist logic of small science, which fragments and operates from closed paradigms, to move towards validating a grand science capable of integrating the complexity of Life as its central axis, [6]. Beyond instrumental reforms, the real challenge is to question and revolutionize the scientific foundations of conventional economics. This discipline has historically been articulated on the margins of biological, ecological, and complex dynamics, relying on the classical and neoclassical matrix based on mechanistic, deterministic, and linear models that exclude Life both in their theoretical conception and in their method. Therefore, from its own paradigm, the dominant economy cannot offer substantive, sustainable solutions, as it lacks the epistemological categories and ontological sensitivity and/or disposition necessary to understand the vital processes, ecological thresholds, and interdependent relationships that sustain Life.

Consequently, the appeal to sustainability in conventional economics reveals itself to be an illusion or, at best, a utopia sustained by reductionist epistemic frameworks, [21]. From the perspective of modern physics, particularly the second law of thermodynamics, and the application of complexity theory, Life is understood as a phenomenon of maximum complexity. Therefore, it is not a closed system, nor can it be analyzed under the assumption of *ceteris paribus*, much less an optimal equilibrium. On the contrary, Life constantly interacts with its environment, generating disorder and continuous transformation.

To argue, then, that a system can be maintained indefinitely based on perpetual growth is to ignore the physical laws that govern nature. It is therefore essential to recognize that every economic process entails irreversible costs in terms of natural, biological, ecological, and physical resources. Thus, no system can be sustained without recognizing biophysical limits, without depleting resources, or without degrading ecosystems, [7]. By ignoring this reality, the modern economy has built an essentially unsustainable structure in which nature is reduced to a simple input or imputed cost in the linear production process, alien to the complex dynamics of living systems.

Thus, even if it is given a twist by betting on bio-based materials or clean technologies, perpetuating the conventional economic model does not guarantee a real solution if its structural core is not addressed. The roots of the problem lie in

extractivist mentalities, historical relations of domination, the logic of accumulation, and deep power asymmetries, [22], [23]. Thus, rather than resolving socioecological conflicts, current transition strategies tend to reconfigure dispossession through new discourses of sustainability or decarbonization.

However, the profound transformations required by this historic moment cannot be managed from within institutional frameworks or prevailing logics. All real change is uncertain, plural, and emergent; therefore, it cannot be codified in technical manuals or universal models. These transformations challenge the very foundations of Western modernity and open space for radical reflection on knowledge, power, and Life.

Here, the proposals for the decoloniality of knowledge and the mental models that have nourished critical approaches, including those of degrowth [10], [15], resonate as they question the modern civilizational model and its development paradigm. Far from merely opposing perpetual growth, these approaches denounce how "green" or "sustainable" versions have been repressed and pigeonholed to continue feeding the logic of accumulation, at the expense of nature, cultures, and communities, [24].

In this context, the bioeconomy should not continue as a technocratic institutional strategy at the service of green capitalism. On the contrary, it should be configured as an opportunity to promote profound, just, and decolonial socioecological transformations. This requires placing environmental justice, degrowth, and the ancestral knowledge of Latin American regions at the center, [25]. Thus, using the bioeconomy to validate a perpetual green growth approach constitutes not only a technical error but also an act of manipulation that sustains the status quo. In this way, the bioeconomy becomes a symbolic sustainability strategy for global governance, while the real conditions of Life on the planet continue to deteriorate.

3 Applications of Bioeconomy in Latin America

Theoretical and epistemic tensions are evident in the practical applications of the bioeconomy in Latin America, where promises of sustainability coexist with deep structural contradictions. Recent studies, focusing on economic models and efficiency approaches, clearly reveal the limits, contradictions,

and possibilities facing their territorial implementation, [26], [27].

To give a specific example, in Colombia, economic policies based on ambitious objectives have been proposed, articulating goals with green growth policy. These seek to position biodiversity as a strategic resource for innovation and the market, [28]. However, despite the institutional discourse promoting the bioeconomy as a development strategy, initiatives are strained by fragmented structures, asymmetrical power relations, and poor coordination between sectors.

