Technological Trajectories in Biogas: From Agricultural Roots to Industrial Integration

Trajetórias Tecnológicas do Biogás: Das Raízes Agrícolas à Integração Industrial

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Resumo: Este artigo mapeia trajetórias tecnológicas na pesquisa global sobre biogás por meio de detecção de trajetórias em redes de citação temporais, aplicada a 58.452 documentos do OpenAlex (1990–2024). A análise identifica 17 comunidades de pesquisa em estrutura núcleo-periferia e revela uma evolução em três fases: experimentação agrícola (anos 1990), industrialização (anos 2010) e inflexão rumo à circularidade (anos 2020). O Brasil, concentrado na comunidade g13, apresenta quatro trajetórias que documentam a transição de estimativas de potencial energético da vinhaça para biorrefinarias circulares integradas ao RenovaBio. A análise de main path revela uma cadeia de nove artigos (2009–2025) que conecta macro-estimativas a modelos de bioeconomia circular. Núcleos maduros coexistem com nichos emergentes, indicando espaço para reconfiguração. O método é implementado no pacote R `birddog`.

Palavras-chave: trajetórias tecnológicas, biogás, vinhaça, biorrefinarias, redes de citação, Brasil.

Abstract: This paper maps technological trajectories in global biogas research through trajectory detection on temporal citation networks, applied to 58,452 documents from OpenAlex (1990–2024). The analysis identifies 17 research communities in a core–periphery structure and reveals a three-phase field evolution: agricultural experimentation (1990s), industrial upgrading (2010s), and a 2020s inflection toward circularity. Brazil, concentrated in community g13, exhibits four trajectories documenting the transition from vinasse energy potential estimates to circular biorefineries aligned with the RenovaBio framework. A key-route main path analysis reveals a nine-paper citation backbone (2009–2025) connecting macro-level estimates to circular bioeconomy models. Mature cores coexist with emerging niches, indicating scope for technological reconfiguration. The method is implemented in the open-source R package `birddog`.

Keywords: technological trajectories, biogas, vinasse, biorefineries, citation networks, Brazil.

1. Introduction

Biogas sits at the intersection of three pressing global challenges: the energy transition, agricultural waste management, and the circular bioeconomy. As countries pursue decarbonization and resource efficiency, the valorization of agricultural and agro-industrial residues (sugarcane vinasse, animal manure, crop residues, and food processing waste) through anaerobic digestion has become a strategic technological route (Manikandan *et al.*, 2023; Martín-Espejo *et al.*, 2022). Biogas not only produces renewable energy but also enables nutrient recovery and greenhouse gas abatement, making it a cornerstone of circular agri-food systems.

Despite the growing strategic importance of biogas, understanding how its research base has evolved over more than three decades requires systematic empirical evidence. The field spans multiple technological routes, from traditional anaerobic digestion and biomethane upgrading to emerging frontiers such as power-to-gas systems, nanoparticle-enhanced processes, and hybrid microgrids. Moreover, different countries and regions have channeled their research efforts toward distinct biogas applications shaped by local production contexts: Europe has built its knowledge base around energy crops and centralized plants, Southeast Asian countries have focused on small-scale rural digesters, and Brazil has carved a distinctive niche in the valorization of high-organic-load agro-industrial waste, particularly sugarcane vinasse (Salomon; Lora, 2009).

Existing reviews of biogas research tend to be narrative or focused on specific sub-technologies, and they rarely trace how research communities form, grow, recombine, and decline over time. A systematic mapping of the dynamic structure of the biogas knowledge base, one that reveals not only what researchers study but how the collective direction of inquiry shifts, is lacking. This paper addresses this gap by applying trajectory detection on temporal citation networks to map the evolution of global biogas research as a system-level process.

Specifically, we analyze 58,452 biogas-related documents from OpenAlex (1990–2024), identify seventeen research communities organized in a core–periphery structure, and characterize their dynamics through four interpretable states: emergence, convergence, divergence, and dormancy. Beyond the global mapping, we examine Brazil's distinctive trajectory within the field, tracing how Brazilian research evolved from early estimates of vinasse energy potential toward the design of integrated circular biorefineries aligned with the RenovaBio policy framework.

This paper contributes in three ways: (i) it maps the global biogas knowledge structure into seventeen communities and reveals a three-phase periodization of the field (agricultural experimentation, industrial upgrading, and circularity); (ii) it identifies six systematic trajectory patterns across these communities; and (iii) it details Brazil's role as a leader in agro-industrial biogas research, contextualizing its trajectory within the global field and drawing implications for agricultural policy and the bioeconomy.

The analysis uses the `birddog` R package, an open-source implementation of the trajectory-detection pipeline, enabling replication and extension to other agro-industrial domains.

