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Article

A Spatial Multi-Criteria Framework for Data-Driven Anaerobic Co-Digestion Substrate Selection in Tropical Regions

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Abstract

The transition to a circular bioeconomy in developing economies is frequently hindered by the operational failure of biogas facilities due to feedstock supply discontinuity. Whilst biochemical potential is traditionally the primary selection criterion, this study postulates that logistic reliability serves as the governing constraint for sustainable implementation. To validate this paradigm shift, a spatially explicit decision-making framework integrating Shannon Entropy and TOPSIS was developed and applied to a representative tropical agro-industrial region. By evaluating conflicting criteria covering logistic availability, technical efficiency, and biochemical stability, the model identified Annual Residue Production as the dominant weighting factor. Results established Cattle Manure as the universal baseload substrate essential for mitigating seasonality risks, outweighing higher-yielding but intermittent agricultural residues. Spatial analysis further revealed distinct bioenergy clusters dictating tailored technological strategies: a high-potential Rice-Livestock cluster suitable for centralised industrial plants overseeing recalcitrant biomass, and a Cassava-Livestock cluster favourable for decentralised, low-tech digestion. This data-driven approach demonstrates that successful substrate selection must transcend theoretical yield maximisation to prioritise supply chain reliability, providing a robust roadmap for de-risking bioenergy investments in tropical regions.

Keywords: anaerobic co-digestion; circular bioeconomy; feedstock logistic reliability; bioenergy clusters; Multi-Criteria Decision Analysis (MCDA); lignocellulosic biomass; livestock waste; agricultural residue

1. Introduction

Globally, the transition towards sustainable energy systems constitutes one of the most pressing challenges of the 21st century [1]. The agricultural sector plays a paradoxical role in this scenario, since while it is responsible for feeding a growing population, it generates approximately 180 billion tonnes (Gt) of lignocellulosic waste annually worldwide [2]. Despite the immense potential of these residues, it is estimated that only 1.6% to 2.2% of the global biogas potential is currently exploited, representing a missed opportunity to mitigate between 3.29 Gt and 4.36 Gt of CO₂ equivalent emissions per year accounting for 10 % to 13 % of GHGs emissions worldwide [3,4].

In Latin America, a region that serves as a global food basket, the disparity between biomass availability and energetic valorisation is stark [5]. Colombia, for instance, generates an estimated 71.9 Mt/year of agricultural residues and 105 Mt/year of livestock waste [6]. However, waste management infrastructure often lags behind production capacity, leading to open-air disposal and environmental degradation [7]. The Caribbean region of Colombia, and specifically the department of Sucre, epitomizes this scenario. This territory is characterised by a vigorous agro-industrial vocation, contributing significantly to the national starch supply. Sucre produces over 576 kt/year of agricultural products, including cassava, rice and maize, accounting for approximately 10.8 %, 4.6 % and 3.5 % of the national production area, respectively [8]. Simultaneously, the region sustains a consolidated livestock sector with an inventory that supports the local dairy industry but generates over 3.6 Mt of livestock manure [6].

This high productivity brings an intrinsic challenge for the department of Sucre regarding the management of these organic streams. In rural areas of Sucre, crop residues like cassava stems and rice straw are typically left to decompose in open fields or burned. Additionally, the improper handling and direct discharge of livestock manure into wetlands has accelerated nutrient pollution, leading to eutrophication, harmful cyanobacteria growth, and the release of GHGs [9], which severely compromise local food security and water supplies. Consequently, there is an urgent need to transition from a linear waste disposal model to a circular bioeconomy approach, transforming these thousands of tonnes of “waste” into renewable energy vectors [10].

Anaerobic digestion (AD) stands out as a mature technology for treating organic waste while producing biogas and digestate [11]. However, the mono-digestion of single substrates often faces biochemical limitations that hinder process stability. For instance, cattle manure, despite its high buffering capacity [12], typically presents low Carbon-to-Nitrogen (C/N) ratio and modest methane yields [13]. Conversely, lignocellulosic residues, such as cassava stems and rice straw, possess significant biochemical methane potentials (BMP) but are hindered by their complex structural composition. Their high lignin content acts as a recalcitrant barrier, leading to slow hydrolysis rates and incomplete degradation [14]. Furthermore, these substrates often suffer from rapid acidification and nutritional imbalances—specifically high C/N ratios and low buffering capacity—which can result in process instability and failure in standalone digestion systems [15].

Anaerobic co-digestion (AcoD)—the simultaneous digestion of two or more substrates—emerges as a robust solution to these constraints [16]. By blending complementary substrates, AcoD balances the C/N ratio, dilutes potential inhibitors (such as ammonia or volatile fatty acids), and optimises the moisture content [17]. The synergistic effect achieved in AcoD not only enhances methane production kinetics but also improves the rheological properties of the digestate [18], potentially making the process more techno-economically feasible for regional implementation.

While the synergistic effects of AcoD offer clear metabolic advantages, the successful deployment of this technology requires transitioning from theoretical potential to territorial feasibility. Maximising methane yields becomes irrelevant if the substrates suffer from seasonal scarcity [19], prohibitive logistic-associated costs [20], or high competition from existing local markets [21]. Consequently, the selection process must transcend purely biochemical parameters to evaluate the specific “bioenergy vocation” of each territory, grounding the assessments on relevant, multidimensional criteria [22,23].

To address this complexity, Multi-Criteria Decision Analysis (MCDA) coupled with Geospatial Information Systems (GIS) has become a standard approach for bioenergy planning. Recent literature has extensively applied these tools for biogas plant site selection, focusing on identifying optimal locations for centralised facilities based on aggregated regional availability [24–27]. For instance, studies by Soha et al. [24] and Shi et al. [25] utilise GIS-MCDA to optimise supply areas and spatio-temporal stability for large-scale plants, while others like Akther et al. [26] and Venier & Yabar [27] focus on suitability analysis for single-site infrastructure in metropolitan or provincial contexts.

However, a critical gap persists in these assessments: they predominantly treat territories as homogeneous supply basins. By evaluating feedstock availability based on regional aggregates

[28,29] or prioritising purely biochemical synergies determined in laboratory settings [30,31], current frameworks often overlook the local spatial co-existence of substrates. This oversight results in a significant divergence between theoretical potential and operational viability, where mixtures identified as biochemically optimal (e.g., through C/N ratio balancing) are presumed feasible without verifying their coexistence within an economically sustainable collection radius at the municipal scale. Consequently, the prevailing focus on facility siting tends to obscure the necessity for a substrate prioritisation framework that accounts for the intra-regional heterogeneity of agro-ecological systems.