Problematic realities, such as governance with low effective participation by local communities, small producers, and peasant organizations, have perpetuated dynamics of exclusion and verticality of knowledge. These structural conditions constitute barriers to the construction of transformative content for the bioeconomy when the epistemic and institutional bases that sustain it are not reconfigured, [11]. A recent case is the department of Caldas, where the territorial bioeconomy strategy has been promoted by provincial governments and development agencies, aiming to articulate agricultural value chains, tourism, and local biodiversity. However, these efforts still face difficulties in consolidating effective governance grounded in genuine integration with rural communities, which are often seen only as beneficiaries rather than active agents in bioeconomic processes, [5].

In this sense, Colombia is a clear example of how the bioeconomy in Latin America, as in Europe, has been included in the public agenda under the commitment to a sustainable path of development, articulated mainly through green growth policies and productive innovation strategies, [1]. However, this incorporation responds more to a conventional economic approach than to a paradigm that seeks to revolutionize production methods and models toward ecosystem health and socio-environmental regeneration at the center of its priorities. This means that, far from questioning the epistemic and structural roots of the extractivist model, public policies have ended up consolidating and instrumentalizing the bioeconomy as a functional component within the framework of economic modernization and global competitiveness.

For its part, Argentina has approached the bioeconomy through plans that focus on the development of agrobiotechnology and biorefineries. However, consolidating a coherent and sustained bioeconomic strategy remains utopian, [29]. The initiatives, although valuable, are

characterized by disjointed trajectories, guided more by market logic than by a real commitment to systemic regeneration or the strengthening of local communities. Institutional networks and public policies have not established a robust framework to enable the bioeconomy to take shape as an inclusive and transformative process. Studies have therefore explored the link between the bioeconomy, entrepreneurship, and territorial development from a situated perspective, highlighting the role of social capital, local appropriation of knowledge, and multilevel coordination in the emergence of inclusive bioeconomic experiences. In this approach, the bioeconomy transcends the techno-productive strategy to become a relational process of collective learning and ecological adaptation. Innovation is no longer understood as vertical technology transfer but is conceived as a socio-technical framework where diverse knowledge, local needs, and alternative forms of development converge. Despite growing global interest in the bioeconomy as a model for sustainable development, this paradigm faces significant limitations in establishing itself as a coherent, transformative national strategy in Argentina, as in other Latin American countries. Bioeconomic development in the country is characterized by the coexistence of diverse, fragmented, and disjointed trajectories that respond to heterogeneous productive, technological, and institutional logics. This situation is not only the result of structural constraints. It is further aggravated by the absence of a sustained and coherent public policy, as well as by persistent macroeconomic instability and weak regulatory frameworks. Under these conditions, coordination among key actors such as the state, companies, R&D centers, and local communities rarely consolidates into something cohesive. What tends to emerge instead are fragmented efforts, often disconnected, with limited capacity to sustain processes over time, [24]. The bioeconomic entrepreneurship and innovation ecosystem, both in Argentina and across Latin America, cannot be understood as operating in neutral conditions. Its trajectory is shaped, quite directly, by economic policies aligned with the prevailing productive model. In practice, priorities remain tied to scalability, cost reduction, and profit generation, which leaves little space for approaches oriented toward regeneration. Innovation, in this context, is mostly directed toward improving efficiency, reducing uncertainty, and expanding markets. What remains largely unaddressed is the extractivist logic that underpins these dynamics. As a result, innovation often ends up reinforcing existing value

chains rather than opening the possibility of deeper eco-social transformations, [6]. Entrepreneurship does not escape this pattern. It tends to move within established market logics, where competition, growth, and short-term returns dominate decision-making. This leads to a persistent emphasis on productive and profitable outcomes, frequently without considering their capacity to regenerate territories, strengthen community ties, or incorporate local and traditional knowledge. This, in turn, limits not only the transformative capacity of the bioeconomic ecosystem but also the potential of entrepreneurship and innovation to become true catalysts for post-extractivist or regenerative transitions—ultimately leading to an overshoot of the system's capacity to regenerate itself. Instead, experiences are emerging from private, academic, or community initiatives, many of which are scattered and lack a coordinating framework to ensure their sustainability, [16]. In Arequipa, for example, projects linked to the circular economy in the textile industry have been developed, and spaces for academic reflection on the bioeconomy and its complexities have been promoted, led by the National University of San Agustín, [25]. However, although these experiences are valuable, they lack political support and remain on the margins of an integrative public policy.