2. Literature review

2.1 Technological trajectories and innovation dynamics

Innovation unfolds through paradigms and trajectories: paradigms define the problem framings and solution principles that guide search, while trajectories represent the feasible paths within a given techno-scientific pattern (Dosi, 1982). Positive feedback and increasing returns can reinforce early choices, generating path dependence (David, 1985) and potential lock-in (Arthur, 1990). Empirically detecting trajectories, therefore, helps identify promising research fronts, monitor consolidation that may signal premature closure, and detect divergence that can open transition pathways.

Citation networks provide a scalable empirical window into these processes, because citations record researchers' choices about which knowledge to build upon (Hummon; Dereian, 1989; Verspagen, 2007). The dominant approach, Main Path Analysis (MPA), extracts influential routes by following citation chains (Batagelj, 2003). However, MPA is route-based and tends to underrepresent trajectories as system-level objects, i.e., communities that form, recruit entrants, split, merge, and decline. In parallel, the emergence-mapping literature has developed tools to detect novelty and rapid growth in research fields (Rotolo; Hicks; Martin, 2015; Carley *et al.*, 2017), but often without an explicit link to evolutionary concepts such as paradigms, path dependence, and lock-in. Our approach bridges these two literatures by treating trajectories as evolving communities and classifying their dynamics into interpretable states.

2.2 Biogas as an evolving technological domain

Biogas research has undergone a remarkable transformation over the past three decades. In its early phase, biogas technology was primarily associated with small-scale rural applications: domestic digesters in developing economies and on-farm manure management in European agriculture (Bond; Templeton, 2011). The 2010s marked a decisive shift toward industrialization. Driven by renewable energy mandates and urbanization, research expanded into biomethane upgrading, grid injection, and large-scale life cycle assessment (LCA), with European research consolidating around energy crops as feedstock and centralized co-digestion plants (Weiland, 2010).

Brazil occupies a distinctive position in this landscape. The country's sugarcane ethanol industry generates massive volumes of vinasse, a high-organic-load liquid effluent whose anaerobic treatment produces biogas as both an energy source and an environmental management solution (Salomon; Lora, 2009). Brazilian research has evolved from early estimates of electric energy potential (Salomon; Lora, 2009) toward sophisticated techno-economic analysis of first and second-generation (1G2G) sugarcane biorefineries (Rodriguez *et al.*, 2018; Volpi *et al.*, 2023), integrated with the RenovaBio decarbonization credits framework. This trajectory positions Brazil not as a follower of the European energy-crop model but as a global leader in the valorization of agro-industrial by-products through biogas technology.

Despite the richness of biogas as a research domain, no prior study has systematically mapped how these different national and regional research paths relate within the global field, or how the collective direction of inquiry has shifted from agricultural experimentation to industrial integration and circularity.

3. Methodology

3.1 Data and corpus

We retrieved 58,452 documents from OpenAlex (Priem; Piwowar; Orr, 2022) using the query `title_and_abstract.search = ‘‘biogas’’`. The corpus spans all indexed document types, with articles comprising the majority (48,869 documents). The dominant language is English (52,114 documents), followed by Indonesian (2,464), Spanish (1,042), and Portuguese (931). Non-English titles and abstracts were translated using the `polyglotr` R package (Iwan, 2026), which interfaces with the Google Translate API.

From this corpus, we constructed a direct citation network retaining only internal citations (edges where both citing and cited documents belong to the dataset), yielding 29,490 connected documents. The giant connected component retains 28,820 documents (approximately 50% of the full corpus), indicating a highly connected knowledge structure. We applied the Louvain algorithm (Blondel *et al.*, 2008) for community detection, identifying seventeen research communities.

3.2 Trajectory detection pipeline

The trajectory-detection methodology follows the `birddog` pipeline (Figure 1), an open-source R package that implements a reproducible sequence of steps previously applied in related empirical studies (Souza, 2016; Souza; Ballini *et al.*, 2021; Souza; Miranda *et al.*, 2022; Miranda *et al.*, 2025; Biazatti *et al.*, 2024; Felizardo *et al.*, 2025; Matos *et al.*, 2023; Maria; Ballini; Souza, 2023).