This study addresses this methodological gap by establishing a spatially explicit decision-making framework that prioritises AcoD mixtures prior to defining plant locations. Using an Integrated Entropy-TOPSIS method, this research moves beyond generic regional assessments to rank specific residue combinations across twenty-six municipalities in the Department of Sucre, Colombia. Unlike traditional studies that seek a universal 'optimal substrate', this work assesses the hypothesis that territorial heterogeneity dictates the formation of distinct bioenergy clusters, where the feasibility of a co-digestion mixture is strictly a function of local dominant crops and livestock density rather than theoretical yield maximisation.

The primary objective of this study is, therefore, to provide a data-driven roadmap that shifts the selection paradigm from biochemical potential to logistic feasibility. By identifying these localised clusters—distinguishing, for instance, between a rice-based industrial cluster and a cassava-based decentralised cluster—this framework serves as a risk mitigation strategy for policymakers and investors. It ensures that bioenergy implementation strategies are grounded in the reality of local supply chain reliability, thereby addressing the operational risks associated with substrate seasonality and spatial dispersion in developing economies.

2. Materials and Methods

2.1. Study Area and Identification of Alternatives

2.1.1. Agro-industrial Profile of the Department of Sucre

The study focuses on the Department of Sucre, Colombia, comprising twenty-six municipalities distributed across five natural sub-regions, each characterised by distinct agro-ecological conditions and residue generation profiles. The Montes de María sub-region includes the municipalities of Chalán, Colosó, Morroa, Ovejas, and Sincelejo, known for their tuber and avocado production. The Mojana region, a major agricultural hub for rice, comprises Majagual, Sucre, and Guaranda. The San Jorge sub-region includes San Marcos, Caimito, La Unión, and San Benito Abad, balancing agriculture with livestock. The central Sabanas sub-region, the epicentre of intensive cattle ranching, encompasses Corozal, San Luis de Sincé, El Roble, Sampués, San Pedro, Los Palmitos, Buenavista, Galeras, and San Juan de Betulia. Finally, the Golfo de Morrosquillo sub-region covers the coastal municipalities of Coveñas, Santiago de Tolú, San Onofre, Tolviejo, and San Antonio de Palmito. This spatial subdivision is critical as the availability of biomass varies significantly. The analysis treats each municipality as a distinct spatial unit for residue quantification.

To illustrate this spatial heterogeneity, **Figure 1** presents the geolocalised density of agricultural production and livestock inventory across the department. **Figure 1a** highlights agricultural production, which is primarily concentrated in the Mojana sub-region (e.g., Majagual and Guaranda) and specific areas of Montes de María (e.g., Ovejas), driven by intensive rice and tuber farming. In contrast, **Figure 1b** reveals the livestock inventory density, showing a high concentration in the central Sabanas sub-region (e.g., Corozal and Sampués) and ranching hubs in San Jorge sub-region (e.g., La Unión). This geospatial distribution of primary production and livestock is a key determinant for estimating the biomass potential and the logistic feasibility of implementing anaerobic digestion plants.

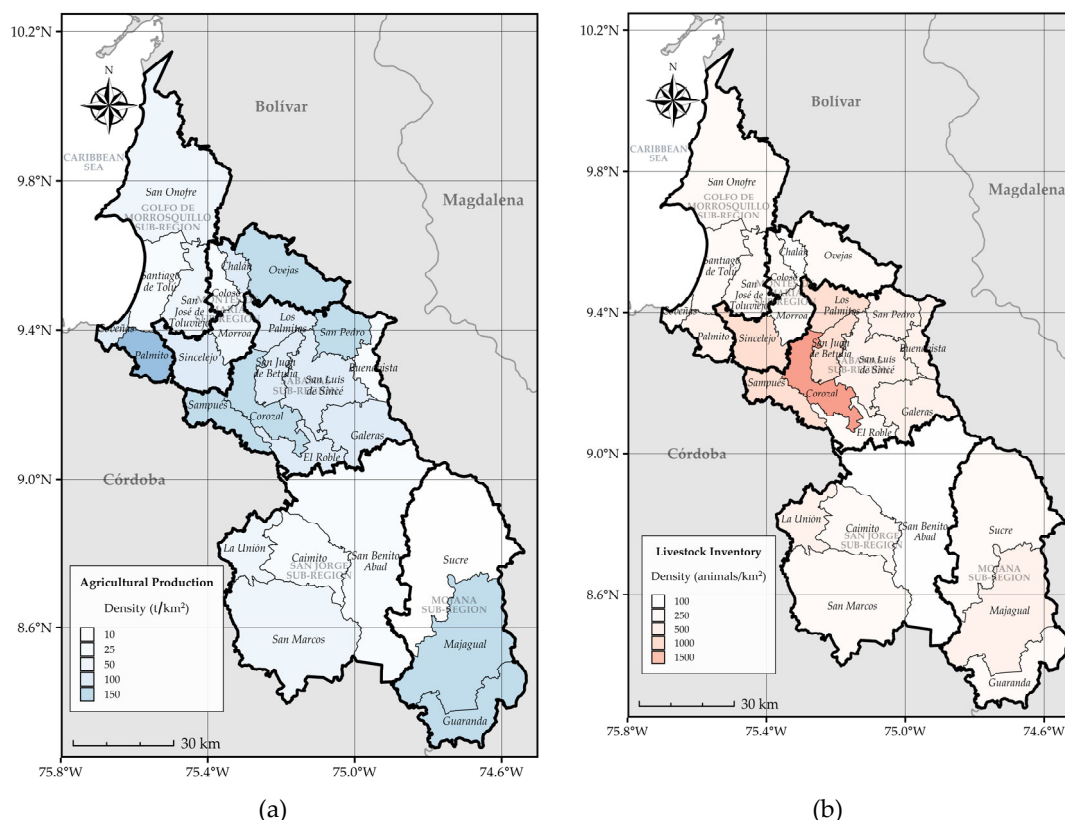


Figure 1. Spatial distribution of agricultural production density (t/km^2) and livestock inventory density (animals/ km^2) in the Department of Sucre: (a) Agricultural production; (b) Livestock inventory. Source: own elaboration with data from: [8].

2.1.2. Selection of Substrates and Residue Generation Factors

The selection of substrates for this study was driven by the predominant agro-economic activities in the Department of Sucre, ensuring that the proposed co-digestion scenarios are regionally relevant and logistically feasible. Consequently, the analysis focuses on the most abundant lignocellulosic residues from staple crops (cassava, yam, maize, and rice) and organic effluents from the livestock sector (cattle, poultry, and porcine manure).

To quantify the theoretical availability of these substrates at the municipal level, specific Residue Generation Factors (RGF) were adopted from specialised literature. These factors, presented in **Table 1**, represent the ratio of residue generated per unit of main product harvested or per animal head, enabling the conversion of agricultural statistical data into biomass potential.

Table 1. Residue generation factors. Source: own elaboration with data from: [6,32–42].