Despite the particularities of each country, a typical regional pattern can be observed: the bioeconomy, as implemented in Latin America, operates under a functionalist logic, subordinated to the imperatives of the market and profitability. Instead of consolidating itself as a complex engine of transformation, bioeconomic entrepreneurship reproduces the same dynamics of competitiveness, scaling, and productive efficiency, blurring its potential to regenerate territories, restore community ties, or integrate local and traditional knowledge, [12]. In sum, the bioeconomy in Latin America has developed within economic policy frameworks oriented toward the objective pursuit of prevailing extractivist dynamics. This condition tends to reproduce and deepen them. This situation limits the possibility of promoting and understanding genuine processes of socioecological regeneration and environmental justice. Consequently, this scenario calls for a profound critique at the epistemic, political, and economic levels, implying the need to reconfigure development models, as proposed in [18], who advance an approach based on identifying fundamental qualities within socioecological systems in order to generate positive cycles of well-being grounded in resilience. As discussed in [20], the role of "regenerative semantics" and new

institutional mechanisms in facilitating transitions to more equitable and ecologically viable economies. These proposals align with the need to move from isolated instruments to true institutional architectures that integrate reciprocity, biophysical limits, and the rights of nature, as argued in this research.

4 Theoretical-methodological

Proposal: A Regenerative Bioeconomic System

In this work, the regenerative bioeconomy does not emerge simply as an additional approach within existing debates. Rather, it takes shape from transdisciplinarity as a critical response to the linear and extractivist logics that have long structured dominant economic models. What is being proposed is not merely an alternative framework but a shift in perspective.

At its core, this approach advances an integral vision in which social, ecological, cultural, and symbolic dimensions are not treated as separate domains, but as elements of a dynamic and coevolutionary system. In this sense, the theoretical methodological framework is oriented not only toward understanding complex realities, but also toward guiding transformative processes aimed at building sustainable, resilient, and just territories.

This framework is articulated through a set of fundamental principles. These principles should not be read as fixed categories, but as orientations that remain open to reinterpretation in specific contexts:

1. Complexity. Socioecological systems cannot be reduced to linear cause-and-effect relations. They are inherently non-linear, which means that even small interventions may trigger significant, and at times unexpected, consequences. This challenges simplified approaches to planning and intervention.
2. Interdependence, reciprocity, and systemic networks. The relationships between humans, communities, and ecosystems are not external or secondary. They are constitutive. From this perspective, reciprocity becomes a necessary condition for regeneration, rather than a complementary principle.
3. Systemic regeneration. Regeneration is not understood as a final outcome, but as an ongoing process. It involves restoring systemic health while also engaging with questions of ecological integrity and environmental, social, and cultural

justice. These dimensions cannot be addressed in isolation.

The theoretical and methodological framework builds upon these principles. However, it does not translate them into rigid prescriptions. Instead, it operates as a set of guiding orientations for processes that remain necessarily open and evolving. Within this logic, the framework is articulated through the following dimensions:

- Systemic health dimension. This dimension repositions health beyond fragmented or sectoral interpretations. It draws attention to health as an integral, holistic, and resilient process, closely linked to regeneration and systemic evolution. Human, community, environmental, and ecological health are not treated separately, but as interconnected expressions of the same underlying dynamics. In this sense, health is better understood as an emergent property of the interaction between nature, society, and culture. It cannot be reduced to isolated medical or environmental indicators.
- Biological and ecological metabolism dimension. This dimension examines the flows of matter and energy within socioecological systems, taking inspiration from the bioeconomic perspective presented in [7]. Yet, it moves beyond deterministic interpretations. Rather than a closed mechanism, metabolism is approached as an open and indeterminate process, where the degrees of freedom of the system play a decisive role in shaping its resilience or vulnerability. From this standpoint, it becomes unavoidable to recognize that economic processes are embedded within biophysical limits, and that sustainability depends on metabolisms aligned with natural cycles.
- Network management dimension. Here, attention shifts to the web of relationships that connect social, economic, cultural, and ecological actors. The network is not reduced to a technical tool for coordination. It is better understood as a living fabric of interactions through which knowledge, practices, and territories are continuously reconfigured. This perspective foregrounds inclusive governance, active community participation, and the recognition of local and ancestral knowledge in decision-making processes. These networks do not simply connect actors. They generate nodes of power, cohesion, and resilience, enabling the articulation between local and global dynamics, as well as between ancestral and contemporary forms of knowledge.