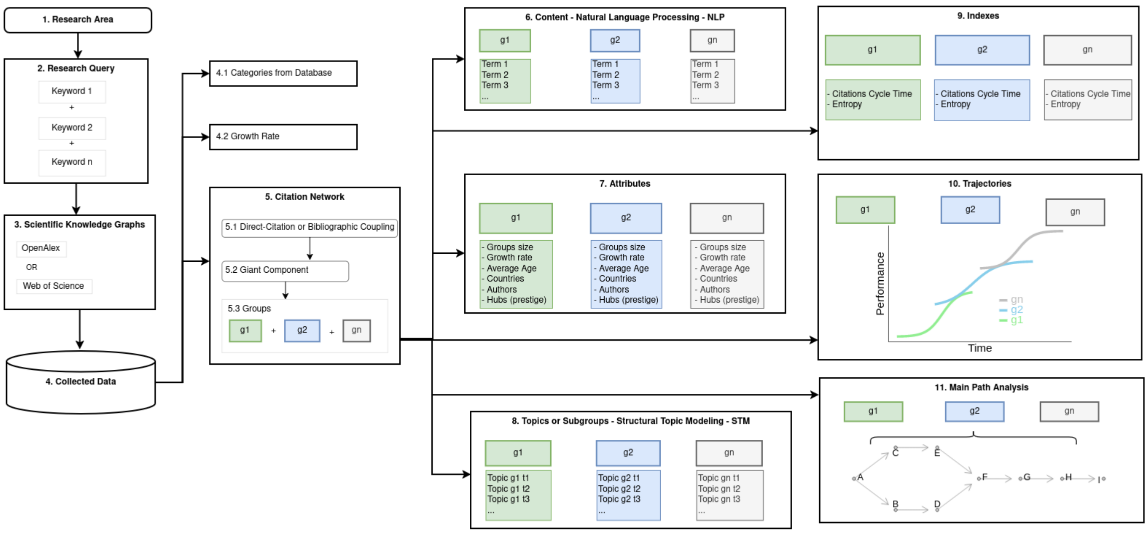

Figure 1 – Workflow of the `birddog` trajectory-detection pipeline. The procedure can be applied to either scientific publications or patents.
Source: Authors' elaboration.

The pipeline proceeds in three stages. First, the *static mapping* constructs the citation network, identifies the giant component, and detects communities via the Louvain algorithm. Each community is characterized by representative terms extracted from titles and abstracts (tf–idf weighting) and by hub roles based on within-group and cross-group connectivity (Guimera; Amaral, 2005).

Second, the *dynamic tracking* generates a sequence of reverse cumulative clusterings: for each year, a cumulative subnetwork is built and partitioned using consistent settings. Clusters are linked across consecutive years using Jaccard similarity (threshold $\tau_J = 0.1$), forming a temporal directed acyclic graph (DAG). Main trajectories are extracted as maximum-score paths on this DAG using dynamic programming, retaining the top three disjoint trajectories per group with a minimum path length of five consecutive years.

Third, each trajectory is *classified* using two complementary indicators: citation cycle time (CCT), which measures the pace of knowledge turnover (Kayal; Waters, 1999), and Shannon entropy, which captures thematic concentration versus diversification. Together, these indicators support classifying trajectories into four dynamic states: *emergence* (low CCT, rising entropy), *convergence* (declining CCT, declining entropy), *divergence* (declining CCT, rising entropy), and *dormancy* (rising CCT, declining entropy). The full technical details and parameter specifications are available in the `birddog` package documentation (`roneyfraga.com/birddog`).

4. Results: global biogas field

4.1 Knowledge structure

The seventeen communities detected by the Louvain algorithm partition the giant component into research groups of varying size, maturity, and structural role (Table 1).

Table 1 – Summary of the seventeen research communities detected in the biogas citation network. Growth rate is the annual exponential growth coefficient (%). Dominant hub type follows the Guimera e Amaral (2005) classification: provincial (R5, within-group influence), connector (R6, cross-group bridging), and kinless (R7, field-wide bridging).

Group	Description	Docs	Avg. year	Growth (%)	Dominant hub
g1	Biogas Production & Standardization	6,448	2017	9.7	Kinless (R7)
g2	Rural Adoption & Developing Economies	4,157	2015	8.3	Kinless (R7)
g3	Large-Scale Systems & Life Cycle Assessment	2,960	2016	8.0	Kinless (R7)
g4	Upgrading & Biomethane	2,893	2017	11.3	Connector (R6)
g5	Digestate & Nutrient Recovery	1,937	2017	11.7	Kinless (R7)
g6	Microbiology & Metagenomics	1,805	2015	7.0	Kinless (R7)
g7	Reforming & Hydrogen Production	1,588	2017	10.8	Provincial (R5)
g8	In-situ Upgrading & Power-to-Gas	1,529	2017	12.6	Kinless (R7)
g9	Engine Applications & Emissions	1,289	2016	9.0	Kinless (R7)
g10	Algal Biorefineries	924	2017	10.3	Connector (R6)
g11	Monitoring & Farm Management	853	2017	10.0	Provincial (R5)
g12	Modeling & Machine Learning	818	2017	10.9	Kinless (R7)
g13	Techno-Economic Risk Analysis	598	2015	8.1	Kinless (R7)
g14	Nanoparticles & Yield Enhancement	442	2017	12.4	Connector (R6)
g15	Biorefinery Reliability & Computational Fluid Dynamics	295	2011	6.1	Kinless (R7)
g16	Bioelectrochemical Cells	47	2013	4.5	Connector (R6)
g17	Hybrid Microgrids	31	2019	15.1	Provincial (R5)