Sector	Source	Specific Residues (Alternatives)	Residue Generation Factor (RGF)
Agriculture	Avocado Crop	A1: Avocado Prunings	0.06 t/fruit
Agriculture	Cassava Crop	A2: Cassava Leaves	0.09 t/tubers
Agriculture	Cassava Crop	A3: Cassava Stems	0.41 t/tubers
Agriculture	Cassava Crop	A4: Cassava Stump	0.13 t/tubers
Agriculture	Coconut Crop	A5: Coconut Prunings	0.59 t/fruit
Agriculture	Maize Crop	A6: Maize Stover	1.07 t/grain
Agriculture	Mango Crop	A7: Mango Prunings	0.37 t/fruit
Agriculture	Oil Palm Crop	A8: Oil Palm Prunings	1.83 t/fruit

Sector	Source	Specific Residues (Alternatives)	Residue Generation Factor (RGF)
Agriculture	Plantain Crop	A9: Plantain Leaves	0.39 t/fruit
Agriculture	Plantain Crop	A10: Plantain Pseudostem	4.17 t/fruit
Agriculture	Rice Crop	A11: Rice Straw	1.16 t/grain
Agriculture	Watermelon Crop	A12: Watermelon Stubble	1.50 t/fruit
Agriculture	Yam Crop	A13: Yam Stubble	0.36 t/tubers
Livestock	Cattle Farming	A14: Cattle Manure (Calf < 1 year)	1.46 t/animal
Livestock	Cattle Farming	A14: Cattle Manure (Small 1-2 years)	2.92 t/animal
Livestock	Cattle Farming	A14: Cattle Manure (Medium 2-3 years)	3.65 t/animal
Livestock	Cattle Farming	A14: Cattle Manure (Large > 3 years)	5.48 t/animal
Livestock	Pig Farming	A15: Pig Manure (Small 0-6 months)	0.37 t/animal
Livestock	Pig Farming	A15: Pig Manure (Adult > 6 months)	0.73 t/animal
Livestock	Poultry Farming	A16: Poultry Manure (Large/Adult)	0.08 t/animal

2.2. Definition of Decision Criteria

To provide a holistic assessment of the substrate suitability for anaerobic co-digestion, a set of ten conflicting criteria was established. These criteria were selected to address the multidimensional nature of bioenergy projects, encompassing supply chain reliability, bio-energy efficiency, and biochemical stability. As detailed in Table 2, the criteria are categorised into three domains:

- *Availability and Logistics (C1, C6, and C10)*: These criteria assess the feasibility of the supply chain. High annual production and total solids content are desirable for reducing collection radii and transport costs; while competing local uses (e.g., animal feed) represent a barrier to energy valorisation.
- *Physicochemical Properties (C2, C3, C4, and C5)*: These parameters determine the theoretical energy yield and process stability. Special attention is given to the C/N ratio and moisture content, which must fall within specific biological ranges to avoid inhibition.
- *Lignocellulosic Composition (C7, C8, and C9)*: Reflecting the complexity of tropical biomass, these criteria evaluate the biodegradability kinetics. High cellulose and hemicellulose fractions are preferred for rapid conversion, whereas lignin acts as a recalcitrant barrier limiting hydrolysis.

Table 2. Definition of decision criteria for the ENTROPY-TOPSIS model. Source: own elaboration based on: [43–49].

Criteria	Units	Criteria Type	Description
C1: Annual Residue Production	t/year	Benefit	Determines process viability and scale; ensures continuous raw material supply.
C2: Biochemical Methane Potential	L/kg of VS	Benefit	Indicates biomass energy potential and generation efficiency.
C3: Carbon-to-Nitrogen Ratio	mol/mol	Range	Critical for process stability and biogas production balance (optimal: 20 to 30).
C4: Moisture Content	% wt.	Range	Enhances microbial degradation and process yields (optimal: 80 % to 90 %).
C5: Volatile Solids	%	Benefit	Represents biodegradable fraction indicating biogas production potential.
C6: Total Solids	%	Benefit	Optimises logistics and storage volume; facilitates efficient reactor feeding.
C7: Cellulose Fraction	%	Benefit	Primary source of fermentable sugars influencing AD efficiency.
C8: Hemicellulose Fraction	%	Benefit	Secondary source of fermentable sugars affecting degradation efficiency.

C9: Lignin Fraction	%	Cost	Recalcitrant polymer that hinders biological conversion efficiency.
C10: Local Market Use	Scale: 1 to 5	Cost	Evaluates competition with existing local applications (feed, compost, etc.).

2.3. Data Acquisition and Matrix Construction

2.3.1. Municipal Biomass Inventory and Data Collection

Data for estimating agricultural residue production were based on the main product values of the evaluated crops reported by the Agronet database (Colombian Ministry of Agriculture and Rural Development) [8]. Similarly, data required for livestock residue calculations were obtained from the same source, determining the reported annual animal inventory for each of the twenty-six municipalities ($k = 1, 2, \dots, 26$).

The Annual Residue Production (C1) for each specific residue i in municipality k was calculated individually to serve as a criterion for that specific alternative. This calculation follows Equation (1).

$$APR_{i,k} = P_{i,k} \cdot RGF_i \quad (1)$$

Where $APR_{i,k}$ is the estimated annual production of residue i in municipality k (t/year); $P_{i,k}$ is the reported annual production of the main crop or the animal inventory associated with residue i in municipality k ; and RGF_i is the Residue Generation Factor for residue i , as defined in **Table 1**. This allows for the creation of a spatially explicit decision matrix where the feasibility of a mixture depends on the local availability of both components in municipality k .

2.3.2. Experimental Characterisation

The thermal and physical properties of the substrates were determined through proximate analysis in accordance with international standards. Specifically, moisture content was evaluated following ASTM E871-82, while volatile matter and ash content were assessed using ASTM E872-82 and ASTM E1755-01, respectively. Fixed carbon was subsequently derived by difference. The ultimate analysis was performed to quantify the elemental composition, employing a Velp EMA 502 elemental analyser and following the protocols outlined in ASTM D591-92.

The lignocellulosic composition (C7, C8, C9) was analysed to determine the structural carbohydrate fractions essential for methane yield estimation. The content of cellulose (X_C), hemicellulose (X_H), and lignin (X_L) was quantified using the Van Soest method (AOAC 973.18). These experimentally determined fractions were then input into the model proposed by Thomsen et al. [50] (Equation 2) to calculate the theoretical Biochemical Methane Potential (C2), ensuring the energy estimates reflect the specific biochemical reality of the region's biomass.

$$BMP_i = 378x_{C,i} + 354x_{H,i} - 194x_{L,i} + 313x_{E,i} \quad (2)$$

Where BMP_i is the Biochemical Methane Potential (L of CH₄/kg of VS); $X_{C,i}$, $X_{H,i}$, and $X_{L,i}$ represent the fractions of cellulose, hemicellulose, and lignin, respectively; and $X_{E,i}$ is the fraction of extractives (non-structural components like soluble sugars, proteins, waxes, etc.), calculated by difference.