- **Symbolic cultural dimension.** This dimension brings into focus the meanings, values, and worldviews that shape economic practices. Regeneration, in this sense, cannot be reduced to material or technical adjustments. It requires a transformation at the level of imaginaries. Recovering ancestral knowledge, strengthening cultural identities, and fostering a regenerative ethic oriented toward the redignification of nature become central elements. Without this symbolic shift, structural transformation remains limited.
- **Economy for life dimension:** This is based on the indeterminacy inherent in living things: it does not follow deterministic or dualistic laws, but instead recognizes complexity as a condition of possibility. In this sense, the economy unfolds in degrees of freedom that allow for innovation, emergence, and diverse ways of inhabiting the biosphere [6]. It is not oriented toward designing new economic models but rather toward rethinking the economy from the perspective of Life itself. Life is here the axis around which economic activity pivots, displacing growth and accumulation as central goals. This dimension represents a transition towards a bioeconomy where the economy learns from Life, submits to its complexity, and reintegrates into its regenerative cycles.

These dimensions constitute the research proposal, which is a regenerative bioeconomic system:

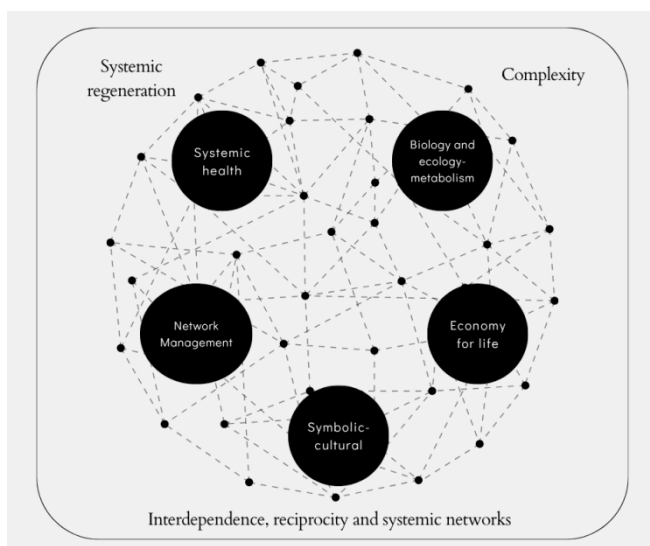


Fig. 1: Regenerative Bioeconomic System (Interconnected Dimensions)-Graphic Vision.
Source: created by the authors

This systemic organization is graphically represented in Figure 1, which illustrates a circular

network in which each dimension is interconnected with all the others. This design seeks to represent the idea that regeneration cannot be thought of in sectoral or disciplinary terms, but rather as a web of interdependencies, [30]. The circularity of the diagram emphasizes the non-hierarchical nature of the components and their openness to feedback, coevolution, and emergence.

More than an operational framework for measuring indicators, this proposal should not be understood as a closed or prescriptive scheme. In fact, reading it in those terms would limit its scope from the outset. Rather, it constitutes an epistemic and methodological tool oriented toward rethinking territories, economies, and cultures from a regenerative perspective. In this sense, the graph does not operate as a fixed model. It is better understood as a conceptual map that remains deliberately open, one that can be reinterpreted and resignified according to the specificity of each context and territorial reality. Its value lies precisely in that openness. From this perspective, the regenerative bioeconomic system does not simply expand the dominant economic framework. That would be insufficient. What is at stake is the need to move beyond reductionist approaches that have historically fragmented life into measurable units. This is not a minor adjustment, but a shift in how life itself is conceptualized within economic reasoning. Accordingly, the proposal opens the horizon toward an epistemology of Life. Here, the economy cannot be reduced to processes of extraction or optimization. It must be understood differently: as a system that metabolizes, regenerates, and coevolves in accordance with the complexity of living systems, [31].