The structure is consistent with a core–periphery pattern. Group 1 (Biogas Production & Standardization, 6,448 documents) is the field's foundational core, whose biochemical methane potential assay protocols underpin research across multiple communities; its kinless hubs (R7) bridge the entire field. Group 6 (Microbiology & Metagenomics, 1,805 documents) serves as the field's knowledge engine, with predominantly provincial hubs (R5) reflecting a self-contained specialist subdiscipline dominated by Germany. Group 4 (Upgrading & Biomethane, 2,893 documents) is one of the highest-growth communities (11.3% annual), with connector hubs (R6) linking it to both the core anaerobic digestion group and the power-to-gas community. Among the emerging niches, Group 17 (Hybrid Microgrids, 31 documents) is the smallest but fastest-growing (15.1% annual), led by India, while Group 14 (Nanoparticles & Yield Enhancement, 442 documents) is another fast-growing niche (12.4%) with exclusively connector hubs.

The geographic distribution (Figure 2) reveals that developing countries concentrate in application-oriented communities linked to domestic challenges: Indonesia in monitoring and farm management (g11), Brazil in techno-economic analysis (g13), and Malaysia in modeling and machine learning (g12). This pattern suggests that local production contexts and resource endowments channel scientific contributions toward specific communities.

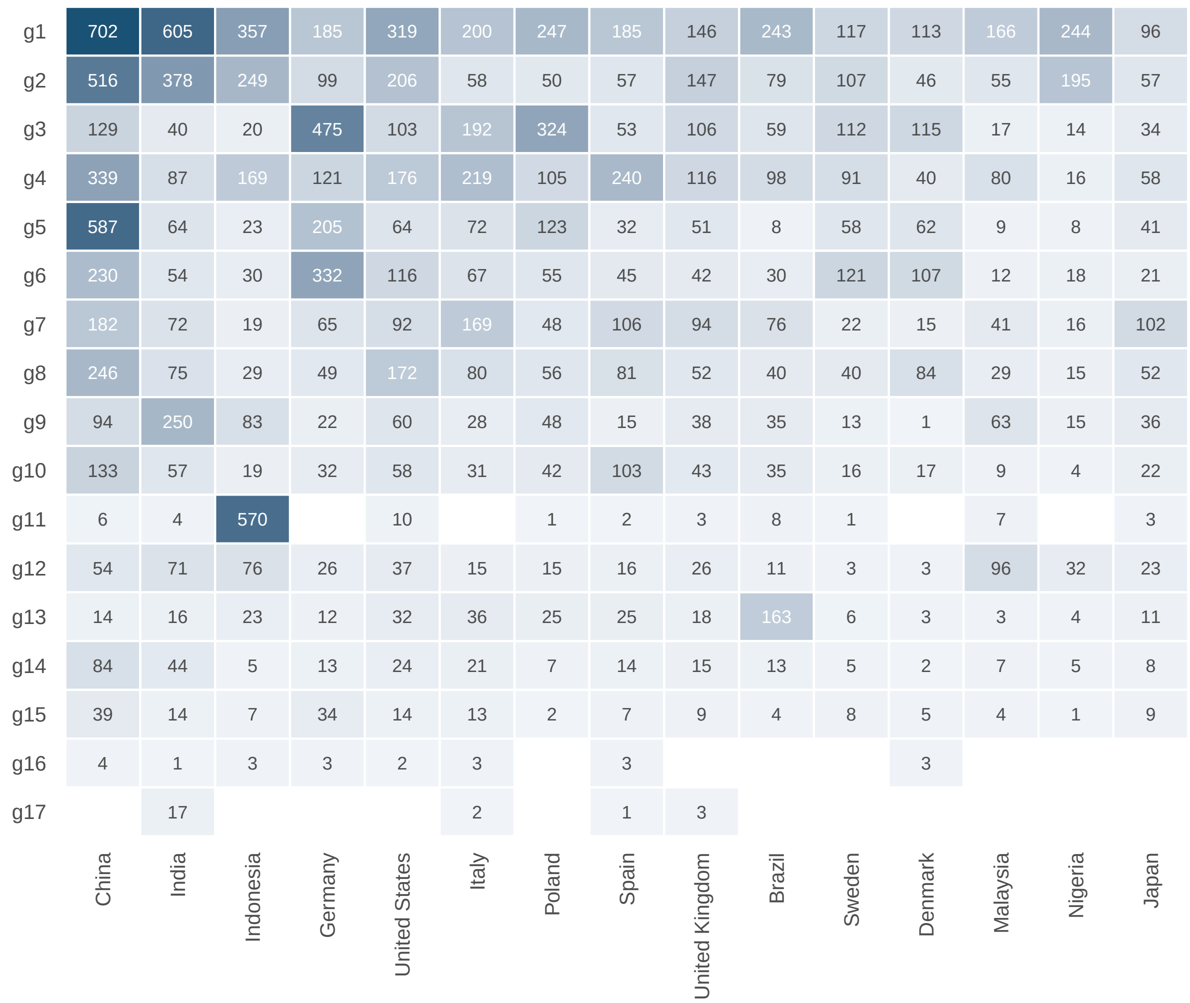

Figure 2 – Geographic distribution of publications by research community. Rows show the seventeen groups; columns show the fifteen most productive countries. Cell shading indicates the number of documents.

Source: OpenAlex data. Authors' elaboration.

4.2 Trajectory dynamics

From the trajectory extraction across all seventeen groups, we highlight six exemplary intra-group trajectories that collectively illustrate the four dynamic states (Table 2).

Table 2 – Six exemplary intra-group trajectories illustrating the four dynamic states. Em = Emergence; Di = Divergence; Co = Convergence; Do = Dormancy/Shift. CCT = citation cycle time trend; Entropy = normalized Shannon entropy trend.

Trajectory	Theme	State	CCT	Entropy	Core → Shift
g17:tr1	Hybrid Microgrids	Em	Low (3–4 yr)	Rising	Thermal profiles → microgrid optimization
g14:tr1	Nanoparticle Anaerobic Digestion	Em	Declining	Rising	Fe/Co/Ni NPs → $Cu@Fe_3O_4$ nanostructures
