

Systematic Review

Toward Sustainable Bioenergy Supply Chain Management in Latin America: A Systematic Review of Optimization, Circular Valorisation, Methane Mitigation, and Traceability of Agricultural and Livestock Residues

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Abstract

The agricultural and livestock sectors of Latin America produce a large number of residues that could be converted into energy through bioenergy production processes. However, the bioenergy sector still faces several limitations across the region, including fragmented logistics systems, weak coordination among institutions, and limited integration of environmental, digital, and compliance-related performance indicators. This review systematically analyses residue-based bioenergy value chains in Latin America between 2015 and 2025 using the PRISMA methodology to evaluate selected peer-reviewed studies and regional reports indexed in Scopus, ScienceDirect, SpringerLink, and IEEE Xplore, and institutional repositories. The final synthesis included 37 studies and institutional contributions, which were further disaggregated into 208 country–residue observations for the regional and feedstock distribution analysis. The review identified three main research gap categories: the limited integration of collection and logistics systems, the insufficient treatment of uncertainty, circularity, and traceability within optimization models, and the weak incorporation of governance and institutional coordination into bioenergy value-chain design. The analysis includes biogas, biomethane and related residue-based systems, with attention to supply-chain optimization, policy alignment, methane mitigation metrics, and traceability requirements. Results indicate that although technologies such as biomass pretreatment, process intensification, and upgrading processes continue to improve conversion performance, most studies still focus mainly on technical feasibility and biomass potential. Less attention is given to governance constraints, uncertainty analysis, and monitoring systems capable of supporting regulatory compliance. This research introduced the Sustainable Bioenergy Chain Management Framework (SBCMF) to respond to these limitations and bring together different aspects of bioenergy management within one analytical structure. The framework combines supply-chain optimization under spatial and temporal constraints, circular economy valorisation, methane-related climate performance, and



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digital traceability, while also linking techno-economic system design with governance and monitoring requirements. In this way, it can help support the development of more transparent and low-carbon bioenergy systems across Latin America.

Keywords: agricultural residues; supply chain optimization; circular economy; biomass valorisation; sustainability; methane mitigation; policy integration

1. Introduction

In Latin America, large quantities of agricultural and livestock residues are generated each year, which have great potential for energy recovery and circular-economy applications [1–4]. There are some notable bioenergy projects currently in the region, but the growth of optimized and long-lasting value chains remains uneven. The lack of progress is mostly due to logistical challenges, insufficient coordination across different levels of government, and the limited integration of environmental and digital performance indicators [5–8]. Recent reviews [7–10] indicate that most evaluations regarding biomass and biogas potential predominantly emphasize resource mapping, while insufficiently addressing the practical design and execution of supply chains. Consequently, disparity persists between assessments of renewable resource potential and the execution of feasible, low-carbon initiatives.

Given the growing emphasis on sustainability, the region is promoting its circular-economy agenda [6,11]. However, structural barriers such as limited data quality, weak institutional coordination, and slow technology adoption continue to limit large-scale deployment and cross-sector integration [10–12]. These challenges are emerging as global policies that are calling for stronger traceability and greater climate accountability [5]. The European Union’s Regulation on Deforestation-Free Products (EUDR), which entered into force in 2023, imposes stricter sustainability criteria on commodities connected to Latin American agro-industrial supply chains [12–15]. Although recent discussions have focused on phased implementation and possible extensions for certain operators, the overall trend is clear: the transition is toward verifiable, geolocated, and deforestation-free supply chains [16,17].

As methane continues to pose a serious threat to our planet and contribute to climate change, methane mitigation is now a strategic priority for reaching near-term climate goals. The urgency of reducing agricultural CH₄ emissions within this decade has been recognized worldwide and nationally by various organizations under the Global Methane Pledge; for example, many studies show that there are major, inexpensive ways to reduce methane emissions associated with livestock production [18,19]. In livestock-dense areas, bioenergy projects provide an ideal solution as they can reduce methane emissions through capturing and avoiding them, while also providing benefits of improving climate, increasing the security of energy sources, recovering nutrients, and developing rural areas [20,21].

Through advances in technology, the conversion of biogas and biomethane is being used to add value to the different types of residual products (agricultural waste and industrial by-products) that are available [22]. The development of biogas and biomethane systems is beyond traditional digestion and upgrading processes toward a more integrated and efficient way of doing things. The recent literature [23–27] on advanced biogas and biomethane systems also includes pretreatment, process intensification, and upgrading technologies with corresponding increases in yields, improved process stability, and reduced lifecycle impacts. This is important because it relates directly to decentralized supply chains in Latin America. However, the literature shows that various elements of supply

chain optimization (for example hub location, transportation routes, system size, product integration energy and bio-fertilizer, and risk management) do not currently align with government policies and/or certification and traceability systems, particularly in developing countries [28–31].

The changing dynamics of bioenergy in Latin America provide many chances to create new businesses while also showing varied potential across the region. According to the studies conducted by [32–36], there is significant technical potential for bioenergy generation from agricultural byproducts (crop residues and livestock manure); however, logistical, infrastructure, and capital constraints have delayed the development of new projects. Results from [37–39] demonstrated that there has also been increasing interest in circular economy strategies and using biomass. Reliable data and sound governance are both critical factors to developing a financially viable biomass value chain. Furthermore, ongoing research from ecological economics regarding the EUDR illustrates the current impact on Latin American exporters, especially soy, beef, and coffee, which all require traceable, deforestation-free supply chains [7,14,15,17]. Bioenergy projects can enhance transparency in land use through these supply chains while concurrently benefiting these projects.

Emerging as a significant methodological trend with direct relevance to the region are converging approaches integrating optimization, environmental assessment, and geospatial analysis. The existing literature indicates that mixed-integer linear programming (MILP), life cycle assessment (LCA), and geographic information systems (GIS) are typically utilized together and in conjunction with each other to examine the economic and environmental performance of bioenergy network designs under uncertainty [40–42]. Collective consideration of logistics, market structures, and traceability regarding bioenergy potential has been historically limited, apart from the fact that those variables clearly impact on both the long-term climate and development consequences of bioenergy [40]. As policy requirements continue to evolve, this limitation will only increase as bioenergy value chains will increasingly be expected to provide an integrated solution that combines both cost and emissions performance with verified traceability and measurable methane reductions.

By linking current advances in bioenergy research with the evolving sustainability and policy context of the region, a full review of this literature can add value in three primary ways. First, it describes the present situation of bioenergy value chains throughout Latin America using a variety of feedstocks, technologies, and organizational forms while also cataloguing places where innovation (such as process intensification, advanced upgrading, and the recovery of nutrients) may provide the greatest impact [28,33,38]. Second, it provides an approach to integrate and to assess optimization techniques (e.g., planning the location of production facilities, multi-level logistics, and multi-criteria decision-making) along with LCA to better understand their implications for decentralized and smallholder-based supply chains that exist throughout Latin America [20,30]. Third, it proposes a conceptual framework that integrates regulatory frameworks, methane mitigation measurement, and digital tools, creating a clearer path between technical design and profitable, export-oriented bioenergy systems [13,14,19,37,40].

This research provides a novel viewpoint on bioenergy optimization within the constraints of sustainability, pointing to how technological innovation, environmental performance, and institutional governance overlap. The goal is to relate the required technical efficiency model to the evolving demand for verifiable value chains that comply with regulatory obligations. This research makes an important contribution to the literature by making connections among supply chain optimization, methane mitigation objectives and circular economy principles, as well as meeting emerging traceability requirements for frameworks like the EUDR. The focus of this research extends beyond cost and emission

of metrics and includes consideration of data accuracy, institutional coordination, and characteristics of decentralized and smallholder-based systems in Latin America.

This systematic review is mainly positioned within the field of bioenergy supply-chain management. It brings together technological, economic, environmental, regulatory, and institutional perspectives that influence the design and implementation of residue-based bioenergy systems. Social aspects are considered when they relate to smallholder participation, cooperation, governance, and access to infrastructure. However, sociological issues such as public acceptance, community opposition, protests, or conflicts related to bioenergy facilities are outside the main scope of this study. The limited number of studies on these issues does not mean they are absent in practice but shows that more research is needed in Latin America.

The study has two main goals. First, to provide a comprehensive overview of the state of knowledge regarding the management and optimization of bioenergy value chains related to agricultural residues within Latin America while also identifying current trends, research methods and persistent technical, logistical, and institutional obstacles affecting the development of these value chains. The second goal is to develop an integrated approach to Sustainable Bioenergy Chain Management (SBCMF) that integrates the use of optimization tools (e.g., MILP and LCA), circular economy strategies, methane accounting, and digital traceability, all of which are intended to guide the establishment of a regionally based and practical roadmap for policymakers, researchers, and practitioners to promote the transparent establishment of low-carbon bioenergy systems in compliance with all applicable regulations throughout Latin America.

The existing literature on bioenergy remains fragmented across different analytical perspectives. Previous reviews have generally focused on biomass potential, technological performance, or policy analysis, while giving less attention to the integration of supply-chain optimization, methane mitigation, digital traceability, governance, and smallholder or decentralized systems within a single regional framework. Table 1 was therefore developed to summarize the recurring patterns identified across representative groups of reviews rather than to compare individual publications. This comparison also shows how the present study extends previous work by linking techno-economic modelling with compliance, traceability, and governance requirements relevant to the Latin American context.

Table 1. Comparison of this study with existing bioenergy review literature.

Analytical Dimension	Typical Bioenergy Potential Reviews	Optimization-Focused Reviews	Policy-Focused Reviews	This Study
Regional focus on Latin America	✓	~	~	✓
Agricultural residues emphasis	✓	~	×	✓
Supply-chain optimization	×	✓	×	✓
Integration of LCA with optimization	~	✓	×	✓
Methane mitigation explicitly addressed	×	×	✓	✓
Traceability/EUDR relevance	×	×	✓	✓
Digitalization (IoT, MRV)	×	×	×	✓
Governance integration	~	×	✓	✓
Smallholder system focus	×	×	×	✓
Conceptual integration framework	×	~	×	✓
Strategic implementation pathways	×	×	✓	✓

✓ Explicitly addressed; ~ Partially addressed; × Not systematically addressed. Source: the authors.

2. Research Approach Description

2.1. Review Design and Scope

The analysis was conducted following a systematic form of analysis and modelling framework (PRISMA), providing the basis for developing an understanding of how agricultural and livestock waste value chains have been created and optimized within the bioenergy sector in Latin America from 2015 to 2025. Aspects of the study were also focused on identifying and analyzing the different types of modelling methods and optimization techniques for the energy sector in the region, emphasizing the analysis on biogas and biomethane systems, which represent the primary technologies used to convert waste into valuable energy products in the region. The results of this analysis show the major trends, characteristics, and barriers that are currently limiting the potential for growing bioenergy value chains within the bioenergy sector in Latin America.