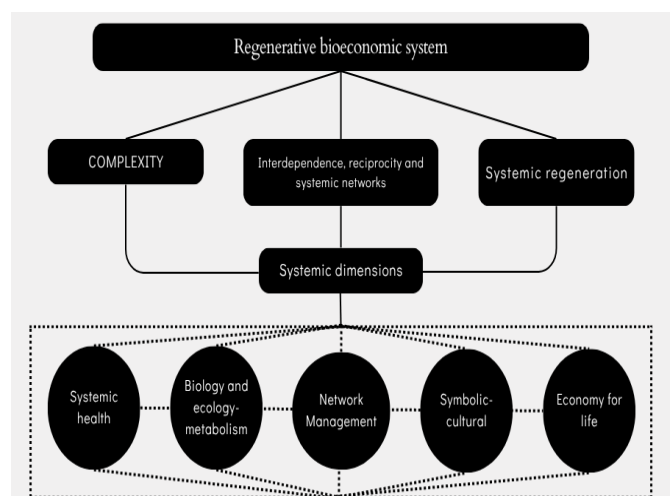


Fig. 2: Regenerative Bioeconomic System (Interconnected Dimensions)- Conceptual Vision.
Source: Created by the authors.

This theoretical methodological framework offers a tool for rethinking and reconfiguring the bioeconomy from a regenerative perspective. Still, its relevance does not lie only in its integrative capacity. By bringing together ecological, social, cultural, and symbolic dimensions within a systemic and dynamic configuration, it also questions the foundations of conventional development models. In the context of Latin America, this takes on particular significance. It allows movement toward development trajectories that prioritize Life, justice, and sustainability, while recognizing the plurality of knowledges, practices, and worldviews that shape territorial processes. These elements are not secondary. They are constitutive. It is important to emphasize that this proposal should not be interpreted as a rigid methodological prescription. Such a reading would contradict its very premise. On the contrary, it is conceived as an open framework of intelligibility that accompanies processes of territorial transformation without reducing their complexity. As such, it remains a tool under continuous construction, grounded in the principles of complexity and indeterminacy. It acknowledges both the entropic limits that condition living systems and the degrees of freedom that enable their transformation. These two dimensions do not cancel each other out. They coexist in tension. Within this framework, each dimension operates in constant articulation with the others. What emerges from this interaction is non-linear dynamics that exceed the traditional separation between society and nature. More than resolving that divide, the proposal displaces it, pointing instead toward a horizon of coevolution, reciprocity, and care.

5 Systemic Formalization of Regenerative Bioeconomic Dynamics: A Complexity Approach

Building upon the theoretical and methodological framework developed in the previous section, this section delves deeper into the analytical understanding of the interrelationships that structure the regenerative bioeconomic system. While Section 4 outlines the conceptual architecture of the system and defines its fundamental dimensions, the present section moves in a different direction. Its aim is to advance a systemic formalization capable of analytically representing the dynamics that emerge from the interaction among those dimensions.

This does not imply reducing the phenomenon to a closed or mechanistic scheme. On the contrary, what is sought here is a form of representation that can still hold the relational, adaptive, and coevolutionary character of the system without flattening it, [32].

At this point, a clarification becomes necessary. Any attempt to operationalize this framework inevitably faces a tension: the risk of simplifying complexity. Moving toward formalization should not lead to the reduction of socioecological systems into deterministic relationships or linear chains of causality. Rather, it requires working with forms of abstraction that remain open, capable of accommodating uncertainty, emergence, and non-linearity. In this sense, responding to biological and social complexity with classical statistical tools, based on assumptions of normality, independence of variables, and isolated causalities, as occurs in linear parametric tests or static regressions, creates epistemological tension with the principles of thermodynamics and the foundations of complexity theory. Living systems do not behave as closed and stable structures; rather, they are characterized by continuous exchanges of energy and matter, nonlinear dynamics, and emergent phenomena arising from interactions among multiple components. Consequently, the objective of this section is not to apply conventional statistical tests, but rather to offer a conceptual formalization that allows us to represent the interdependencies, feedback loops, and emergent dynamics that characterize the regenerative bioeconomic system.

Consistent with the dimensions developed in section 4, the regenerative bioeconomic system can be analytically represented by a dynamic state vector X_t , composed of five fundamental variables:

$$X_t = (H_t, M_t, N_t, C_t, L_t) \quad (1)$$

In other words, X_t , it is not an individual variable but a state vector (a set of variables) representing the complete state of the regenerative bioeconomic system at discrete time t , simultaneously encompassing all structural dimensions. In this formulation, the temporal variable should not be interpreted solely as a conventional chronological measure, but as a unit of transition between system states associated with the territory's metabolic, institutional, and adaptive cycles. Thus, each increment represents a phase of socioecological reorganization in which the system's dimensions interact, provide feedback, and co-evolve.