2.3.3. Assessment of Local Market Utilisation and Competition (C10)

To quantify the operational risk associated with feedstock accessibility, a semi-quantitative assessment of the Local Market Utilisation (C10) was conducted. Unlike physicochemical properties, this criterion evaluates the 'opportunity cost' of diverting a residue from its current application to energy generation. An elevated level of existing competition implies a lower availability for AD or AcoD projects, categorising C10 as a Cost-type criterion.

The market scores were ascertained through a triangulation of secondary data sources, including:

- *Official Agrarian Reports*: Statistical data from the Ministry of Agriculture and Rural Development (Agronet) and the Mining-Energy Planning Unit (UPME) regarding biomass residual factors and current disposal practices.
- *Scientific Literature Review*: Analysis of regional studies focusing on the waste management practices specific to the department of Sucre.
- *Departmental Development Plans*: Review of official documents from the Government of Sucre describing local agricultural supply chains.

Based on this evidence, a five-point Market Competition Scale was established to translate qualitative logistics data into numerical inputs for the TOPSIS algorithm. The scoring rubric was defined as follows:

1. *Score 1 (Negligible Competition)*: Residues currently treated as a disposal liability. There is no established market; the producer incurs costs for removal or burning. These are the most favourable for AD.
2. *Score 2 (Low Competition)*: Residues with minimal economic value, limited to sporadic on-farm nutrient cycling or inefficient uses with high perishability constraints.
3. *Score 3 (Moderate/Seasonal Competition)*: Residues with an established but fluctuating market. Competition arises during specific seasons (e.g., dry periods) for uses such as animal ensilage or bedding.
4. *Score 4 (High/Captive Competition)*: Residues integrated into mature commercial supply chains or possessing high captive use value for internal energy generation within industrial facilities.
5. *Score 5 (Prohibitive Competition)*: Commodities with a high market price where energy valorisation is economically unfeasible due to the cost of acquisition.

Each alternative (A1 to A16) was assigned a discrete integer value based on its predominant management practice in the Department of Sucre.

2.4. Implementation of the Integrated Entropy-TOPSIS Method

The ranking of alternatives was performed using a multi-step computational framework implemented in the R statistical environment.

2.4.1. Pre-Processing

Before normalization, criteria that are neither strictly Benefit nor Cost types must be converted. The C/N ratio (C3) and Moisture Content (C4) are range criteria with optimal intervals [L,U] (e.g., [20,30] for C/N). To integrate these into the TOPSIS framework, values were converted to a "Benefit" type using the following transformation, where values closer to the optimal range receive higher scores:

$$x'_{ij} = \begin{cases} 1 & \text{if } L \leq x_{ij} \leq U \\ 1 - \frac{L - x_{ij}}{\max(L - x_{min}, x_{max} - U)} & \text{if } x_{ij} < L \\ 1 - \frac{x_{ij} - U}{\max(L - x_{min}, x_{max} - U)} & \text{if } x_{ij} > U \end{cases} \quad (3)$$

Where x_{ij} is the raw value, and x'_{ij} is the transformed value used in subsequent steps.

2.4.2. Normalisation of the Decision Matrix

To allow comparison across dimensions with different units, the decision matrix was vector-normalised. For each element x_{ij} (after range conversion), the normalised value r_{ij} is calculated using Equation (4):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (4)$$

2.4.3. Determination of Objective Weighting Factors via Shannon Entropy

Shannon Entropy was used to calculate objective weights (w_j). First, the probability of the j -th criterion for alternative i (p_{ij}) is calculated using Equation (5):

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}^2} \quad (5)$$

The entropy value (E_j) for each criterion is computed as:

$$E_j = -\frac{1}{\ln m} \sum_{i=1}^m p_{ij} \cdot \ln p_{ij} \quad (6)$$

Finally, the degree of divergence ($d_j = 1 - E_j$) is used to determine the objective weight w_j :

$$w_j = \frac{d_j}{\sum_{j=1}^n d_j} \quad (7)$$

2.4.4. Calculation of the Weighted Normalised Decision Matrix

The weighted normalised decision matrix V is obtained by multiplying the normalised matrix by the entropy weights:

$$v_{ij} = r_{ij} \cdot w_j \quad (8)$$

2.4.5. Calculation of the Ideal and Negative-Ideal Solutions

The Positive Ideal Solution (A^+) and the Negative Ideal Solution (A^-) are defined as:

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\} = \left\{ \left(\max_i v_{ij} | j \in \mathcal{J} \right), \left(\min_i v_{ij} | j \in \mathcal{J}' \right) \right\} \quad (9)$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\} = \left\{ \left(\min_i v_{ij} | j \in \mathcal{J} \right), \left(\max_i v_{ij} | j \in \mathcal{J}' \right) \right\} \quad (10)$$

Where \mathcal{J} represents the set of benefit criteria and \mathcal{J}' the set of cost criteria.

2.4.6. Calculation of Relative Closeness to the Ideal Solution

The Euclidean distances of each alternative to the positive ideal (S_i^+) and negative ideal (S_i^-) solutions are calculated:

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (11)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (12)$$

The relative closeness coefficient (CC_i) represents the final ranking score:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (13)$$

An alternative with a CC_i closer to one is considered superior.

2.5. Formulation of Anaerobic Co-digestion Scenarios Based on Local Availability

To evaluate the theoretical energy potential of implementing circular economy strategies at the local level, specific AcoD scenarios were defined for each municipality. These scenarios were constructed by pairing the highest-ranked agricultural residue (R_{Agri}^*) with the highest-ranked livestock residue (R_{Liv}^*) obtained from the Entropy-TOPSIS assessment for each specific location. This approach ensures that the proposed mixtures are not only theoretically optimal but also logistically feasible based on local dominance.

The scenarios were characterised by four key indicators derived from the mass balance of the available substrates. First, the Total Gross Availability (TA_k) for municipality k was calculated as the sum of the annual generation of the best-ranked substrates:

$$TA_k = Q_{\text{Agri},k}^* + Q_{\text{Liv},k}^* \quad (14)$$

Where $Q_{\text{Agri},k}^*$ and $Q_{\text{Liv},k}^*$ are the annual quantities (t/year) of the best agricultural and livestock residues in municipality k , respectively.