The technological approach includes anaerobic digestion and co-digestion systems, biomethane purification processes, and some thermochemical and hybrid technologies processed within distinct supply chain, techno economic or optimization-oriented models. The literature reviewed is assessed in terms of how the studies describe the flow of material and energy as well as how the process specific information is integrated into model for making decisions at the system level for logistical planning, facility configuration, environmental evaluation and overall value chain optimization considering technology performance based on input parameters.

The representation of the biogas chain can be explained by using mixed integer linear programming (MILP) that is interpreted by the following equation:

$$\min Z = \sum_i C_i^{\text{feed}} F_i + \sum_{i,j} C_{ij}^{\text{trans}} T_{ij} + \sum_k C_k^{\text{capex}} Y_k + \sum_k C_k^{\text{opex}} Y_k$$

Under the following operational and physical constraints:

Feedstock availability constraints

$$F_i \leq A_i$$

Mass and methane yield balances

$$M_k = \sum_i Y_{\text{CH}_4,i} \alpha_{ik} F_i$$

Energy balances

$$E_k = \eta_k M_k \text{LHV}_{\text{CH}_4}$$

Transport flow constraints

$$T_{ij} \leq \bar{T}_{ij} Y_j$$

Facility placing and sizing

$$Y_k \in \{0, 1\}$$

Emissions or circularity constraints

$$\text{GHG}(F, T, Y) \leq \Gamma$$

where the variables and parameters are:

- F_i : quantity of residue collected from source i ($\text{t} \cdot \text{yr}^{-1}$)
- A_i : available residue at source i ($\text{t} \cdot \text{yr}^{-1}$)
- $Y_{\text{CH}_4,i}$: specific methane yield of feedstock i ($\text{m}^3 \text{CH}_4 \cdot \text{t}^{-1}$)
- α_{ik} : distribution coefficient of feedstock i to plant k

- M_k : methane produced at facility k ($\text{m}^3 \text{CH}_4 \cdot \text{yr}^{-1}$)
- η_k : energy conversion efficiency (–)
- LHV_{CH_4} : lower heating value of methane ($\text{MJ} \cdot \text{m}^{-3}$)
- E_k : energy output at facility k ($\text{MWh} \cdot \text{yr}^{-1}$)
- T_{ij} : transported mass between nodes i and j ($\text{t} \cdot \text{yr}^{-1}$)
- $\bar{T}_{ij}$: transport capacity ($\text{t} \cdot \text{yr}^{-1}$)
- Y_k : binary decision variable indicating digester installation at location k
- $C_i^{\text{feed}}, C_{ij}^{\text{trans}}, C_k^{\text{capex}}, C_k^{\text{opex}}$: unit costs of feedstock, transport, capital, and operation
- I : maximum allowable GHG emissions ($\text{kg CO}_2\text{e} \cdot \text{yr}^{-1}$)

The review analysis focusses on incorporating the temporal variability in feedstock supply into the supply-chain optimization models. There are studies [43–45] that use scenario-based or stochastic modelling to illustrate seasonal variation in the availability of feedstock residues and the production of methane from biomass through anaerobic digestion. By defining each of the seasonal scenarios as a discrete scenario with a probability linked to it, the scenario models account for the differences in biomass production and substrate characteristics, including material differences between crops, at the specified intervals of the harvesting cycle, dry season, and post-harvest period. Incorporation of temporal variability is important for evaluating system reliability, sizing of infrastructure, and the long-term economic performance of the biogas production process for dynamically changing supply conditions.

The integration of LCA into MILP optimization models is a strategic approach of the analysis by incorporating emissions at the system level, resources available for nutrient recovery and circularity indicators as either analogous constraints or secondary objectives within the MILP models [46,47]. Such integrated modelling approaches support simultaneous evaluations of economic performance, energy output and environmental consequences, and therefore provide a single structure for decision support [45]. This combined approach moves beyond traditional cost minimization and enables analysis of tradeoffs between economic efficiency and environmental performance, which enables improved system level planning [48].

Several structural constraints will emerge from this analytical perspective. Biomass flows are usually treated as aggregated inputs in most optimization models with no traceability based on origin, location, or compliance [49,50]. Similarly, the emissions associated with methane mitigation are often reported as generic emission factors and not through a separate accounting system focusing on avoided emissions, leaking risk, or fulfilment of nationally determined contribution commitments [51]. Factors impacting smallholder involvement, such as minimum supply amounts, transaction costs, cooperative aggregation arrangements, and unequal access to infrastructure, are not often modelled explicitly. This omission significantly limits the relevance of many optimization studies to decentralized production scenarios [52].

In Latin America, these restrictions are of particular concern because biomass is widely distributed, there are different types of farms, and the regulations are changing. Therefore, models that do not consider institutional, environmental, and logistical interactions can struggle to provide appropriate guidance for planning decisions.

2.2. Data Sources and Research Strategy

The data collection strategy was developed to provide comprehensive, transparent, and replicable coverage of scientific and institutional knowledge related to the management and optimization of bioenergy value chains based on agricultural residues in Latin America. The review considered topics such as biomass availability, conversion technologies, logistics and supply-chain optimization, life-cycle assessment, methane mitigation, and digital tools

for traceability and verification. Scientific publications together with institutional reports were used to support the analysis of these topics across the region.

Scientific publications were collected from indexing databases focused on engineering, energy systems, and environmental sciences, including Scopus, ScienceDirect, SpringerLink, and IEEE Xplore. The study was also supported with information from institutional sources such as FAOSTAT, IEA Bioenergy, IRENA, and regional databases from the United Nations Economic Commission for Latin America and the Caribbean (ECLAC/CEPAL). These sources contain information related to agricultural residue generation, energy consumption trends, sustainability indicators, and policy developments in the region.

The search terms were developed through 3 primary concepts:

- (1) the types of feedstocks used, including agricultural residues, livestock manure, and agro-industrial by-products;
- (2) the bioenergy pathways and assessment methods described in the literature, such as biogas and biomethane production, anaerobic digestion, supply-chain optimization, life-cycle assessment, and mixed-integer optimization methods; and
- (3) the geographical emphasis on Latin America and several countries in the region. These dimensions were later combined to create keyword searches such as “biogas” AND “agricultural residues” AND “optimization” AND “Latin America” OR the name of a specific country.

The search strategy was applied using combinations of Boolean operators adapted to each database. The main search string was: (“bioenergy” OR “biogas” OR “biomethane” OR “anaerobic digestion”) AND (“agricultural residues” OR “livestock manure” OR “agro-industrial by-products” OR “biomass residues”) AND (“supply chain” OR “optimization” OR “life cycle assessment” OR “techno-economic analysis” OR “traceability”) AND (“Latin America” OR “Brazil” OR “Mexico” OR “Colombia” OR “Argentina” OR “Chile” OR “Peru” OR “Ecuador” OR “Central America”). Searches were limited to documents published between 2015 and 2025, written in English or Spanish, and focused on peer-reviewed articles, conference papers with sufficient methodological detail, and institutional reports relevant to the regional context.

The methodology used provided the basis for identifying case studies that are relevant to bio-energy system design and evaluation in Latin America. The literature review also considered retrieving documents, removing duplicates, and using both temporal and thematic filters to apply subsequent filters to the documents. In addition to these filters, backward and forward reference screening was used to identify highly cited and/or methodologically relevant papers. Based on this process, only documents that directly addressed agricultural/livestock waste produced in Latin America, the conversion of waste into bioenergy, modelling of supply chains for bioenergy, and/or assessment of environmental impacts of bio-energy production were included in the final selection of documents.

2.3. Screening and Selection Criteria

After the initial document retrieval, all records were imported into the reference-management tool (Mendeley Reference Manager—version 2.139.0) to remove duplicate records and carry out standardized preprocessing. Titles, abstracts, and keywords were then screened to evaluate their thematic relevance to agricultural or livestock residues, bioenergy conversion pathways, supply-chain modelling, environmental assessment, or digital traceability applications within the Latin American context.

Table 2 presents a structured summary of the inclusion and exclusion criteria applied during the screening process. The table distinguishes between the conditions used to retain studies and those that justified their exclusion, reflecting the interdisciplinary scope of the

research area together with the methodological rigour required to evaluate bioenergy value chains in Latin America.

Table 2. Summary of screening and selection criteria.

Criteria	Description and Validation
	Included
Geographic relevance	Studies need to explicitly include agricultural, livestock, or agro-industrial residues in Latin America.
Bioenergy pathway	Studies contain anaerobic digestion, biomethane upgrading, co-digestion and hybrid biorefineries relevant to the region's residue streams.
Analytical or modelling method	Studies make use of quantitative methods for example, optimization modelling, lifecycle assessment, techno-economic analysis, or geographic information systems (GIS) based spatial tools.
Methodological transparency	Studies provide a sufficient amount of detail regarding assumptions, system boundaries, indicators and/or data sources to give other researchers enough information to evaluate or replicate the study.
Document type	The types of documents reviewed include peer-reviewed articles, conference papers with a high degree of analytical detail and/or institutional reports with high quality datasets and/or information related to the region of interest.
	Excluded
Lack of methodological detail	Studies which did not contain an explanation of the methods used; system boundaries; or quantitative metrics.
Laboratory-only studies	Experimental work with no link to a supply chain or other system. Laboratory-based studies without regional analysis.
Irrelevant biomass types	Studies using a biomass source irrelevant to agricultural, or livestock systems within a country in Latin America; or being incompatible with an agricultural, or livestock system in other countries in Latin America.

Source: the authors.

A final screening stage was carried out to ensure that only studies directly related to the integrated assessment of bioenergy value chains in Latin America were included in the synthesis. This filtering process helped maintain methodological consistency among the selected studies and supported the analysis presented in the following sections.

The selection process was conducted in two stages. First, titles, abstracts, and keywords were screened to identify studies aligned with the review scope. Second, the full texts of potentially eligible studies were assessed according to the inclusion and exclusion criteria presented in Table 2. Screening decisions were reviewed by the authors, and any disagreements regarding eligibility were resolved through discussion until consensus was reached. No automation tools were used to decide study eligibility.

Data from the selected studies were extracted using a structured approach based on the analytical domains defined in Table 3. The extracted information included country or region, residue type, bioenergy pathway, modelling or assessment method, main sustainability indicators, traceability elements, and reported technical, environmental, or institutional limitations. The extracted data were reviewed by the authors to ensure consistency with the review objectives. No automation tools were used for data extraction, and no study investigators were contacted to obtain or confirm additional data.

Table 3. Analytical domains used to structure the review.