g8:tr1	Power-to-Gas	Di	Declining	Rising	Microbial electrolysis + anaerobic digestion coupling → cascading circular systems
g12:tr1	AI & Optimization	Co	Declining	Declining	Neural networks → AutoML
g5:tr1	Digestate Valorization	Di	Stable	Rising	Bio-slurry review → circular bioeconomy
g1:tr1	Anaerobic Digestion Standardization	Do	Rising	Declining	Biochemical methane potential assays → circularity & grid integration

Emergence appears most clearly in the field's smallest and newest communities. Group 17 (Hybrid Microgrids) exhibits the lowest CCT in the corpus (3–4 years), indicating rapid displacement of older references, a hallmark of fast-moving research fronts. Group 14 (Nanoparticle-Enhanced Anaerobic Digestion) displays a similar pattern: declining CCT and rising entropy signal a niche still consolidating, evolving from early iron/cobalt/nickel nanoparticle studies toward advanced $Cu@Fe_3O_4$ nanostructures.

Divergence describes trajectories where the dominant path splits into sub-paths exploring distinct directions. Group 8 (Power-to-Gas) diverges from early microbial electrolysis cell work toward cascading circular bioenergy systems. Group 5 (Digestate & Nutrient Recovery) shows a parallel divergence: from agronomic bio-slurry studies toward a circular bioeconomy reframing.

Convergence appears in Group 12 (Modeling & Machine Learning), where declining entropy alongside declining CCT indicates concentration on fewer methodological approaches. The main trajectory traces an arc from heterogeneous early modeling (neural networks, fuzzy logic, genetic algorithms) toward AutoML as the emergent dominant paradigm.

Dormancy with paradigmatic shift characterizes Group 1 (Anaerobic Digestion Standardization), the largest community. Rising CCT and declining entropy suggest a mature trajectory approaching paradigmatic closure. However, the trajectory analysis reveals a recent discontinuity: a shift from experimental yield optimization anchored in biochemical methane potential assays (Angelidaki *et al.*, 2009) toward circularity and grid integration themes, suggesting that paradigmatic reorientation can occur even within a dormant trajectory.

The trajectory visualization for Group 13 (Techno-Economic Risk Analysis), discussed in detail in Section 5, illustrates the sequential replacement pattern characteristic of Brazilian biogas research (Figure 3).