The physico-chemical properties of the substrate mixture were estimated assuming a complete mixing model based on the availability ratio. The Weighted Biochemical Methane Potential (BMP_{Mix}) and the Weighted Volatile Solids (VS_{Mix}) were calculated as follows:

$$BMP_{\text{Mix},k} = \frac{Q_{\text{Agri},k}^* \cdot BMP_{\text{Agri}} + Q_{\text{Liv},k}^* \cdot BMP_{\text{Liv}}}{TA_k} \quad (15)$$

$$VS_{\text{Mix},k} = \frac{Q_{\text{Agri},k}^* \cdot VS_{\text{Agri}} + Q_{\text{Liv},k}^* \cdot VS_{\text{Liv}}}{TA_k} \quad (16)$$

Where BMP_{Agri} and BMP_{Liv} represent the biochemical methane potential of the individual residues, and VS_{Agri} and VS_{Liv} represent volatile solids content of the individual residues.

Finally, the Global Methane Potential (GMP_k), which represents the theoretical maximum energy recovery capacity for the municipality per year, was determined by integrating the total availability with the mixture's organic quality:

$$GMP_k = TA_k \cdot VS_{\text{Mix},k} \cdot BMP_{\text{Mix},k} \quad (17)$$

This variable serves as a proxy for the scalability of biogas projects in each territory, integrating both the quantity and quality of the prioritised waste streams.

3. Results

3.1. Municipal-Level Waste Generation Inventory

The municipal inventory, summarised in **Figure 2**, presents the total annual residue generation across the twenty-six municipalities. Majagual recorded the highest total biomass potential in the department, accumulating approximately 478.4 kt/year. This figure comprised 118.8 kt of agricultural residues—the maximum value observed for this category among all municipalities—and 359.6 kt of livestock residues. San Luis de Sincé and San Marcos followed as the subsequent largest producers, with total generation values of roughly 407.6 kt and 388.5 kt, respectively. In San Luis de Sincé, livestock waste constituted the predominant fraction (388.7 kt), whilst agricultural residues contributed 18.9 kt to the total mass.

In contrast, the municipalities of Chalán, Coveñas, and Colosó exhibited the lowest generation rates, with total combined residues remaining below 32 kt/year in each location. Regarding the composition of the waste streams, livestock residues exceeded agricultural residues in all evaluated territories. For instance, in Sucre and San Onofre, livestock waste accounted for over 90% of the locally generated biomass. Apart from Majagual, significant quantities of agricultural residues were recorded in Guaranda (52.1 kt) and Ovejas (43.0 kt), although these values remained lower than their respective livestock residue counterparts (150.8 kt and 118.6 kt, respectively).

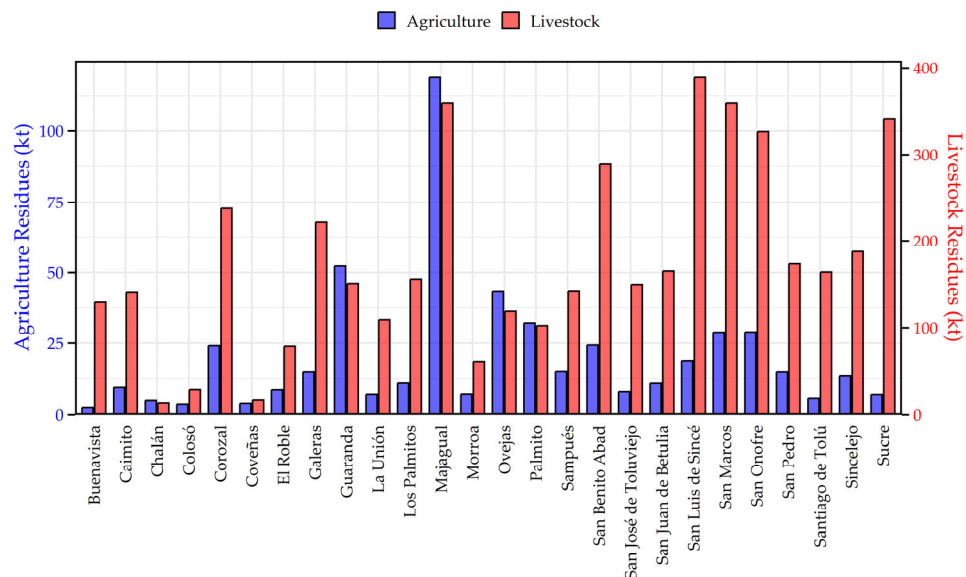


Figure 2. Total annual residue generation (kt/y) by municipality in the Department of Sucre, categorised by sector (Agricultural vs. Livestock).

3.2. Physicochemical Characterisation of Residues

The physicochemical characterisation of the sixteen selected substrates is detailed in **Table 3**. The C/N ratio exhibited a wide variation across the alternatives, ranging from a minimum of 6.68 in Poultry Manure (A16) to a maximum of 52.61 in Plantain Pseudostem (A10). Livestock residues (A14–A16) generally recorded lower C/N values compared to agricultural residues, with the exception of Cassava Leaves (A2), which presented a ratio of 10.99. Regarding MC, Plantain Pseudostem (A10) showed the highest value at 93.17 %, whilst Mango Prunings (A7) recorded the lowest at 47.63 %. The VS content ranged from 71.26 % in Poultry Manure to 94.42 % in Cassava Stump (A4).

Lignocellulosic composition analysis revealed distinct structural differences among the substrates. Cellulose content was highest in Plantain Pseudostem (66.01 %) and Coconut Prunings (65.33 %), whereas Pig Manure (A15) recorded the lowest fraction at 9.86 %. Hemicellulose content varied from 5.73 % in Poultry Manure to 28.49 % in Plantain Pseudostem. Regarding lignin, the highest concentrations were observed in Cassava Leaves (26.35 %) and Watermelon Stubble (25.08 %), whilst Poultry Manure and Avocado Prunings presented the lowest values, with 5.73 % and 6.62 %, respectively.

The BMP values demonstrated significant variability across the evaluated residues. Plantain Pseudostem (A10) yielded the highest theoretical potential at 433.6 L CH₄/kg VS, followed by Maize Stover (A6) with 381.5 L CH₄/kg VS. Conversely, the livestock residues recorded the lowest methane yields, with Cattle Manure (A14) and Pig Manure (A15) producing 136.4 L CH₄/kg VS and 146.9 L CH₄/kg VS, respectively.

3.3. Local Market Utilisation and Competition Assessment

The assessment of local market utilisation, detailed in **Table 4**, categorised the sixteen substrates based on their existing competition levels. A total of six residues received the lowest Market Score of 1, indicating negligible competition. This group included Avocado Prunings (A1), Cassava Stump (A4), Mango Prunings (A7), Plantain Pseudostem (A10), Watermelon Stubble (A12), and Yam Stubble (A13). The primary drivers associated with this score were disposal costs, land clearance requirements, and on-field nutrient cycling.