Domain	Focus	Description of Analytical Scope
Technological performance and system configuration	Conversion pathways	This area of the study analyses process assumptions, substrate characteristics, methane yields, operating conditions, and the arrangement or systems of anaerobic digestion, co-digestion, methane upgrading, hybrid processes.
Supply chain design and optimization modelling	Logistics and system design	Evaluation of spatial modelling, transport and location, cost/emission/energy trade-offs, uncertainty treatment, seasonal variability, and the use of deterministic/stochastic multi-objective optimization strategies.
Environmental and circularity assessment	Sustainability metrics	It includes assessing GHG emissions, avoided methane emissions, resource use efficiency, nutrient recovery and the way lifecycle/circularity indicators are integrated into system evaluation or optimization goals.
Governance, policy, and traceability integration	Compliance and institutional context	It incorporates regulatory requirements, methane accounting, sustainability certifications, digital monitoring systems, and studies with emerging frameworks such as the Global Methane Pledge and EU Deforestation Regulation.
Regional and socioeconomic context	Contextual conditions	Contextual conditions referring to identifying country specific conditions, residue types, organizational structures (i.e., smallholder, Agro-industrial cluster) and whatever infrastructure or institutional factors may limit or enable the feasibility and deployment of these systems.

Source: the authors.

Bibliometric Support Analysis

As a complement to the systematic review, a bibliometric analysis was conducted using VOSviewer (version 1.6.21) to visualize the relationships among the most frequently occurring keywords in the selected literature. Bibliographic records exported from Scopus were processed after the screening and eligibility stages defined by the PRISMA methodology. Author keywords and indexed keywords were standardized by merging synonymous terms and removing duplicates to improve consistency. The resulting keyword co-occurrence network was used to identify the main thematic clusters and their relationships within literature. This analysis was intended to complement the qualitative synthesis rather than replace it.

2.4. Analytical Framework

Due to the diverse production systems in Latin America and the interdisciplinary nature of bioenergy research, it was impossible to evaluate how bioenergy systems are designed, evaluated, and implemented using only one type of analysis. In this context, an integrated framework is developed around five inter-related analytical domains that allow a structured evaluation of the overall design, performance, and implementation of bioenergy systems.

In addition to the main analytical domains, other variables were extracted when available, including publication year, country, feedstock source, system scale, technology readiness level, modelling assumptions, system boundaries, policy or regulatory context, and implementation barriers. When information was missing or unclear, it was not estimated by the authors; instead, the absence of such information was considered when discussing methodological limitations and gaps in the reviewed literature.

Studies were assigned to each synthesis domain according to their main analytical contribution. For example, studies focused on conversion pathways were considered

under technological performance, while studies addressing facility location, logistics, transport flows, or optimization models were grouped under supply-chain design. Studies dealing with emissions, nutrient recovery, policy alignment, traceability, or socioeconomic conditions were synthesized within the corresponding environmental, governance, or regional domains described in Table 3.

2.5. Quality Assessment, Bias Control and Study Limitations

The methodological quality of the selected studies was evaluated using a simple form developed to suit the different types of evidence included in this review. The assessment considered seven criteria: clarity of the study objective, definition of system boundaries, transparency of data sources, description of modelling assumptions and analytical methods, methodological reproducibility, reporting of uncertainty and limitations, and applicability to the Latin American context. Each criterion was scored as 0 when it was not reported, 1 when it was partially reported, and 2 when it was clearly reported. The maximum score was 14 points. Studies scoring 11–14 points were classified as high quality, those scoring 7–10 points as moderate quality, and those scoring 0–6 points as low quality. Low-quality studies were excluded from the final synthesis. The authors reviewed the assessment results, and differences were resolved through discussion until consensus was reached.

As the review was designed as a qualitative and analytical synthesis rather than a quantitative meta-analysis, formal effect measures such as risk ratios, mean differences, or confidence intervals were not estimated. Instead, the synthesis was based on descriptive and comparative indicators related to technological performance, supply-chain modelling, sustainability metrics, governance, and traceability.

No formal sensitivity analysis, statistical assessment of reporting bias, or certainty assessment such as GRADE was conducted, because the review did not involve meta-analysis, pooled estimates, quantitative model recalibration, or the evaluation of intervention effects. In this logic, the strength and applicability of the evidence were judged through a qualitative reading of the reviewed studies. Authors focused on whether similar patterns appeared across the analytical domains, how clearly each study reported its data sources, system boundaries and modelling assumptions, and whether the findings were relevant to the Latin American context. Cases with incomplete information or uncertain results were treated with caution when drawing conclusions from literature. These aspects were considered when interpreting the strength of the evidence and the main limitations of the reviewed literature.

Published research is unevenly distributed across Latin America. Brazil, Mexico, and Colombia, are more frequently represented in the available literature than other countries. This regional characteristic may limit the extent to which the findings can be generalized to the region.

Another limitation is that many of the studies reviewed have approached different methodologies to report their data. Differences in system boundaries, modelling assumptions and the amount of methodological details provided make it difficult to make direct comparisons of results or to carry out a more quantitative synthesis of the different studies. Furthermore, in many cases, important data was not explicitly reported, such as assumptions about the availability of residue, distances covered by transport and process efficiencies. As a result, researchers may lack key input data for their models, which introduces uncertainty when interpreting the modelling results.

This review did not include non-digital grey literature or unpublished reports, which may have offered additional local insights but often lack the methodological transparency required for consistent integration into a systematic review.

3. Results

The search and selection process is summarized in the PRISMA flow diagram shown in Figure 1. After identification of records from scientific databases and institutional sources, duplicate records were removed and the remaining documents were screened by title, abstract, and keywords. Potentially eligible documents were then assessed in full text according to the inclusion and exclusion criteria defined in Table 2. The final synthesis included 37 studies and institutional contributions addressing bioenergy value chains based on agricultural and livestock residues in Latin America. For the regional and feedstock distribution analysis, these studies generated 208 country–residue observations, since some documents addressed more than one country, residue category, or bioenergy pathway.

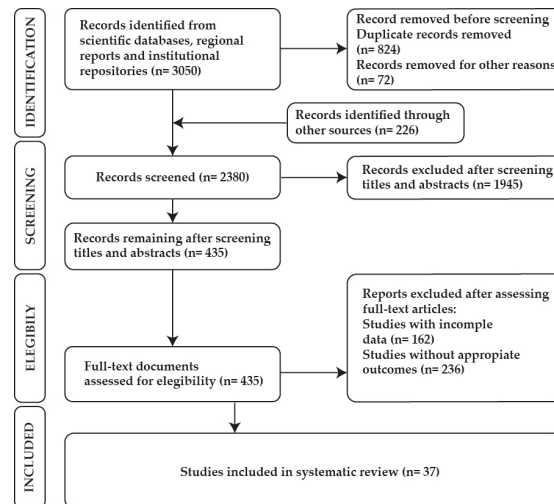


Figure 1. PRISMA flow diagram showing the identification, screening, eligibility assessment, and final inclusion of records used in the systematic review.

The main reasons for exclusion at the full-text stage are summarized in the PRISMA flow diagram. Documents that initially appeared relevant were excluded when they lacked a clear connection with Latin American agricultural or livestock residue systems, focused only on laboratory-scale conversion without supply-chain or regional analysis, addressed biomass types outside the scope of the review, or did not provide sufficient methodological detail to support the synthesis.

The assessment of the selected studies showed that most provided enough information on their objectives, data sources, system boundaries, and analytical methods to be included in the synthesis. However, recurrent weaknesses were found in the reporting of modelling assumptions, feedstock availability, transport distances, process efficiencies, uncertainty treatment, and uncertain or negative findings. Because the synthesis was descriptive rather than statistical, formal sensitivity, reporting-bias, and certainty analyses were not applied. As an alternative, confidence in the evidence was judged according to the consistency of findings across studies, the clarity of the reported methods, and the relevance of the results to Latin American bioenergy systems. These considerations guided the interpretation of the results, especially for optimization models, environmental performance, and the transferability of findings across regional contexts.

3.1. Study Characteristics

The 37 studies and institutional contributions included in the systematic review were heterogeneous in terms of geographical scope, residue type, bioenergy pathway, and main indicators assessed. Table 4 summarizes the main characteristics extracted from the included studies.

Table 4. Characteristics of the included studies on bioenergy value-chain management from agricultural and livestock residues in Latin America.

Study	Country/Region	Residue or Feedstock	Bioenergy Pathway/System	Main Indicators Assessed
Gebreyessus, 2022 [1]	Latin America and the Caribbean/ Circular bioeconomy context	Spent coffee grounds	Biomass valorisation/Circular bioeconomy	Valorisation routes, resource recovery, environmental relevance
Silva et al., 2024 [2]	Brazil, Chile, Mexico	Biomass pellets	Solid bioenergy/Biomass valorisation	Social impacts, supply-chain hotspots, circular bioeconomy indicators
Luna-del Risco et al., 2022 [3]	Colombia	Dairy cattle and swine manure	Biogas/Anaerobic digestion	Biogas potential, methane potential, energy recovery
Sanchez et al., 2024 [4]	Colombia	Residual biomass from non-centrifugal sugar chain	Biomass valorisation/Green market deployment	Residue availability, valorisation potential, green market opportunities
Pulido-Ocegueda et al., 2026 [6]	Mexico/Regional modelling context	Multi-product biomass residues	Biomass supply chain/Water–energy–food nexus	Water, energy, food interactions, supply-chain performance
Samaniego and Espinosa, 2026 [12]	Ecuador/South America	Bioeconomy resources	Sustainable bioeconomy transition	Resource efficiency, bioeconomy transition indicators
Barros et al., 2025 [16]	Brazil/Eastern Amazon	Oil palm expansion and related agro-industrial land-use systems	Biomass and land-use traceability context	Land-use change, crop expansion, spatial monitoring
Hernandez Guzman et al., 2025 [17]	Latin America and the Caribbean	Livestock-driven land-use systems	Methane and GHG context for livestock systems	GHG emissions, livestock-driven deforestation, land-use pressure
Marinkovic and Vogt-Schilb, 2024 [19]	Latin America and the Caribbean	Energy systems	Low-carbon energy planning	Future emissions, climate-goal consistency, power-sector planning
Tehseen et al., 2026 [21]	Latin America and the Caribbean/agricultural context	Manure	Hydrogen and biofertilizer from manure	Environmental impacts, hydrogen production, biofertilizer recovery
Yörüklü et al., 2025 [23]	Latin America and the Caribbean/ Global biomethane context	Gaseous feedstocks/biogenic gases	Biological methanation/Biomethane	Biomethane production, process performance, technological readiness
Pilarski et al., 2025 [24]	Latin America and the Caribbean/ Agricultural context	Agricultural residues and manure	Biogas production in agriculture	Biogas yield, environmental impacts, socioeconomic aspects
Foret et al., 2025 [25]	Latin America and the Caribbean/ Biogas upgrading context	Biogas streams	Biogas upgrading to renewable natural gas	Upgrading efficiency, emerging technologies, RNG production
Prajapati et al., 2026 [27]	Latin America and the Caribbean/Waste-to-energy context	Waste biomass	Waste-to-energy pathways	Feedstock use, technology performance, LCA indicators

Table 4. Cont.