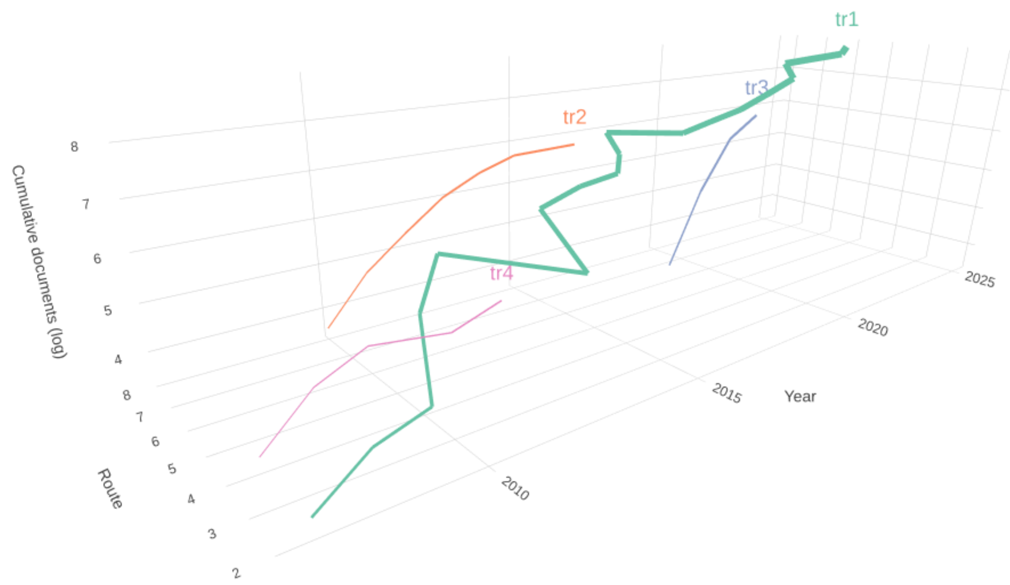

Figure 3 – Three-dimensional trajectory visualization for Group 13 (Techno-Economic Risk Analysis). Each trajectory line represents a cluster of documents that attracts new publications through citation proximity over time. The x-axis represents publication year, the y-axis the route position, and the z-axis the cumulative document count. Four trajectories are visible: tr1 (2007–2025, dominant path), tr2 (2010–2016, bridging), tr3 (2019–2022, specialized), and tr4 (2007–2011, foundational). The convergence of parallel paths toward a central thematic core reflects the community's maturation around industrialization and circularity.

Source: Authors' elaboration using `birddog`.

4.3 Three-phase periodization

The combined structural and trajectory evidence converges on a three-phase periodization of the biogas field. The first phase, spanning the 1990s and early 2000s, was characterized by *agricultural experimentation*: domestic biogas plants in developing economies (g2) and early anaerobic digestion studies (g1) formed the field's foundation. The second phase, accelerating through the 2010s, marked an *industrial upgrading* stage focused on biomethane purification, grid injection, and life cycle assessment optimization (g4, g3). The third phase, emerging in the 2020s, represents an *inflection toward circularity and systems integration*: digestate valorization within the circular bioeconomy (g5), biogas–electricity grid coupling (g8), and hybrid microgrids (g17).

The system-wide trajectory patterns reinforce this periodization (Table 3). Communities associated with the 1990s–2000s exploration phase (g2, g6) exhibit persistent competition among multiple trajectories, consistent with high variety and no dominant design. Communities from the 2010s industrialization stage (g11, g12) display replacement patterns, where newer trajectories sequentially displace older ones. The branching groups (g4, g8, g15) concentrate in the 2020s inflection, where new paths actively diverge from established cores.

Table 3 – Classification of the seventeen groups by intra-group trajectory pattern. Si = single trajectory; Re = replacement; Co = persistent competition; Br = branching/divergence; Do = dormancy with shift; Em = emerging.

Pattern	Groups	Interpretation
Si	g5, g9, g16	Paradigmatic homogeneity—unified search direction with no competing alternatives
Re	g11, g12, g13, g14	Convergence via sequential displacement—newer trajectories replace older ones
Co	g2, g3, g6, g7, g10	Persistent plurality—multiple search paths coexist without clear dominance
Br	g4, g8, g15	Divergence—new paths branch from the established core
Do	g1	Mature core with paradigmatic reorientation in recent trajectory segment
Em	g17	Single trajectory by youth, not by consolidation

5. Results: Brazil's biogas trajectory

5.1 Brazil in the global biogas field

The geographic analysis (Figure 2) reveals that Brazilian biogas research is primarily concentrated in Group 13 (Techno-Economic Risk Analysis, 598 documents), a community specialized in the energy potential of sugarcane vinasse and landfill gas. Unlike European contributions, which dominate the core anaerobic digestion community (g1) and the energy-crop life cycle assessment community (g3), Brazil's niche reflects its agro-industrial production context: the world's largest sugarcane ethanol industry generates massive volumes of vinasse, a high-organic-load liquid effluent that is both an environmental liability and a biogas resource.

Group 13 is characterized by kinless hubs (R7) that bridge multiple communities, particularly linking to g1 (anaerobic digestion fundamentals) and g5 (Digestate & Nutrient Recovery). This structural position indicates that Brazilian techno-economic research does not exist in isolation but connects the applied assessment of agro-industrial biogas with foundational process knowledge and circular economy frameworks.

5.2 Trajectory evolution of g13

The trajectory analysis of Group 13 detects four trajectories that track the evolution of Brazilian biogas research from foundational anaerobic treatment studies to circular bioeconomy strategies (Figure 3).