Five substrates were assigned a Market Score of 2, comprising Cassava Leaves (A2), Cassava Stems (A3), Coconut Prunings (A5), Plantain Leaves (A9), and Cattle Manure (A14). The competition

factors identified for these residues included high perishability, specific agricultural applications such as vegetative propagation, and logistical constraints related to collection. Intermediate competition (Market Score 3) was recorded for three substrates: Maize Stover (A6), Rice Straw (A11), and Pig Manure (A15), where the determining factors were seasonal fluctuations, animal feed demand, and environmental management risks.

The highest competition level observed in the study corresponded to a Market Score of 4, assigned to Oil Palm Prunings (A8) and Poultry Manure (A16). For these residues, the key drivers limiting availability were internal energy valorisation within extraction mills and established commercial value as organic fertiliser, respectively. No residues were assigned a Market Score of 5.

Table 3. Physicochemical characterisation of selected substrates.

Residue	C/N Ratio	MC (%)	VS (%)	TS (%)	EC (%)	CellC (%)	HemC (%)	LigC (%)	BMP (L/kg VS)
A1: Avocado Prunings	16.79	68.32±0.36	89.38±0.59	93.12±0.26	15.77±0.77	46.57±0.54	25.30±1.81	6.62±1.32	302.1±7.6
A2: Cassava Leaves	10.99	63.00±1.80	89.89±0.06	91.93±0.17	33.87±0.92	40.75±1.20	18.81±0.61	26.35±0.92	275.5±6.1
A3: Cassava Stems	32.19	69.86±0.85	93.98±0.09	94.60±0.10	13.85±0.85	35.42±0.92	7.63±1.96	21.67±0.24	162.2±8.2
A4: Cassava Stump	31.47	58.22±0.27	94.42±0.59	93.28±0.07	11.33±1.59	38.61±0.32	13.87±0.51	10.12±0.56	210.9±5.5
A5: Coconut Prunings	44.65	49.52±1.19	85.86±1.67	95.77±0.17	21.20±0.86	65.33±0.32	21.19±0.51	19.72±0.56	350.1±3.6
A6: Maize Stover	30.05	65.52±0.56	91.11±0.02	93.58±0.17	22.68±0.04	60.87±1.16	26.58±1.06	7.06±0.24	381.5±5.8
A7: Mango Prunings	25.92	47.63±0.51	87.88±0.56	91.14±0.12	19.82±0.27	56.02±1.12	18.57±0.22	20.07±0.43	300.6±4.5
A8: Oil Palm Prunings	27.50	60.61±0.68	87.60±1.27	94.84±0.17	24.21±0.15	63.91±0.92	18.46±1.96	22.49±0.24	339.1±7.8
A9: Plantain Leaves	21.87	76.99±0.56	86.26±0.06	93.90±0.20	20.08±1.15	46.81±0.91	21.07±0.47	9.98±0.75	295±5.4
A10: Plantain Pseudostem	52.61	93.17±0.15	85.09±0.11	90.87±0.15	32.31±0.01	66.01±0.91	28.49±0.64	9.24±0.29	433.6±4.2
A11: Rice Straw	20.66	62.33±0.75	79.53±0.10	93.36±0.22	22.41±0.17	38.53±0.46	15.23±0.18	18.40±0.22	234±2.0
A12: Watermelon Stubble	15.55	75.61±2.88	86.66±0.35	93.03±0.10	40.05±0.54	42.74±1.62	13.59±1.77	25.08±1.47	286.4±9.4
A13: Yam Stubble	18.93	75.15±0.11	85.42±0.44	92.50±0.25	26.24±0.74	55.13±0.77	19.88±1.11	23.73±0.10	314.9±5.4
A14: Cattle Manure	28.33	73.06±2.30	79.13±0.62	93.22±0.07	10.68±0.33	24.41±0.15	13.26±0.12	18.68±0.07	136.4±1.3
A15: Pig Manure	14.05	61.82±3.07	83.11±0.25	93.16±0.18	27.26±0.40	18.15±0.20	9.86±0.11	21.63±0.09	146.9±1.5
A16: Poultry Manure	6.68	55.44±2.29	71.26±0.43	92.83±0.15	27.16±0.54	42.08±1.14	28.79±0.50	5.73±0.17	334.9±5.0

C-N Ratio: Carbon to Nitrogen Atomic Ratio, MC: Moisture Content, VS: Volatile Solids Content, TS: Total Solids Content, EC: Extractives Content, CellC: Cellulose content, HemC: Hemicellulose Content, LigC: Lignin Content, BMP: Biochemical Methane Potential.

Table 4. Assessment of local market utilisation and competition for selected residues in Sucre.

Residue	Market Score (1–5)	Key Competition Driver	Justification and Current Local Uses
A1: Avocado Prunings	1	Disposal Cost	Treated as waste to be pruned and discarded/burned. Negligible market value or competition.
A2: Cassava Leaves	2	Perishability	Left in the field or occasionally used for small-scale animal feed. High perishability limits marketability and transport range.
A3: Cassava Stems	2	Agricultural Use	Traditionally used by farmers in Sucre for vegetative propagation (cloning) of the cassava plant. Stems are cut into stakes for replanting; however, a surplus remains after selecting viable stakes.
A4: Cassava Stump	1	Land Clearance Cost	The root stump is usually left in the ground and requires manual or mechanical removal to prepare the land for the next cycle. No current commercial use; represents a disposal cost.
A5: Coconut Prunings	2	Collection Logistics	Mostly left in the field. Fibrous nature makes decomposition slow. Low competition, but collection can be labour intensive.
A6: Maize Stover	3	Animal Feed	Intense competition as cattle feeds during dry periods (ensilage). Availability for energy fluctuates with climatic conditions.
A7: Mango Prunings	1	Disposal Cost	Treated as waste to be pruned and discarded/burned. Negligible market value or competition.
A8: Oil Palm Prunings	4	Internal Energy Use	Often recycled within the plantation for nutrient cycling or used as fuel in extraction mill boilers. High captive use limits external availability.
A9: Plantain Leaves	2	Local Packaging/Feed	Leaves have a niche market for traditional food packaging (e.g., tamales) and minor use as animal feed but supply vastly exceeds demand.
A10: Plantain Pseudostem	1	Nutrient Cycling	Minimal current use. Left to decompose in the field to recycle nutrients. Exceptionally low competition, high potential for valorisation.

A11: Rice Straw	3	Seasonality	Often burned in the field (illegal but common) or used for cattle bedding/feed during dry seasons. Seasonality affects its competitive use.
A12: Watermelon Stubble	1	Nutrient Cycling	Crop residues are typically left in the field for decomposition and soil incorporation. No significant commercial market exists.
A13: Yam Stubble	1	Collection Logistics	Aerial vines remaining in the field after harvest. Difficult mechanisation due to entangled growth. Often burned or left for soil incorporation; no significant market value.
A14: Cattle Manure	2	Soil Amendment	Primarily used as direct fertiliser on pastures, though often in excess and inefficiently managed. Low commercial value, making it highly available for AD.
A15: Pig Manure	3	Environmental Risk	Used for fertilisation but poses environmental challenges due to odour and runoff. Moderate competition, often requires treatment before disposal.
A16: Poultry Manure	4	Commercial Value	High demand as a potent organic fertiliser for crops and fish farming. Established commercial value creates significant competition for energy use.