Study	Country/Region	Residue or Feedstock	Bioenergy Pathway/System	Main Indicators Assessed
Cho et al., 2026 [28]	Latin America and the Caribbean/ Biomass supply-chain context	Biomass resources	Biomass supply and pretreatment	Supply cost, pretreatment, environmental performance
Serrano-Arévalo et al., 2026 [30]	Latin America and the Caribbean/ circular economy context	Energy carriers from biomass and other sources	Circular energy systems	Energy carrier integration, circularity, system performance
Spizzirri et al., 2026 [31]	Latin America and the Caribbean/ Agricultural context	Agricultural waste and by-products	Renewable energy from agricultural waste	Technology options, energy recovery, sustainability pathways
Pardo Cuervo et al., 2024 [32]	South America	Residual lignocellulosic biomass	Biomass valorisation/Biorefinery pathways	Residue availability, lignocellulosic conversion routes, valorisation potential
Gallego-Schmid et al., 2024 [33]	Latin America and the Caribbean	Circular economy resource streams	Circular economy and biomass-related systems	Drivers, barriers, opportunities, implementation strategies
Rodrigues et al., 2025 [34]	Global with relevance to Latin America	Organic residues and waste streams	Biogas production	Biogas technologies, process highlights, production trends
Lapiso and Roubík, 2025 [36]	Global South	Organic residues	Biogas as circular-economy technology	Biogas contribution to circular economy and sustainable development
Alcocer-García et al., 2025 [37]	Mexico/Regional bioenergy context	Biomass residues	Bioenergy/biomass valorisation	Resource use, value-chain performance, sustainability indicators
Roudneshin and Sosa, 2024 [40]	Latin America/Regional modelling context	Agricultural and livestock residues	Bioenergy network design	Cost, emissions, facility location, spatial performance
Şenol, H., 2026 [43], Efthymiadou et al., 2025 [44], Kumar and Sowlati, 2025 [45]	Latin America/Agricultural regions	Seasonal biomass residues	Biogas/anaerobic digestion	Seasonal supply, methane production, system reliability
Flores-Siguenza et al., 2025 [46], Banerjee, N., 2023 [47]	Regional/Biomass systems	Agricultural residues	Bioenergy supply-chain optimization	Cost–emission trade-offs, energy output, circularity indicators

Table 4. Cont.

Study	Country/Region	Residue or Feedstock	Bioenergy Pathway/System	Main Indicators Assessed
Larrahondo Chavez, D. et al., 2025 [48]	Latin America and the Caribbean/ Bioenergy planning context	Biomass residues	Bioenergy system planning	Economic efficiency, environmental performance
Bastos et al., 2025 [49], Ananda et al., 2025 [50]	Regional/Biomass logistics context	Biomass flows	Bioenergy supply-chain systems	Biomass origin, availability, transport flows
Cenci and Biffis, 2025 [51]	Climate/Bioenergy context	Livestock manure and organic residues	Methane mitigation through bioenergy	Avoided emissions, leakage risk, climate contribution
Munonye, W.C., 2025 [52]	Decentralized agricultural systems	Smallholder biomass residues	Decentralized bioenergy systems	Participation, aggregation, infrastructure access
Møller et al., 2022 [53]	Agricultural systems	Livestock manure and agricultural residues	Agricultural biogas	GHG emissions, nutrient effects, environmental impacts
Kandagatla et al., 2025 [54]	Agro-industrial context	Rice mill wastewater and rice straw	Anaerobic co-digestion	Biogas kinetics, methane yield, particle size, ISR
Senevirathne and Kaparaju, 2025 [55]	Latin America and the Caribbean/ Digestate management context	Anaerobic digestate	Nutrient recovery/Digestate valorisation	Agronomic value, nutrient recovery, digestate quality
Anacleto et al., 2025 [56]	Latin America and the Caribbean/ Agricultural digestate context	Digestate	Circular digestate use in agriculture	Safety, circularity, digestate quality, nutrient recovery

Source: the authors.

Bibliometric Mapping of the Reviewed Literature

The bibliometric analysis performed with VOSviewer helped identify the main thematic structure of the reviewed literature. The keyword co-occurrence network shown in Figure 2 reveals four interconnected clusters that characterize research on sustainable bioenergy supply chain management in Latin America.

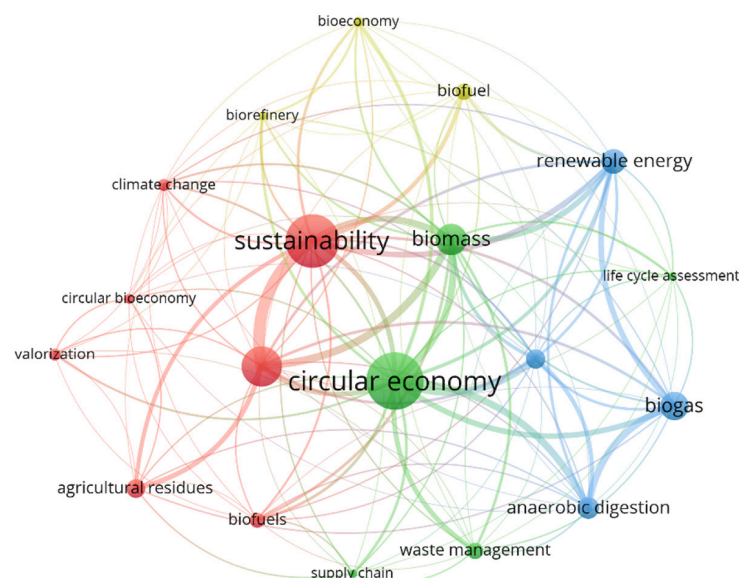


Figure 2. Keyword co-occurrence network map from selected bibliographic data from 2015 to 2025. Source: the authors.

The green cluster is centred on circular economy and biomass. It also connects with waste management and supply chain, showing the growing interest in the recovery and coordinated use of biomass resources within circular production systems. The blue cluster includes biogas, anaerobic digestion, renewable energy, and life cycle assessment. This cluster reflects the strong technological and environmental focus of the literature, particularly on biological conversion processes and the evaluation of their environmental performance.

The red cluster is organized around sustainability and includes terms such as agricultural residues, valorisation, circular bioeconomy, and climate change. These relationships show that the sustainable management and valorisation of residual biomass remain central topics in the reviewed studies. The yellow cluster links bioeconomy, biofuel, and biorefinery, representing research focused on integrated biomass conversion and the development of bio-based products and energy carriers.

The keyword co-occurrence network indicates that the literature is mainly concentrated on technological development, sustainability, and circular biomass utilization. However, terms directly related to supply-chain optimization, traceability, governance, methane accounting, and institutional coordination are less visible and less strongly connected in the network. This result supports one of the main findings of the review: although bioenergy technologies and circular valorisation have received considerable attention, their integration with optimization, monitoring, policy, and governance remains limited. The bibliometric evidence therefore reinforces the need for an integrated framework such as the Sustainable Bioenergy Chain Management Framework proposed in this study.

3.2. Regional Distribution of Research

For the regional distribution analysis, the 37 studies and institutional contributions included in the systematic review were disaggregated into 208 country–residue observations. This approach was used because several documents reported evidence for more than

one country, residue category, or bioenergy pathway. The highest number of observations corresponded to Brazil ($n = 47$), followed by Colombia ($n = 33$), Mexico ($n = 27$), Argentina ($n = 21$), Chile ($n = 15$), Peru ($n = 14$), Ecuador ($n = 10$), Costa Rica and Guatemala ($n = 8$ each), Bolivia ($n = 7$), Paraguay and Uruguay ($n = 5$ each), and other Latin American countries ($n = 8$). These observations were distributed across livestock residues, agro-industrial residues, crop residues, forestry residues, and mixed or multiple residue streams.

A heat map representing the geographical and feedstock distribution of the reviewed studies is shown in Figure 3. The heat map highlights the number of contributions made by each country and residue category. As shown, most contributions came from Brazil, Colombia, Mexico, and Argentina, with livestock and agro-industrial residues accounting for the largest share of the studies. There are research gaps in countries where agricultural and livestock production have a significant presence but remains poorly represented in the literature.

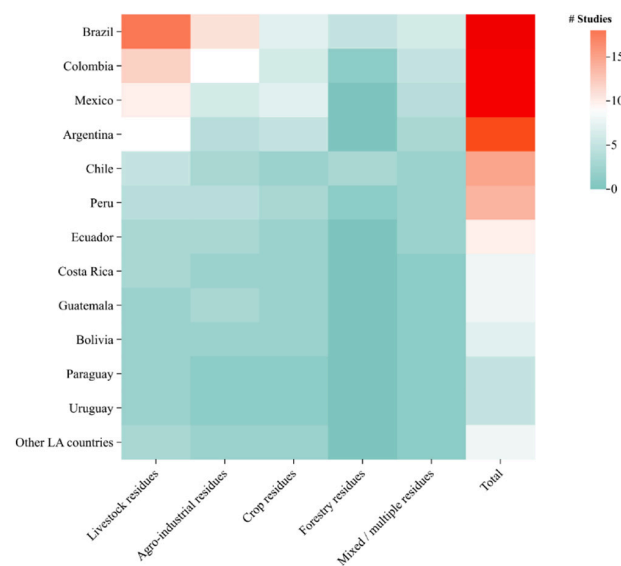


Figure 3. Heatmap showing the number of country–residue observations by country and residue type used in bioenergy value-chain analyses in Latin America (2015–2025). Figure generated using <https://www.chiplot.online/> on 15 January 2026. Source: the authors.

Brazil, Colombia, Mexico, and Argentina appear frequently in the literature, due to their large agriculture economies, more developed bioenergy programmes, and the availability of public and private funding to support bioenergy-related research and development (Figure 4). By comparison, the research base remains limited for countries such as Paraguay, Bolivia, Guatemala, Honduras, and several Caribbean nations, even though they have significant agricultural activity and abundant biomass resources with potential for bioenergy development and utilization. These results are consistent with previous findings reported in the literature [57,58].

Table 5 provides general context on the development of bioenergy power capacity in selected Latin American countries. Brazil maintained the largest installed capacity, while Argentina, Colombia, and Chile showed notable relative growth during the period. However, these figures cover total bioenergy power capacity and should not be interpreted as capacity derived only from agricultural and livestock residues.

The types of residues studied also vary across regions. In Brazil and Colombia, most studies focus on livestock feedstocks, particularly cattle, swine, and poultry manure. This emphasis can be explained by their heavy reliance on livestock production. There are also studies conducted in Colombia and other Central American countries that have focused on the conversion of coffee pulp, banana and plantain residues, and cane sugar residues into

new value-added products. On the other hand, Mexico and Argentina are more heavily represented within the agro-industrial waste systems, such as dairy effluent, maize stover, and agro-processing waste streams. Forest residues account for the smallest number of studies to date. The few available studies have been conducted mainly in southern Brazil and Chile, where forestry activities are more prevalent [58].