From a formal perspective, the system can be interpreted as a discrete-time dynamic system, in

which the future state of the system depends on the interaction between its components at present:

$$X_{t+1} = F(X_t) \quad (2)$$

where the function represents the set of interaction processes that link the different dimensions of the system. This formulation states that no dimension evolves in isolation; rather, its dynamics emerge from the interplay among the other dimensions that constitute the socioecological system.

For analytical purposes, the evolution of each dimension can be represented through the conceptual dynamic relationships summarized in Table 1 (Appendix), which synthesizes the functional representation of each systemic dimension within the regenerative bioeconomic framework.

This normalization does not correspond to a classical statistical probability distribution. On the contrary, it represents an index of the system's state. Values close to 0 indicate low levels of development or even collapse in a given dimension. In contrast, values close to 1 reflect a greater degree of consolidation of regenerative capacities, approaching the biophysical limits or the system's carrying capacity. This mathematical bound is also a fundamental requirement for the future implementation of System Dynamics models, as it allows the incorporation of nonlinear saturation functions that prevent infinite exponential growth and enable the coherent modeling of ecological and planetary limits.

Additionally, from the perspective of discrete mathematics and network theory, the system can be represented as a complex socioecological network:

$$G = (V, E) \quad (3)$$

where G represents the graph describing the relational structure of the regenerative bioeconomic system, in this representation, V corresponds to the set of nodes of the system, $V = \{H, M, N, C, L\}$, which represent the five structural dimensions described above. In contrast, E represents the set of edges or links connecting these dimensions and symbolizing the flows of interaction, feedback, and mutual influence between them.

Unlike conventional statistical models that assume independence between variables or homogeneous interactions across observations, network representations recognize that interactions are local, relational, and dependent on the system's structure. This relational topology provides an appropriate methodological basis for the future application of tools such as Agent-Based Modeling and Complex Network Analysis, in which nodes and

their connections define the specific channels through which territorial agents exchange resources, information, and decisions. Under this approach, macro-territorial dynamics emerge from the interaction of multiple micro-local decisions, allowing for the exploration of socioecological coevolutionary processes without imposing reductionist assumptions incompatible with the complexity of living systems.

To facilitate understanding of these dynamic interrelationships, Figure 3 presents a schematic representation of the regenerative bioeconomic system. The circular structure of the diagram reflects the system's non-hierarchical nature and multiple feedback loops among its components, thereby integrating the systemic architecture shown in Figure 2.

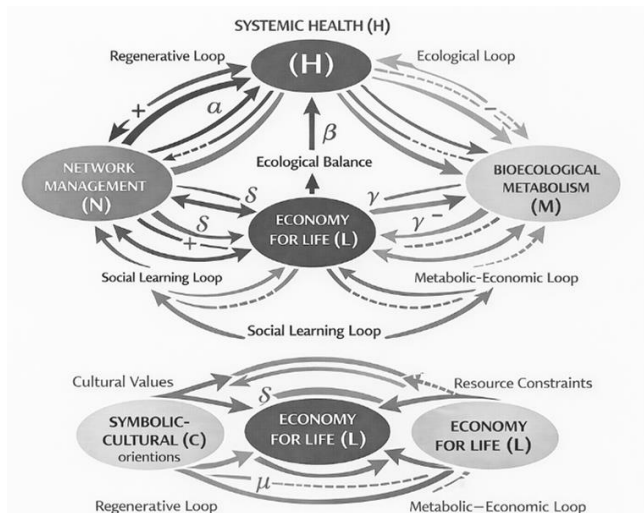


Fig. 3: Graphical representation of the systemic formalization of the regenerative bioeconomy

Source: Created by the authors.

It is important to emphasize that the formalization presented is neither a predictive nor a deterministic model. Its objective is to offer an analytical tool that allows for the representation of the relational dynamics of the regenerative bioeconomic system and the understanding of the interdependencies that structure territorial transformation processes. In this sense, the proposed framework seeks to lay the groundwork for future empirical research that can operationalize these dimensions using simulation tools, systems dynamics, or agent-based modeling. Thus, the formalization contributes to interpreting socioecological trajectories from a perspective of interdependence, coevolution, and regeneration, consistent with the inherent complexity of living systems and with the principles that guide a regenerative bioeconomy.