Trajectory tr1 (2007–2025) is the group's dominant path. It tracks the long-term thematic shift from general energy potential estimates toward advanced systemic integration. Papers entering after 2020 (Volpi *et al.*, 2023) highlight a recent push toward 1G2G biorefinery integration and the role of biogas in the national grid. The most recent entry (Melo *et al.*, 2024) frames methane production from vinasse as a critical environmental management solution for São Paulo state.

Trajectory tr2 (2010–2016) bridged the gap between basic research and industrial application. Anchored by studies on landfill modeling and multi-waste quantification, it moved the group toward estimating Brazil's generation potential from large-scale waste streams, preparing the ground for the economic analyses that followed.

Trajectory tr3 (2019–2022) represents a more recent phase of specialized research, with late entries focusing on process stability and specific industrial residues. Its emergence alongside tr1 indicates that even as the dominant trajectory consolidated, new specialized fronts continued to form.

Trajectory tr4 (2007–2011) established the technical foundations of the group. Anchored by canonical works on anaerobic treatment of high-organic-load effluents, these papers focused on the basic biological performance of reactors rather than the economic or systemic modeling that characterizes later phases. This trajectory did not persist as an independent branch; its contributions were absorbed into the broader research agenda as the community matured.

The four trajectories are supported by a key-route main path that illustrates a clear linear progression in the field's priorities: from macro-estimates of electric potential for biogas in Brazil (Salomon; Lora, 2009), through infrastructure and multi-waste studies in the mid-2010s, to regional economic modeling for São Paulo (Pereira; Cavalett; Bonomi, 2020), and finally to the circular bioeconomy transition anchored by recent integrative work (Deepanraj; Senthilkumar *et al.*, 2023).

The 3D trajectory visualization (Figure 3) shows several parallel paths that eventually align toward a central thematic core. This visual pattern, combined with declining entropy (0.85 to 0.7) and declining CCT (8.5 to 6.5 years), indicates a community that is rapidly maturing and narrowing its focus around industrialization and circularity.

5.3 Core knowledge lineage: key-route main path

To complement the system-level trajectory analysis, we extract the key-route main path (Liu; Lu, 2012) for Group 13, identifying the citation backbone that defines the community's intellectual lineage (Figure 4).

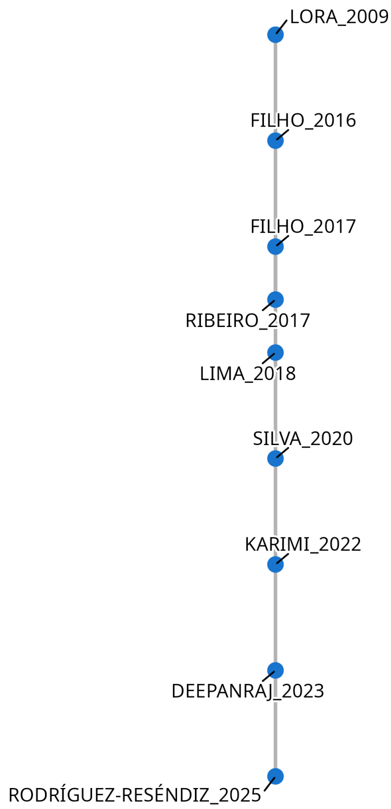

Figure 4 – Key-route main path for Group 13 (Techno-Economic Risk Analysis). Each node represents a document on the highest-traversal citation chain. The sequence reveals a linear progression from macro-level potential estimates to circular bioeconomy modeling.
Source: Authors' elaboration using `birddog`.

The main path traces a nine-document chain spanning 2009 to 2025 and reveals three thematic phases. The first phase (2009–2016) established macro-level potential: Salomon e Lora (2009) estimated aggregate electric potential for biogas in Brazil, and Santos, Barros e Tiago Filho (2016) narrowed the focus to wastewater treatment plant feasibility. The second phase (2017–2020) expanded and regionalized the analysis: Santos, Barros e Tiago Filho (2017) and Ribeiro *et al.* (2017) assessed multiple organic wastes and vinasse-specific economics, Lima *et al.* (2018) proposed combining landfill and wastewater biogas for distributed generation, and Silva *et al.* (2020) modeled vinasse biogas for São Paulo state. The third phase (2022–2025) shifted toward integration: Karimi, Ehrampoush e Tabatabaee (2022) reviewed bioreactor configurations, Deepanraj, Senthilkumar *et al.* (2023) reframed vinasse within the circular bioeconomy, and Rodríguez-Reséndiz *et al.* (2025) applied predictive modeling to sugar agro-industry by-products.

5.4 Current research fronts

Three interconnected research fronts characterize Brazil's current position in the biogas field.