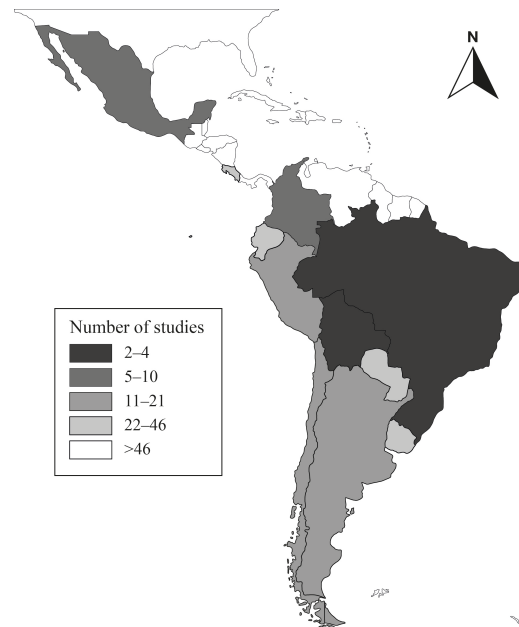


Figure 4. Concentration of bioenergy value-chain observations in Latin American countries with the highest representation in the reviewed literature. Source: the authors.

Table 5. Installed bioenergy power capacity in selected Latin American countries, 2015–2025.

Country	Capacity (MW) 2015	Capacity (MW) 2025	Change (%)
Brazil	14,079	18,373	30.5
Mexico	725	890	22.8
Chile	466	765	64.2
Argentina	219	435	98.6
Colombia	237	422	78.1
Peru	197	236	19.8
Ecuador	144	167	16

Source: Prepared by the authors based on IRENASTAT electricity-capacity data by country and technology. Available online: https://pxweb.irena.org/pxweb/en/IRENASTAT/_Power%20Capacity%20and%20Generation/Country_ELECCAP_2026_H1_v-PX%201.px/, accessed on 14 July 2026. Percentage changes were calculated by the authors.

The literature also shows considerable variability regarding spatial scale, ranging from farm scale and cooperative systems to higher-level regional planning efforts. Most case studies remain highly localized in nature, typically examining a limited number of municipalities or regions of agricultural production, with very few conducting international cross-case comparisons. As a result, this pattern supports our earlier statement that most of the research being conducted in Latin America continues to be shaped by specific local conditions, limiting the extent to which findings are transferable across different agricultural contexts and reducing the integration of regional datasets into cohesive modelling approaches [59,60].

3.3. Technological Trends in the Valorisation of Agricultural and Livestock Residues

3.3.1. Anaerobic Digestion and Biogas Systems as the Main Research Focus

Anaerobic digestion (AD) was the most frequently reported technological pathway among the reviewed technology-pathway observations for agricultural and livestock

residues in Latin America (Figure 5). Many factors contribute to the widespread adoption of AD to utilize heterogeneous feedstock. Another important reason is that the nature of AD allows for both centralized and decentralized designs [61]. AD systems will also support the methane mitigation goals established in regional and global climate change agendas. The study conducted by [62] describes the production of biogas from cattle, swine, or poultry waste as the primary source of feed for AD, but it also describes the addition of agricultural–industrial feedstocks to help provide a consistent supply of material, thus increasing the efficiency of the overall system. In addition to energy generation, the development of AD systems commonly results in a significant reduction in uncontrolled methane emissions, as well as improved management of organic waste streams on a local level [53].

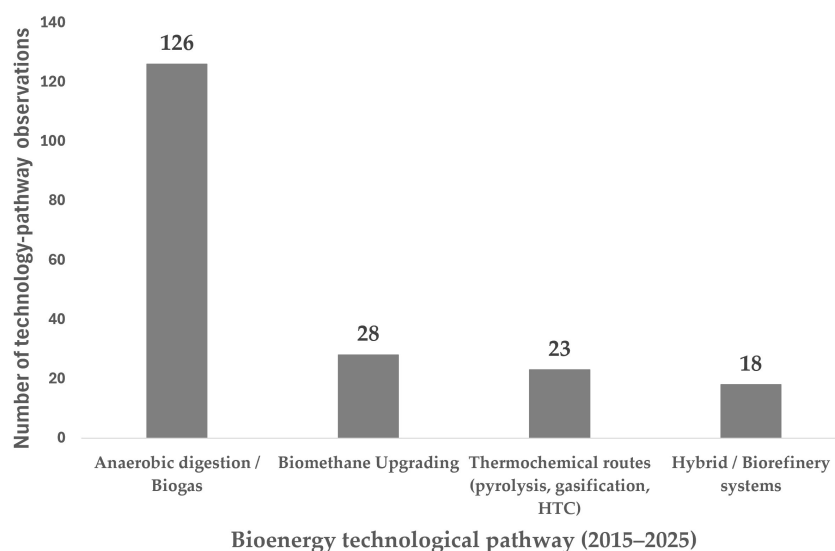


Figure 5. Distribution of technology-pathway observations identified in the reviewed literature on bioenergy value chains from agricultural and livestock residues in Latin America (2015–2025). Source: the authors.

3.3.2. Co-Digestion Strategies and Process Synergies

Co-digestion has been consistently implemented as a developing strategy for residue-based bioenergy systems, offering increased methane production, greater process stability, and improved nutrient balance within mixtures. Table 6 displays the most frequently documented co-digestion combinations and the associated methane yield improvements observed among selected Latin American locations. Throughout, the data supports a consistent pattern in the pairing of livestock manure with agro-industrial residues to produce a better-balanced substrate and increase biodegradability. Observed increases in methane yield from co-digestion depend on several factors, including feedstock characteristics, mixing ratio, and operating conditions. However, studies have shown that methane yields resulting from co-digestion are measurably greater when compared to mono-digestion systems [54,63,64]. The various combinations of coffee pulp with sugarcane by-products, dairy effluents, and palm residues perform notably well in countries that have active agro-industrial sectors. Table 6 also indicates both the technical viability associated with these mixtures and their geographic distribution, thus demonstrating the extent to which local residue availability influences co-digestion systems. These findings contribute to understanding process efficiency based on well-balanced substrates and support the inclusion of co-digestion configurations into planning models that incorporate optimization criteria.

Table 6. Common co-digestion combinations reported in the literature, including substrate pairs, and reported methane yield improvements.

Country/Region	Primary Substrate	Co-Substrate(s)	Motivation for Co-Digestion	Reported Methane Yield Change	System Scale	Observations
Brazil	Cattle manure	Sugarcane vinasse	Improve biodegradability and C/N balance	+15–30%	Pilot/modelling	Widely studied due to ethanol industry integration
Brazil	Poultry manure	Agro-industrial wastewater	Dilution of ammonia inhibition	+10–25%	Pilot	Improves process stability
Colombia	Cattle manure	Coffee pulp	Valorisation of seasonal residues	+20–40%	Laboratory/modelling	Strong seasonal variability
Colombia	Swine manure	Dairy effluents	Increase organic loading and buffering	+10–20%	Pilot	Common in smallholder systems
Mexico	Dairy manure	Maize silage	Enhance methane productivity	+25–45%	Pilot/full scale	Often linked to farm-scale AD
Mexico	Cattle manure	Fruit and vegetable waste	Improve substrate degradability	+20–35%	Laboratory/pilot	Urban–rural integration cases
Argentina	Dairy manure	Whey	Increase readily degradable COD	+30–50%	Pilot	Strong synergy due to lactose content
Chile	Cattle manure	Agro-industrial residues	Increase energy yield	+15–30%	Laboratory	Limited full-scale adoption
Peru	Livestock manure	Fruit-processing residues	Improve vs. conversion	+15–25%	Laboratory	Early-stage research
Ecuador	Manure	Banana residues	Valorize agro-industrial waste	+10–20%	Laboratory	Substrate logistics remain challenging

Source: The authors.

3.3.3. Nutrient Recovery and Development of Bio-Based Products

The recovery of nutrients such as nitrogen (N), phosphorus (P), and potassium (K) from digestate is gaining importance as a complementary strategy to energy generation (Figure 6). As the focus on recovering nutrients moves towards a circular bioeconomy, biofertilizers produced from digestate will help restore soil fertility and reduce our dependence on synthetic products. Unfortunately, some barriers continue to limit the wider implementation of nutrient recovery from digestate. These barriers include differences in digestate nutrient composition, a lack of standardized digestate quality indicators, lack of clarity on the regulatory framework regulating the use of digestate as fertilizers, fears of contaminating the digestate product with pathogens/chemical contaminants, and insufficient market outlets for end-products [55,56]. New uses of digestate are also being explored such as using digestate in renewable materials production, using digestate as an organic soil amendment with improved nutrient profiles, and the creation of integrated AD/biochar systems. However, these applications remain at an early stage of implementation, representing a gradual expansion of industrial systems based on residues.

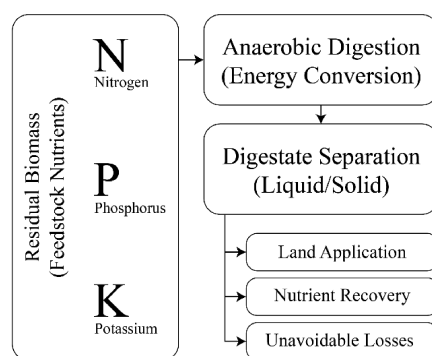


Figure 6. Nutrient flows (N–P–K) in conventional AD/digestate systems. Source: the authors.

3.3.4. Thermochemical Conversion Pathways and Their Limited Regional Adoption

Thermochemical conversion methods such as pyrolysis, gasification, and hydrothermal carbonization are still underrepresented in the regional research landscape compared to anaerobic digestion. Most existing studies focusing on these technologies have been conducted in Brazil and Chile [55,56,65,66]. This is largely due to the presence of large amounts of forest residues and lignocellulosic feedstocks in these countries, as well as an existing concentration of research capacity related to thermochemical conversion (Table 7). While these technologies have some advantages such as providing an alternative source of biochar, offering potential for carbon sequestration, and utilizing biomass feedstocks that are less biodegradable than those suitable for anaerobic digestion, thermochemical conversion technology is still being developed on a laboratory or pilot scale basis. The slow development of these technologies in the region appears to be influenced by several factors, including investment costs, technological maturity, and the lack of consistent regulatory and commercial conditions.

Table 7. Characteristics of thermochemical bioenergy studies in Latin America by country, feedstock, technology, and technology readiness level (TRL).