6 Conclusions

This article critically examines the dominant bioeconomic paradigm, drawing attention to how its technocratic, linear, and growth-oriented rationale reflects deeper epistemic and civilizational limitations associated with Western thought. From a transdisciplinary perspective that brings together political ecology, the sciences of complexity, and philosophical reflection, the construction of a regenerative bioeconomy in Latin America cannot be approached as a simple extension of existing models. It requires moving beyond the limits of the linear and productivist paradigm that continues to shape both economic policy and classical economics, where living systems are still reduced to inputs within a productive function.

The theoretical, methodological, and formal proposal developed here can be understood as an initial step toward fostering dialogue among economics, biology, and political ecology. In doing so, it foregrounds Life as an inseparable and non-hierarchical network of relations. This shift makes it possible to reconsider the categories through which the relationship between human societies and the biosphere has been traditionally framed. Rather than relying on linear metrics or mechanistic simplifications, the approach emphasizes circularity and relationality, opening space for a different way of understanding the economy as a living system in which regeneration operates as a guiding principle.

Within this broader framework, the systemic formalization presented in the final section functions as a complementary analytical tool. Its purpose is not to reduce complexity to a deterministic scheme, but to make visible the interactions unfolding among the different dimensions of the regenerative bioeconomic system. What emerges from this perspective is a relational field, where dynamics arise from the interdependencies between ecological, social, cultural, and economic processes, rather than from isolated causal mechanisms. At the same time, the proposal must be situated within its own limits. As an exploratory effort, it remains a conceptual framework in construction, one that still requires empirical grounding as well as the development of indicators capable of engaging with complexity without collapsing it into simplified metrics. In addition, the critical perspective developed here does not seek to encompass the full range of debates surrounding bioeconomy and sustainability. Its intention is more specific: to open a space for dialogue grounded in a Latin American perspective. There is also a broader tension that cannot be overlooked. Any theoretical exercise risks becoming detached from material and political

realities. For this reason, a central challenge moving forward will be to articulate this framework with concrete practices of territorial and community regeneration. Without such articulation, its scope would remain largely conceptual. In this same direction, the proposed formalization can be seen as a first step toward future methodological developments, particularly those based on network analysis and modeling approaches inspired by the sciences of complexity. More than offering a closed model, the proposal operates as a point of departure, one that helps to outline an epistemic horizon for rethinking the economy from the perspectives of Life, interdependence, and reciprocity. Rather than replacing one paradigm with another, the intention is to contribute to the emergence of a plural and dialogical methodological field, where diverse forms of knowledge and the heterogeneity of territorial realities actively participate in the construction of more sustainable futures.

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APPENDIX

Table 1. Functional representation of the dimensions of the regenerative bioeconomic system

System dimension	State variable	Dynamic expression	Function components
Systemic health	H_t	$H_{t+1} = H_t + \alpha R_t - \beta E_t$	R_t : territorial regenerative processes; E_t : entropic or degradative pressures; α, β : interaction parameters that reflect the relative intensity of regenerative and degradative processes on systemic health.
Biological-ecological metabolism	M_t	$M_{t+1} = M_t + \gamma(P_t - U_t)$	P_t : biological production or biomass regeneration; U_t : levels of use or extraction of natural resources; γ : a parameter that expresses the sensitivity of territorial metabolism to the balance between regeneration and extraction.
Network Management	N_t	$N_{t+1} = N_t + \delta Co_t - \lambda Fr_t$	Co_t : dynamics of social or institutional cooperation; Fr_t : processes of institutional fragmentation or conflict; δ, λ : parameters that capture the relative influence of cooperation and fragmentation on territorial governance.
Symbolic-cultural dimension	C_t	$C_{t+1} = C_t + \mu K_t - \nu Lc_t$	K_t : generation and transmission of ecological, scientific, or traditional knowledge; Lc_t : processes of cultural loss or erosion of local knowledge; μ, ν : parameters that reflect the intensity of these processes in the cultural evolution of the system.
Economics for Life	L_t	$L_{t+1} = L_t + \rho B_t - \sigma Ex_t$	B_t : bio-productive or regenerative activities; Ex_t : extractive dynamics that deteriorate the ecological base; ρ, σ : parameters that reflect the relative influence of regenerative and extractive activities on the territorial economy.

Source: Created by the authors.