3.4. Application of the Integrated ENTROPY-TOPSIS Method

3.4.1. Determination of Objective Weights

The vector-normalised decision matrix, presented in **Table 5**, displays the dimensionless scores for the sixteen alternatives across the evaluated criteria (excluding C1, which is calculated per municipality). Regarding the BMP (C2), Plantain Pseudostem (A10) achieved the highest normalised value of 0.370, followed by Maize Stover (A6) at 0.325. Conversely, the livestock residues recorded the lowest scores in this dimension, with Cattle Manure (A14) and Pig Manure (A15) registering values of 0.116 and 0.125, respectively.

In terms of physicochemical properties, the normalised C/N ratio (C3) showed uniform values of 0.299 for nine substrates, including Maize Stover and Cattle Manure. The lowest score for this criterion was observed for Plantain Pseudostem (0.000). Moisture Content (C4) exhibited distinct polarisation; six alternatives, such as Plantain Leaves (A9) and Cattle Manure, shared the maximum normalised score of 0.340, whilst Mango Prunings (A7) received a value of 0.000.

The lignocellulosic composition criteria demonstrated varied distributions. For Cellulose (C7), Plantain Pseudostem and Coconut Prunings obtained the highest scores (0.341 and 0.338), whereas Pig Manure recorded the minimum at 0.094. Regarding Lignin (C9), Oil Palm Prunings (A8) and Poultry Manure (A16) presented contrasting results, with normalised values of 0.311 and 0.079, respectively. Finally, for Local Market Utilisation (C10), Oil Palm Prunings and Poultry Manure

achieved the maximum score of 0.434, while seven residues, including Avocado Prunings (A1), received the baseline score of 0.108.

Table 5. Vector-Normalised Decision Matrix.

Residue	C2: BMP	C3: C/N Ratio	C4: MC	C5: VS	C6: TS	C7: CellC	C8: HemC	C9: LigC	C10: LMU
A1: Avocado Prunings	0.258	0.257	0.31 5	0.259	0.250	0.241	0.320	0.092	0.108
A2: Cassava Leaves	0.235	0.180	0.23 4	0.261	0.247	0.211	0.238	0.365	0.217
A3: Cassava Stems	0.138	0.270	0.33 8	0.272	0.254	0.183	0.096	0.300	0.217
A4: Cassava Stump	0.180	0.280	0.16 1	0.274	0.250	0.200	0.175	0.140	0.108
A5: Coconut Prunings	0.299	0.105	0.02 9	0.249	0.257	0.338	0.268	0.273	0.217
A6: Maize Stover	0.325	0.299	0.27 2	0.264	0.251	0.315	0.336	0.098	0.325
A7: Mango Prunings	0.256	0.299	0.00 0	0.255	0.244	0.290	0.235	0.278	0.108
A8: Oil Palm Prunings	0.289	0.299	0.19 7	0.254	0.254	0.331	0.233	0.311	0.434
A9: Plantain Leaves	0.252	0.299	0.34 0	0.250	0.252	0.242	0.266	0.138	0.217
A10: Plantain Pseudostem	0.370	0.000	0.14 0	0.247	0.244	0.341	0.360	0.128	0.108
A11: Rice Straw	0.200	0.299	0.22 3	0.231	0.250	0.199	0.193	0.255	0.325
A12: Watermelon Stubble	0.244	0.240	0.34 0	0.251	0.250	0.221	0.172	0.347	0.108
A13: Yam Stubble	0.269	0.285	0.34 0	0.248	0.248	0.285	0.251	0.328	0.108
A14: Cattle Manure	0.116	0.299	0.34 0	0.229	0.250	0.126	0.168	0.258	0.217
A15: Pig Manure	0.125	0.220	0.21 6	0.241	0.250	0.094	0.125	0.299	0.325
A16: Poultry Manure	0.286	0.123	0.11 9	0.207	0.249	0.218	0.364	0.079	0.434

The calculation of objective weights via Shannon Entropy, illustrated in **Figure 3**, identified Annual Residue Production (C1) as the criterion with the highest relative importance, assigned a mean weight of 0.761 (± 0.027). This was followed by Moisture Content (C4) with a weight of 0.060, and Local Market Utilisation (C10) with 0.046. The C/N Ratio (C3) and Lignin Fraction (C9) received weights of 0.039 and 0.037, respectively.

The remaining criteria registered weights below 0.030. The structural carbohydrate fractions, Hemicellulose (C8) and Cellulose (C7), were assigned values of 0.021 and 0.018. Finally, the physical parameters of BMP (C2), Volatile Solids (C5), and Total Solids (C6) obtained the lowest objective weights in the assessment, with C5 and C6 recording values of 0.001 and 0.000, respectively.

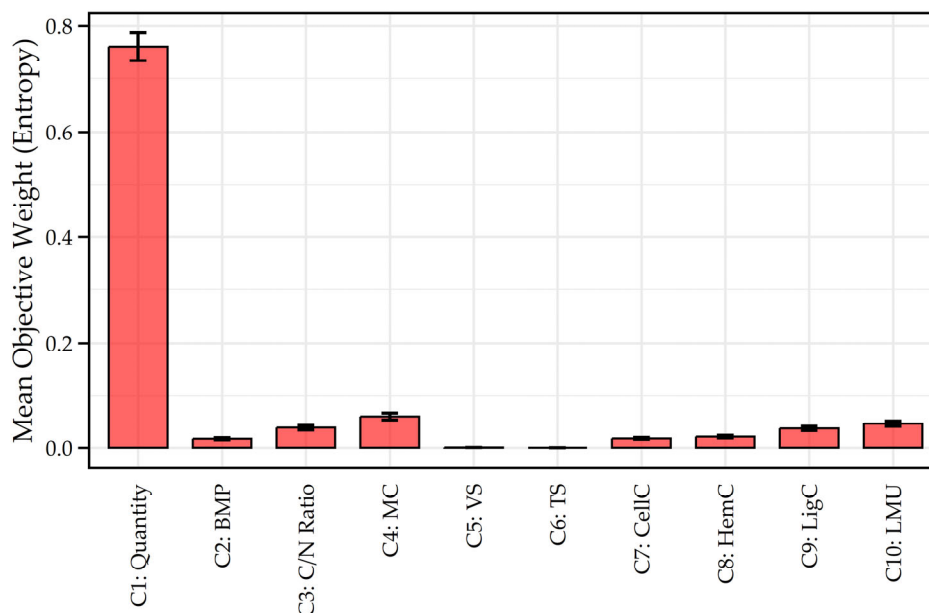


Figure 3. Distribution of Shannon entropy weights for the multi-criteria assessment of residue suitability.