Country	Primary Feedstock	Technology	Main Output	Typical Scale	TRL Range
Brazil	Forestry residues (eucalyptus, pine), sugarcane bagasse	Pyrolysis	Biochar, syngas	Laboratory/pilot	4–6
Brazil	Forestry residues	Gasification	Syngas, heat	Pilot	5–6

Table 7. *Cont.*

Country	Primary Feedstock	Technology	Main Output	Typical Scale	TRL Range
Chile	Forestry residues (sawmill waste, bark)	Pyrolysis	Biochar	Laboratory/pilot	4–5
Chile	Forestry residues	Gasification	Syngas, electricity	Pilot	5
Argentina	Agricultural residues (corn stover, rice husk)	Pyrolysis	Biochar	Laboratory	3–4
Mexico	Agro-industrial residues (bagasse, nutshells)	Pyrolysis	Biochar	Laboratory	3–4
Colombia	Coffee husk, agricultural residues	Hydrothermal carbonization (HTC)	Hydrochar	Laboratory	3
Peru	Agro-industrial residues	Pyrolysis	Biochar	Laboratory	3
Ecuador	Agricultural residues	Pyrolysis	Biochar	Laboratory	3

Source: The authors.

3.4. Optimization and Modelling Strategies

3.4.1. Supply-Chain Optimization Frameworks

Mathematical optimization plays an important role in the planning and management of agricultural waste-based bioenergy value chains [45]. Research articles mainly present decision-making frameworks aimed at minimizing total system costs, maximizing energy output, and reducing GHG emissions [67]. These models are used to inform decision makers about the location of processing facilities, processing capacity, feedstock distribution, and transport configuration across geographically dispersed areas with limited resources [68,69]. Supply chain preparation reflects the operational realities of biomass-based systems, since technical and economic feasibility are strongly influenced by factors like feedstock dispersion, seasonal availability, and transport costs [70,71].

The Mixed-Integer Linear Programming (MILP) technique is the most common type of model used to solve supply-chain design problems. By combining discrete infrastructure decisions such as facility location and capacity expansion with continuous flow variables such as biomass transport and energy generation, MILP provides a practical way to represent these systems. In contrast to LP-only models, MILP incorporates binary or integer decision variables that are essential for modelling infrastructure selection. It also offers greater computational efficiency and scalability compared to mixed-integer non-linear programming (MINLP) approaches, which can become difficult to solve as regional networks increase in size. These advantages help explain the widespread use of MILP in bioenergy supply-chain development [72,73].

Seasonal variations in biomass availability and changes in market conditions are often represented through discrete scenarios rather than probabilistic approaches [74]. This helps capture variability across different operating conditions, but it does not always reflect how infrastructure or investment decisions respond under long-term climatic or economic uncertainty [75].

Most optimization-based analyses are carried out within individual countries or sub-national regions, often focusing on specific agricultural basins or livestock production clusters. These studies provide detailed insight into local system configurations and resource conditions [76]. At the same time, because they are built around specific local contexts, their results are not easily transferable to regions with different farm size distributions, transport infrastructure, or governance structures. Scaling this type of analysis to larger geographic areas usually requires significant adjustments in data, assumptions, and model structure [77]. This can be particularly challenging where biomass supply is

decentralized and reliable data on production, transport distances, or operational costs are limited, which makes calibration and validation more demanding.

3.4.2. Use of Mixed-Integer Linear Programming (MILP) and Hybrid Models

MILP, among the models included in Table 8, is the most widely utilized optimization tool in the studies surveyed, primarily owing to its capacity to model discrete decisions. MILP models are often extended using hybrid approaches that integrate GIS to account for spatial heterogeneity, as well as Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) to incorporate environmental and economic performance metrics [78–80].

Table 8. Optimization and modelling approaches applied to bioenergy value-chain design in Latin America.

Modelling Approach	Typical Decision Scope	Optimization Objectives	Integrated Tools	Common Limitations
Deterministic MILP	Facility location, capacity, flows	Cost, energy output	None	Ignores uncertainty and seasonality
GIS-MILP	Spatial siting, transport routing	Cost, emissions	GIS	High data requirements
MILP-LCA	Network design with environmental metrics	Cost–emissions trade-off	LCA	Linearized environmental impacts
MILP-TEA	Economic feasibility assessment	Net present value, cost	TEA	Limited policy sensitivity
Scenario-based optimization	Seasonal supply and demand	Expected system performance	Stochastic scenarios	Limited treatment of policy risk
Multi-objective optimization	Trade-offs between metrics	Cost, energy, GHG	Weighted sums/ ϵ -constraint	Requires subjective weighting

Source: The authors.

However, the increasing scope and complexity of these hybrid models often require several simplifying assumptions, including linearized process behaviour, fixed yields, and static demand profiles [72,79]. These assumptions make the models more manageable, but they may also reduce their ability to represent the operational variability of real bioenergy systems. This is of particular interest in supply-chain optimization studies, where many models remain exploratory or scenario-based. In these cases, models are mainly used to explore alternative scenarios, while validation is often limited to simulated datasets rather than empirical calibration with data from real bioenergy systems.

3.4.3. Treatment of Decentralized and Cooperative System Configurations

Several studies consider decentralized and cooperative bioenergy systems, which are relevant in Latin America because many agricultural residues are produced by small- and medium-sized farms [81,82]. These systems include networks of small plants, cooperative facilities supplied by several farms, and arrangements where biomass is collected before conversion. Their design commonly includes limits on collection distance, shared investment, and the amount of biomass available from each producer.

Cooperative or clustered systems may become economically feasible when individual farms do not generate enough residues to support their own plants. Biomass aggregation can improve plant use and reduce the risk of insufficient feedstock, if transport distances and collection costs remain reasonable. Nevertheless, their performance also depends on a stable biomass supply and effective coordination among participants [81].

Current optimization models usually represent cooperation through aggregated biomass flows or shared infrastructure decisions. Coordination costs, participation incentives, unequal risk distribution, and possible conflicts among producers are rarely included

as model variables [83]. For this reason, a cooperative system may appear economically attractive in the model but may face difficulties during its practical implementation.

3.4.4. Limitations of Current Modelling Approaches

The literature indicates that there are several structural limitations in the use of optimization models for bioenergy supply chains [84,85]. As shown in Table 9, modelling approaches are focused on economic or energy objectives, while environmental, institutional, and governance aspects are generally treated as secondary constraints or as external evaluation indicators. These operational aspects remain weakly represented within the optimization structure, even though hybrid formulations have expanded the analytical perspective of these models. Elements such as digital traceability, methane mitigation accounting, and compliance with evolving regulatory frameworks are often considered outside the model or through simplified assumptions.

Table 9. Treatment of uncertainty and decentralization in optimization models.

Aspect	Explicitly Modelled	Partially Considered	Neglected
Seasonal feedstock variability	✓		
Price volatility		✓	
Policy uncertainty			✓
Cooperative ownership	✓		
Behavioural participation			✓

Source: the authors.

Another limitation is the availability and reliability of input data. Information on residue availability, transport infrastructure, and operational performance is often incomplete or highly aggregated, which limits the spatial and temporal resolution of optimization models [71]. As a result, models are frequently forced to rely on generalized parameters for biomass supply, transport logistics, and plant performance rather than site-specific operational data. This means that optimization results tend to reflect theoretical system configurations that depend on assumed input values and are therefore sensitive to them rather than to observed field conditions. In practice, this can reduce the reliability of model outputs for investment planning or infrastructure design, especially when they are applied across regions with different agricultural practices, logistics networks, or residue management strategies. In practical terms, their predictive performance is still limited, mainly because the input data often lacks strong empirical support.

3.5. Policy and Institutional Context Reflected in Studies

3.5.1. Alignment with National Bioenergy Policies

The reviewed studies reveal considerable variability in how national bioenergy policies are incorporated into modelling assumptions and system deployment scenarios. Countries with more established regulatory frameworks such as Brazil, Colombia and Mexico refer to national renewable energy strategies, biofuel programmes, and incentive schemes when establishing modelling assumptions in several of the studies [82,86,87]. These policy instruments are incorporated through modelling parameters such as feedstock availability projections, deployment scenarios, and economic assumptions used in techno-economic and optimization models. In this case, modelling approaches are used to explore whether bioenergy systems can operate under existing incentives, such as feed-in tariffs, renewable portfolio standards, and national decarbonization goals.

However, a considerable number of studies on bioenergy system design remain primarily focused on technical and economic aspects, with limited explicit integration

of regulatory conditions into the modelling structure. Other studies [88–90] mention policy frameworks as background information rather than including them as constraints, incentives, or institutional requirements within the models. This limits the ability of the analyses to evaluate whether proposed bioenergy systems would operate within existing regulatory environments, including permitting procedures, grid access regulations, and subsidy eligibility conditions.

An additional limitation is that optimization results may identify technically efficient system configurations without evaluating their compatibility with the institutional and regulatory frameworks that govern bioenergy deployment. While models may indicate technically feasible configurations, regulatory constraints and administrative procedures that affect project development are not always considered. To provide a clearer overview of how institutional aspects are addressed in the literature, Table 10 presents the extent to which policy alignment, methane mitigation commitments, and traceability considerations are incorporated in the reviewed studies.

Table 10. Treatment of policy alignment, methane mitigation, and traceability in reviewed bioenergy studies.

Analytical Dimension	Explicitly Addressed	Partially Considered	Largely Absent	Typical Treatment in Studies
Alignment with national bioenergy policies	Low-moderate	Moderate	High	Policy context mentioned but not often integrated into model constraints
Methane mitigation objectives	Low	Moderate	High	Considered via AD justification but not often quantified
Traceability and certification requirements	Very low	Low	Very high	Discussed qualitatively but not operationalized in models

Source: the authors.

3.5.2. Consideration of Methane Mitigation Objectives

The treatment of methane mitigation varies across the studies reviewed. Anaerobic digestion is often presented to reduce uncontrolled methane emissions from livestock manure and organic residues [91–93]. However, only a limited number of studies quantify methane mitigation, and even fewer link these reductions to national or international climate commitments. As a result, methane emissions are not usually handled as a separate performance indicator in most modelling approaches. Only a few optimization frameworks include methane reduction targets, either in the objective function or as operational constraints.

In the studies where methane is considered, it is generally handled within a broader greenhouse gas (GHG) assessment rather than through methane-specific accounting. Lifecycle-based indicators are commonly used to estimate overall emission reductions, which can make the specific contribution of methane mitigation less visible [94].

Traceability and compliance aspects are also weakly represented in most modelling studies. In many cases, biomass supply is treated as an unrestricted input once availability has been estimated, with limited consideration of where the feedstock comes from, how land use is verified, or whether sustainability certification is in place. In addition, tools such as digital monitoring systems or traceability platforms, and even geolocation-based verification, are not commonly incorporated into optimization models or system evaluation frameworks [45,95,96]. Therefore, these models have limited ability to reflect the types of verification procedures that are increasingly required to confirm emission reductions, validate biomass origin, and demonstrate compliance with sustainability and climate policies.