1G2G biorefinery integration. A major current trend is evaluating biogas's role within first and second-generation (1G2G) sugarcane biorefineries. Research examines the optimal allocation of biogas between electricity generation and biomethane production, comparing economic returns under different configurations and market scenarios (Volpi *et al.*, 2023; Rodriguez *et al.*, 2018). This work positions biogas not as a standalone technology but as an integral component of Brazil's broader bioenergy system.

RenovaBio policy alignment. Brazilian research is increasingly framed within the RenovaBio decarbonization credits framework. Studies employ sensitivity and risk analysis to navigate market uncertainties, evaluating how biogas from vinasse and other agro-industrial wastes can optimize distributed energy generation while maximizing decarbonization credit revenues. This policy-research alignment distinguishes Brazilian biogas research from the more technology-focused European tradition.

Regional environmental solutions. In high-production regions such as São Paulo state, biogas production is now presented as a critical environmental management solution for industrial waste, addressing both energy recovery and effluent treatment requirements (Melo *et al.*, 2024). This framing resonates with the global circularity inflection while remaining grounded in the specific environmental challenges of Brazil's agro-industrial landscape.

5.5 Brazil's international role

Brazil plays a unique role in the global biogas agenda by demonstrating the scalability of biogas in a large-scale agro-industrial context. While European research has consolidated around dedicated energy crops, Brazil has shifted the conversation toward valorizing industrial by-products. This distinction is consequential: energy-crop biogas faces scrutiny over land-use competition with food production, whereas vinasse-based biogas transforms an environmental liability into an energy asset with no additional land requirements.

Brazilian research provides the international community with advanced models of industrial symbiosis, demonstrating how the sugarcane value chain can close its nutrient and energy cycles using biogas technology. Brazil's work on combining landfill gas, wastewater, and agro-industrial waste for distributed generation also serves as a blueprint for developing economies with large primary sectors, such as Argentina (soy processing), India (rice straw and dairy waste), and Southeast Asian nations (palm oil mill effluent).

6. Discussion

The trajectory evidence points to two broader implications. First, the coexistence of dormancy in the field's largest community (g1, rising CCT, declining entropy) with emergence in peripheral niches (g17, g14) indicates that the biogas field has not locked into a single dominant trajectory (Arthur, 1990). Mature cores provide methodological continuity while emerging niches sustain the variety needed for reconfiguration, consistent with "coherent novelty with growth" (Rotolo; Hicks; Martin, 2015; Carley *et al.*, 2017). For policy, this means that the window for shaping technological directions remains open: emergence signals can guide early-stage support, dormancy signals can flag lock-in risk, and divergence patterns can identify branching moments where intervention is most effective.

Second, Brazil's trajectory in g13 illustrates how biogas policy is most effective when aligned with existing agro-industrial chains. Two features distinguish the Brazilian model from the European energy-crop pathway: vinasse-based biogas valorizes an existing waste stream without additional land-use change, and the RenovaBio framework aligns private investment with decarbonization goals through market-based credits. This combination of feedstock advantage and institutional design positions Brazil as a reference for other agricultural economies seeking to integrate biogas into their primary-sector value chains.

7. Conclusions

This paper mapped technological trajectories in global biogas research using a computational model applied to 58,452 documents from OpenAlex (1990–2024). The analysis identified seventeen research communities organized in a core–periphery structure and revealed a three-phase field evolution: agricultural experimentation (1990s), industrial upgrading (2010s), and a 2020s inflection toward circularity and systems integration.

The paper offers three contributions. First, it maps the global biogas knowledge structure and reveals six systematic trajectory patterns (paradigmatic homogeneity, sequential replacement, persistent competition, branching, dormancy with reorientation, and early-stage emergence) that capture how communities organize their search dynamics. Second, it details Brazil's distinctive trajectory from vinasse energy potential estimates to integrated circular biorefineries, positioning the country as a global leader in agro-industrial biogas valorization. Brazilian research, concentrated in community g13, demonstrates how a large primary-sector economy can leverage biogas technology to close industrial nutrient and energy cycles, with the RenovaBio framework providing institutional alignment between research and commercial deployment. Third, it demonstrates the utility of the `birddog` trajectory-detection framework for agricultural-technology domains, providing policy-relevant diagnostics such as emergence, lock-in risk, and transition windows.

Several limitations should guide interpretation. The method was demonstrated on a single domain (biogas); applying it to contrasting agro-industrial cases would strengthen generalizability claims. Parameter choices (Jaccard threshold, clustering algorithm, minimum trajectory length) influence the granularity of detected trajectories. OpenAlex's English-language coverage may underrepresent Brazilian Portuguese-language work, potentially understating Brazil's contribution in applied and policy-oriented research. Future work should extend the analysis to other agro-industrial domains, incorporate patent data to capture trajectories closer to commercial deployment, and implement within-group Structural Topic Modeling for finer subtopic decomposition.

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