In the Latin American context, the governance conditions shaping bioenergy deployment are gaining strategic importance, particularly as national policy agendas become more closely aligned with climate targets, methane mitigation pathways, and sustainability assurance systems [97,98]. Regardless of this growing relevance, traceability remains weakly formalized in optimization models and is hardly incorporated as an explicit constraint, parameter, or decision variable. This means that many studies do not clearly show how compliance requirements could affect feedstock tracking, logistics planning, or the overall costs of bioenergy systems. Figure 7 summarizes the evolution of key policy and institutional milestones related to bioenergy development in Latin America, including major climate commitments, methane mitigation efforts, and emerging traceability requirements that are beginning to shape the regulatory context in which bioenergy systems are deployed.

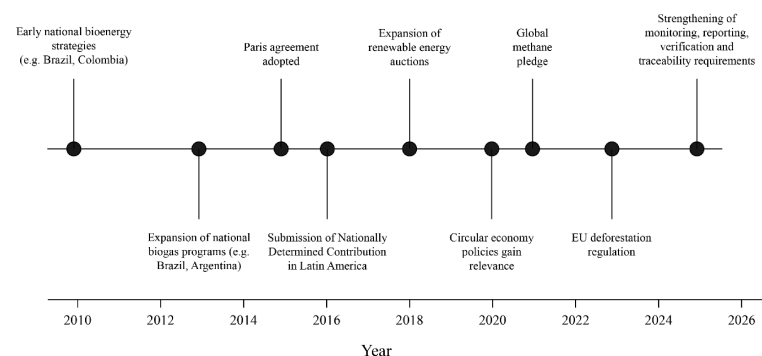


Figure 7. Timeline of key policy and institutional developments influencing bioenergy systems in Latin America (2010–2025). Source: the authors.

3.6. Emerging Patterns and Research Gaps in Bioenergy Value Chain Modelling

Logistical constraints represent a critical structural barrier to the deployment of residue-based bioenergy systems, particularly because biomass supply chains depend on efficient collection, transport, storage, and coordination across dispersed production sites. Agricultural residues are typically generated by geographically dispersed and relatively small producers, and their availability depends on seasonal crop cycles. Studies conducted by [99,100] indicate that these conditions make it difficult to establish stable supply chains and tend to increase transport and coordination costs.

To address these constraints, most modelling studies propose centralized or clustered processing facilities to aggregate biomass from multiple sources. However, the operational arrangements needed to organize residue collection, intermediate storage, and coordinated transport receive limited analytical attention.

As shown in studies such as [71,101,102], logistics are often represented in a simplified way, using transport distances or aggregated biomass supply parameters instead of explicit collection and distribution networks. Under these assumptions, models provide limited insight into how residue aggregation would be organized in practice or how logistical constraints could affect the stability and cost structure of the proposed value chains.

Previous studies [78] also indicate that supply variability, nutrient recovery from residues, and traceability or regulatory verification requirements are generally not included.

Within the formal model structure. Instead, these aspects are treated as contextual considerations rather than as model variables. So, system configurations tend to be driven mainly by economic and energy performance indicators. This means that modelling results provide only partial insight into how biomass supply fluctuations, environmental verification requirements, or nutrient recovery strategies could influence infrastructure sizing, logistics planning, and operational decisions.

Furthermore, studies by [103–106] recognize the role of multi-actor coordination among producers, agro-industrial firms, energy operators, and public institutions in bioenergy value chains. However, the governance arrangements needed to structure, regulate, and sustain these interactions are not often examined within their analytical frameworks. In regions with dispersed producers and heterogeneous production systems, these institutional arrangements can strongly influence whether residue-based bioenergy systems can be implemented and maintained over time.

To synthesize the main issues identified across the reviewed studies, Table 11 summarizes the key technological, logistical, modelling, and institutional factors that influence the development of residue-based bioenergy value chains in Latin America.

Table 11. Emerging patterns and identified gaps in bioenergy value-chain studies in Latin America.

Dimension	Observed Patterns	Identified Gap	Implications for Deployment
Logistics	Recognition of spatial dispersion	Lack of integrated collection systems	High transport cost, limited scalability
Modelling	Strong focus on cost and energy	Limited treatment of uncertainty, circularity and traceability	Lower practical relevance
Governance	Assumed stakeholder coordination	Weak institutional integration	Gap between optimal design and implementation

Source: the authors.

To consolidate the findings of the review, Table 12 summarizes the main research gaps identified across the technological, logistical, environmental, modelling, and institutional dimensions. It also presents the implications of these gaps and the corresponding future research directions for sustainable bioenergy supply chain management in Latin America.

Table 12. Main research gaps and future research directions for Sustainable Bioenergy Value-Chain Management in Latin America.

Analytical Dimension	Observed Pattern	Identified Research Gap	Implication	Future Research Direction
Logistics and collection	Biomass is spatially dispersed and collection is often represented through aggregated transport distances	Limited integration of collection, storage, routing, and conversion decisions	Higher transport costs and lower practical scalability	Develop spatially explicit and multi-stage logistics models
Optimization modelling and decision support	Models mainly prioritize cost and energy output	Seasonal supply, market uncertainty, and operational risk are insufficiently represented	Optimal solutions may not remain feasible under real conditions	Apply stochastic, robust, and scenario-based optimization
Circular valorisation	Energy production receives more attention than digestate and nutrient recovery	Circular products are not often included as decision variables or objectives	Environmental and economic benefits may be underestimated	Include nutrient recovery, digestate quality, and multiple products in optimization models
Methane mitigation	Methane reductions are usually included within general GHG indicators	Limited methane-specific accounting, leakage assessment, and monitoring	Climate benefits cannot be clearly verified	Develop methane-specific baselines, MRV indicators, and leakage constraints
Traceability and digitalization	Biomass is commonly treated as an unrestricted input after availability is estimated	Origin, geolocation, certification, and digital tracking are weakly represented	Models provide limited support for regulatory compliance	Integrate GIS, traceability platforms, and verification requirements
Governance and policy	Stakeholder coordination is often assumed	Institutional roles, transaction costs, and policy constraints are rarely modelled	A gap remains between optimal design and implementation	Combine technical optimization with governance and policy analysis

Table 12. *Cont.*

Analytical Dimension	Observed Pattern	Identified Research Gap	Implication	Future Research Direction
Smallholder participation	Decentralized producers are poorly represented	Minimum supply, aggregation, equity, and infrastructure access are not explicitly considered	Models may not reflect Latin American production structures	Model cooperatives, aggregation mechanisms, participation costs, and social indicators
Regional evidence	Research is concentrated in a few countries and local case studies	Limited cross-country datasets and comparative validation	Findings have restricted regional transferability	Develop harmonized regional databases and comparative country studies

These research directions form a structured agenda for future studies and also provide the basis for the SBCMF proposed in this review. The framework responds to the identified gaps by linking supply-chain optimization, circular valorisation, methane accounting, traceability, and governance within a common analytical structure.

4. Discussion

4.1. Enablers for Circular Bioenergy Value Chains

The results of this study suggest that circular economy principles are widely acknowledged in the Latin American bioenergy literature, but their translation into operational system design remains limited. Studies such as [78,107] link these principles to improved resource management and environmental performance in residue-based bioenergy systems, although they are not commonly represented as parameters within modelling frameworks or optimization structures. This becomes more relevant as these systems evolve toward multi-output configurations that involve energy generation, digestate management, and environmental compliance. Designing such systems requires analytical approaches capable of integrating material flows, environmental verification, and operational decision-making within the same modelling framework.

Data-driven monitoring and control technologies provide a pathway to strengthen this integration by increasing the availability, accuracy, and temporal resolution of operational data across bioenergy value chains [108–110]. For example, Internet of Things (IoT) systems can support continuous monitoring of feedstock availability, process conditions, methane emissions, and digestate quality. The integration of high-quality operational datasets can strengthen the empirical basis of optimization models by reducing input uncertainty and enabling more informed operational decision-making.

As reported by [111–113], digital traceability tools can also record information on biomass origin, transport, and handling practices, which is becoming increasingly relevant as certification and reporting requirements expand. In addition, data analytics and artificial intelligence may help operators anticipate equipment failures, estimate future energy demand, and adjust operational strategies when feedstock supply varies over time.

Experiences reported in Europe and parts of Asia show how digital infrastructures can support the operational management of circular bioenergy systems [111,114]. In these regions, digital platforms are increasingly used to manage nutrient flows, track emissions within measurement-reporting-verification (MRV) systems, and support compliance with sustainability standards. A study by [115] shows that digital monitoring systems can be linked with supply-chain modelling tools, allowing system configurations to be evaluated simultaneously in terms of economic performance, environmental impacts, and regulatory compliance. Compared to these developments, the Latin American literature remains mainly focused on technical feasibility and cost optimization, with less attention given to the role of digital infrastructures in supporting integrated circular bioenergy systems.

The differences observed between regions appear to be related less to the availability of digital technologies than to the institutional conditions required for their implementation. In many Latin American contexts, particularly in agricultural and livestock sectors with dispersed production units and heterogeneous management practices as is the case in countries such as Brazil, Colombia, Mexico and Argentina, the implementation of digital monitoring systems is constrained by fragmented information systems, limited operational datasets, and the absence of standardized traceability protocols [49,111,112]. These factors make it difficult to integrate digital tools into the management of bioenergy value chains. Addressing this will require stronger coordination between energy planning, agricultural management, and environmental monitoring institutions, along with the development of shared data governance frameworks. Pilot-scale initiatives that combine digital monitoring with residue-based resource management could provide practical evidence of how integrated digital infrastructures can improve operational efficiency and regulatory verification in bioenergy systems.

4.2. Institutional and Strategic Pathways for Bioenergy Deployment

The findings indicate that the scaling of residue-based bioenergy systems in Latin America is not primarily limited by technological availability. Conversion pathways for agricultural and livestock residues have already been implemented in several parts of the region, suggesting that the main barriers are more closely related to system integration, supply-chain organization, investment conditions, and institutional support, in which the difficulty appears when trying to move beyond pilot-scale projects. Establishing stable bioenergy value chains requires stronger coordination among institutions, better access to reliable operational data, and policy environments that can sustain long-term deployment. Because of this, implementation strategies need to go beyond technical solutions and address governance arrangements, financing mechanisms, and operational information systems.

Strengthening coordination among the actors involved in bioenergy value chains represents one possible pathway. These actors include farmers, agro-industries, utilities, technology providers, and regulatory institutions. As pointed out in [116,117], cooperation among them is often assumed, but there is little discussion of how it can be organized. Institutional arrangements such as cooperative ownership models, shared logistics services, or regional bioenergy hubs could help integrate biomass resources that are currently dispersed across multiple producers [118–120]. These organizational structures can also facilitate access to financing mechanisms and specialized technical expertise. This is particularly important in regions dominated by small- and medium-scale producers, where individual initiatives often lack the scale needed to achieve economic viability.

Two cases help illustrate these conditions in practice. In Paraná, Brazil, the EnerDinBo plant treats around 700,000 L of pig manure per day from more than 40 producers and has an installed capacity of 2 MW. This project shows how residue aggregation and shared infrastructure can support bioenergy production at a larger scale [121]. In Tolima, Colombia, three small biodigesters installed on coffee farms produced biogas with methane concentrations between 49.1% and 58.1%. The economic analysis reported an internal rate of return of 21% and a payback period of 3.9 years when both biogas and biol were used. However, when the fertilizer benefit of biol was excluded, the net present value became negative, and the payback period increased to 12.5 years [122]. These cases show that project feasibility depends not only on technical performance, but also on producer coordination, system scale, the use of by-products, and suitable support mechanisms.

A second pathway relates to the development of regional information and knowledge systems that can support planning, operational monitoring, and regulatory verification.

Managing bioenergy value chains effectively depends on having reliable data on residue availability, seasonal supply variations, and conversion system performance [76]. In Latin America, this type of information is still limited and often fragmented across institutions. Developing regional databases, digital monitoring tools, and shared standards for data exchange could help improve system operation and better connect modelling tools with real operating conditions. These systems would also support measurement, reporting, and verification processes, as well as traceability practices, which are increasingly important for accessing climate finance, participating in carbon markets, and meeting sustainability requirements in international supply chains.

Financial and technical support also plays a central role in the implementation of these systems. Although residue-based bioenergy projects have already been developed in countries such as Brazil, Mexico, Colombia, and Argentina, expanding them at a larger scale remains challenging. Their development often requires high initial investment and complex operational planning, which makes large-scale replication difficult. In addition, limited access to financing and the perception of high investment risks continue to limit the expansion of these systems across the region [11,33]. Public support instruments, including concessional credit lines, incentives linked to methane mitigation, and technical assistance programmes, could help reduce these constraints. Policy and financial support mechanisms should therefore account for benefits beyond energy generation, including improved resource management, enhanced environmental performance, and compliance with sustainability standards [99]. Strengthening the connection between residue-based bioenergy systems and national climate and sustainability strategies is another necessary step [19,20]. Including these systems in Nationally Determined Contributions (NDCs), methane mitigation initiatives, and circular economy programmes could increase their visibility within national development agendas and reinforce policy support for their development.

4.3. Conceptual Framework for Integrated Bioenergy Value-Chain Management

The analysis developed in Sections 4.1 and 4.2 evidence that systems based on bioenergy generated from residues rely on a mixture of technical, institutional, and informational criteria typically addressed separately in the literature according to the components comprising specific value chains, for example, availability of feedstocks, conversion technologies, logistics organization, and financial performance. Moreover, other aspects presented in this study highlight that there is an array of factors such as digital monitoring systems, traceability systems, or policy conditions that have important influences on the deployment of these systems; however, these aspects are infrequently assessed together within an overarching analytical framework. This means that it is challenging to assess how decisions made in the technical design of systems interact with data availability, regulatory requirements, and the coordination among actors involved in the bioenergy value chain.

The output component of each framework includes different energy products, such as biogas, biomethane, electricity, and heat, as well as digestate-based fertilizers and environmental benefits associated with reduced methane emissions and improved resource management. So, the output component does not only represent the final products of the system. It also provides a basis for evaluating system performance and for generating feedback to support future technical adjustments and operational decisions.

The findings also indicate that other factors, including monitoring systems, traceability mechanisms, and policy conditions, can strongly influence the deployment and long-term operation of residue-based bioenergy systems. However, these aspects are not often assessed together within a single analytical framework. This limits the possibility of understanding how technical design decisions interact with data availability, regulatory requirements, and coordination among the actors involved in the bioenergy value chain.

For this reason, the proposed Sustainable Bioenergy Chain Management Framework (SBCMF) considers information management and governance as enabling dimensions that are directly connected to the physical bioenergy value chain, rather than as external conditions. The information component supports monitoring, traceability, and data processing, which can improve system supervision and provide more reliable inputs for operational and strategic decision-making. At the same time, the governance component reflects the institutional environment in which the project is developed, including policy instruments, regulatory conditions, certification schemes, stakeholder coordination, and incentive mechanisms. These elements are critical for determining whether a project can be implemented, scaled, and sustained over time.

As shown in Figure 8, the SBCMF connects the technical configuration of the bioenergy value chain with information-based support tools and governance conditions. This structure allows monitoring data to feed back into operational decisions, while also supporting reporting, verification, and compliance processes over time.

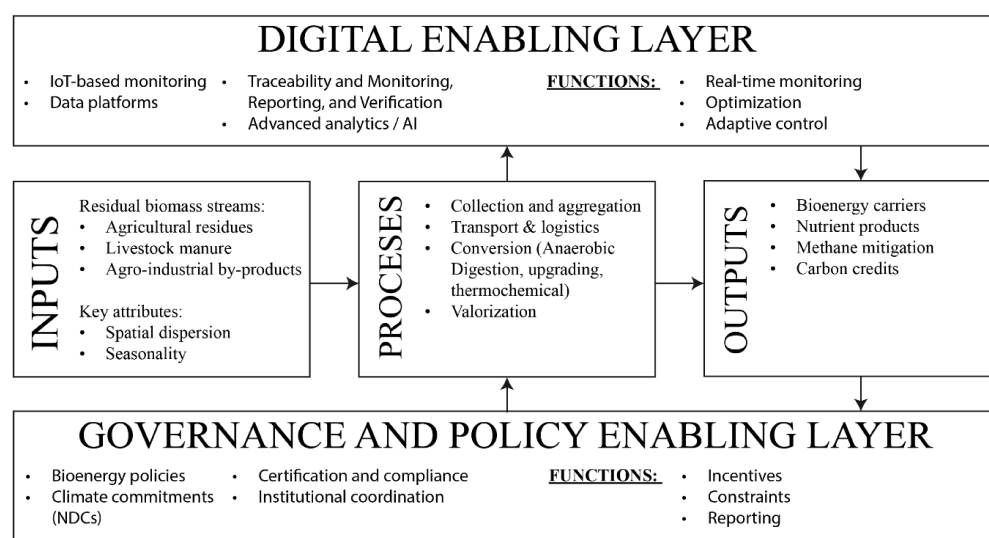


Figure 8. Sustainable bioenergy chain management framework (SBCMF) integrating technical, digital, and governance layers. Source: the authors.

5. Conclusions and Policy Implications

This study assessed the analysis and optimization of bioenergy value chains derived from agricultural residues and livestock waste in Latin America during the 2015–2025 period. The region has considerable biomass availability and an expanding technical knowledge base, which together provide a relevant foundation for the development of residue-based bioenergy systems. But the transition from this potential to operational and scalable systems remains limited. While technological advancements may improve conversion performance, including anaerobic digestion, co-digestion strategies, and biomethane upgrading, the main barriers are not technological in nature; rather, they relate to structural and organizational matters. In Brazil, Colombia, Argentina and Mexico, the biomass resource is spatially distributed, logistics systems are fragmented, and the coordination of energy planning, agriculture and environmental governance is weak, which makes it harder to convert technical potential into stable value chains.

The findings confirm the increasing relevance of optimization methods for the design and assessment of residue-based bioenergy supply chains. Mixed-integer linear programming has emerged as a dominant modelling approach, frequently integrated with GIS, life cycle assessment, and techno-economic analysis to capture spatial, environmental, and economic dimensions of system performance. This trend has enhanced the ability to evaluate

the location of infrastructure, the logistics of transportation, and the trade-off of economic and environmental performance. However, the evidence also indicates that most modelling frameworks continue to prioritize economic and energy-performance objectives, while giving limited attention to methane-specific mitigation accounting, biomass traceability requirements, and institutional coordination mechanisms. This indicates that technical performance alone is insufficient to assess the feasibility of residue-based bioenergy systems, as optimized configurations may fail to capture the regulatory and governance limitations that influence their real-world implementation.

The proposed Sustainable Bioenergy Chain Management Framework (SBCMF) represents a valuable contribution to the field because it provides a basis for making connections among these different technological, digital, and governance aspects using a single analytical perspective. This contribution advances beyond conventional supply-chain optimization by incorporating sustainability-oriented requirements that are increasingly relevant for residue-based bioenergy systems. In particular, it emphasizes the need to link system design with sustainability verification, methane-emission monitoring, and reliable traceability of biomass flows. The SBCMF places these factors not only as external contextual conditions, but also as functional components that interact with the physical bioenergy system and influence its design, operation, and long-term performance. The SBCMF therefore improves understanding of how residue-based systems may evolve relative to climate accountability and sustainability verification.

The results of this research indicate that the future development of bioenergy systems will greatly depend on improved institutional and operational coordination between actors involved in agricultural production, energy infrastructure, and environmental governance. Implementing enhanced coordination will require more interaction between these actors, and therefore organizational arrangements for managing dispersed biomass resources must also be developed. Examples of cooperation such as aggregation cooperatives, regionally coordinated logistics networks, and shared monitoring infrastructures could provide stronger mechanisms for managing biomass flows while enhancing the reliability of the data used for planning and reporting.

In addition to developing these systems, improved financial conditions will be necessary to enable the transition from pilot projects toward larger-scale implementation, as high initial investment requirements and uncertainty associated with long-term operation remain important barriers. Establishing appropriate policy instruments that recognize the climate and resource-management benefits associated with residue valorisation, including methane mitigation and circular resource use, would help improve the overall economic feasibility of these systems. The development of additional financial incentives or financing mechanisms would improve conditions for long-term investment and support the gradual integration of these systems into broader sustainability strategies across the region.

This study brings these dimensions together within a single analytical perspective to emphasize that bioenergy systems need to be examined not only from a technological point of view, but also in relation to the organizational and informational structures that influence their implementation. The proposed framework highlights the need to integrate technical design with the institutional and digital conditions shaping these systems in Latin America. This perspective can support future research and practical initiatives by helping improve planning, coordination and the long-term viability of residue-based systems across different agricultural contexts in the region.

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writing—review and editing, M.L.-d.R., C.J.G.-D., M.G.-P., L.R.-M., D.U.S.-B., E.E.O.G., E.V.-T. and A.D.P.-A. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic Digestion
AI	Artificial Intelligence
CEPAL/ECLAC	Economic Commission for Latin America and the Caribbean
CH ₄	Methane
CO ₂ e	Carbon Dioxide Equivalent
EUDR	European Union Deforestation Regulation
EU	European Union
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GHG	Greenhouse Gas
GIS	Geographic Information Systems
IEA	International Energy Agency
IoT	Internet of Things
LCA	Life Cycle Assessment
LP	Linear Programming
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Nonlinear Programming
MRV	Measurement, Reporting and Verification
NDCs	Nationally Determined Contributions
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SBCMF	Sustainable Bioenergy Chain Management Framework
TEA	Techno-Economic Analysis
TRL	Technology Readiness Level

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