3.4.2. Ranking of Co-Digestion Scenarios by Municipality

The theoretical energy potential and physicochemical properties of the prioritised co-digestion mixtures are detailed in **Table 7**. The GMP exhibited a wide range of variation across the department, with Majagual recording the highest value at 53.6 Million m³/year, derived from a Total Availability of 430.5 kt/year. Following Majagual, the municipalities of San Luis de Sincé, San Marcos, and San Onofre registered substantial potentials of 42.7, 39.5, and 34.1 Million m³/year, respectively. Conversely, the lowest energy potentials were observed in coastal or mountainous municipalities such as Coveñas (1.7 Million m³/year), Chalán (2.0 Million m³/year), and Colosó (3.2 Million m³/year).

Regarding the specific methane yields of the prioritised mixtures, the highest Weighted BMP was recorded in Chalán at 176.6 L CH₄/kg VS, corresponding to a mixture of Cattle Manure and Maize Stover. High BMP values were also observed in municipalities where Rice Straw was the selected co-substrate, such as Guaranda (161.4 L CH₄/kg VS) and Majagual (157.1 L CH₄/kg VS). In contrast, municipalities utilising Plantain Leaves or Cassava Stems generally presented lower weighted yields. For instance, Buenavista and Sucre recorded BMP values of approximately 136.4 L CH₄/kg VS.

The mass balance analysis revealed significant heterogeneity in the Agriculture-to-Livestock mixing ratios. The most balanced proportions were identified in the Mojana sub-region, specifically in Guaranda (1:2.9) and Majagual (1:3.7). A distinct group of municipalities, including San Onofre, Santiago de Tolú, and Sucre, exhibited ratios heavily skewed towards livestock residues. In Sucre, the ratio reached 1:5128.9, whilst Santiago de Tolú recorded 1:1783.9, indicating a mixture composition dominated almost exclusively by manure mass. Despite these variations in mixing ratios, the weighted VS content of the mixtures remained relatively stable across the territory, ranging between 79.1% and 81.1%.

Table 6. Ranking of agricultural and livestock residues per municipality.

Municipality	A	A	A	A	A	A	A	A	A	A1	A1	A1	A1	A1	A1	
	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6
Buenavista	7	13	6	12	16	4	15	9	3	14	11	10	8	1	2	5
Caimito	6	12	8	13	16	3	15	10	5	14	4	9	7	1	2	11
Chalán	9	14	6	13	16	2	15	10	7	3	5	11	8	1	4	12

Colosó	8	14	6	13	16	4	15	10	5	3	12	11	7	1	2	9
Corozal	8	13	3	11	16	5	15	9	6	14	12	10	7	1	4	2
Coveñas	9	14	3	12	16	4	15	10	7	6	13	11	5	1	2	8
El Roble	8	13	2	12	16	7	15	10	6	14	5	11	9	1	3	4
Galeras	8	13	2	12	16	6	15	10	5	14	7	11	9	1	3	4
Guaranda	6	12	9	13	16	5	15	10	4	14	2	8	7	1	3	11
La Unión	7	14	4	13	16	5	15	10	6	12	9	11	8	1	2	3
Los Palmitos	7	13	2	12	16	6	15	9	5	14	11	10	8	1	3	4
Majagual	8	12	10	13	16	7	15	11	6	14	2	3	9	1	5	4
Morroa	9	14	4	13	16	7	15	10	6	3	12	11	8	1	2	5
Ovejas	9	13	3	8	16	2	15	10	7	4	14	11	5	1	6	12
Palmito	11	14	2	9	16	3	15	8	7	4	6	12	10	1	5	13
Sampués	8	13	4	12	16	5	15	9	7	14	11	10	6	1	2	3
San Benito Abad	6	12	8	13	16	5	15	9	4	14	2	10	7	1	3	11
San José de Toluviéjo	8	13	3	12	16	4	15	6	5	14	11	9	7	1	2	10
San Juan de Betulia	7	13	3	12	16	5	15	9	6	14	11	10	8	1	2	4
San Luis de Sincé	5	13	2	12	16	4	15	7	3	14	11	8	6	1	9	10
San Marcos	8	12	9	13	16	5	15	7	6	14	2	11	10	1	3	4
San Onofre	8	14	5	13	16	3	15	4	6	7	12	10	9	1	2	11
San Pedro	6	13	2	10	16	4	15	8	5	14	12	9	7	1	3	11
Santiago de Tolú	6	13	5	12	16	3	15	10	2	14	11	8	7	1	4	9
Sincelejo	7	13	4	12	16	5	15	9	6	14	11	10	8	1	2	3
Sucre	6	12	8	13	16	4	15	9	3	14	5	10	7	1	2	11

A1: Avocado Prunings, A2: Cassava Leaves, A3: Cassava Stems, A4: Cassava Stump, A5: Coconut Prunings, A6: Maize Stover, A7: Mango Prunings, A8: Oil Palm Prunings, A9: Plantain Leaves, A10: Plantain Pseudostem, A11: Rice Straw, A12: Watermelon Stubble, A13: Yam Stubble, A14: Cattle Manure, A15: Pig Manure, A16: Poultry Manure.

3.5. Cluster Analysis of Municipal Bioenergy Potential for AcoD

Table 7 displays the theoretical energy potential and physicochemical characteristics of the prioritised co-digestion mixtures for the twenty-six municipalities. These values correspond to the binary combination of Cattle Manure (A14) with the highest-ranked agricultural residue for each location.

Regarding the GMP, Majagual recorded the highest value in the department, driven by its leading total biomass availability. San Luis de Sincé and San Marcos followed with substantial potentials. Conversely, smaller coastal or mountainous municipalities, such as Coveñas and Chalán, registered the lowest bioenergy capacities.

The composition of the mixtures varied geographically. In the Mojana and San Jorge sub-regions, where Rice Straw (A11) functioned as the agricultural co-substrate, the mixtures exhibited the highest weighted BMP. In the central Sabanas sub-region, prioritised with Cassava Stems (A3), the mixtures yielded moderate BMP values. The highest individual specific methane yield was observed in Chalán, which incorporated Maize Stover (A6).

The Mixing Ratio (Agriculture:Livestock) demonstrated significant heterogeneity across the territory. Municipalities such as Guaranda and Majagual presented the most balanced agricultural-to-livestock proportions. In contrast, locations like Sucre and Santiago de Tolú exhibited ratios heavily dominated by livestock manure, although the Weighted VS content remained relatively stable across the department.

4. Discussion

4.1. Interpretation of Co-Digestion Synergy and Ranking Drivers

The fundamental divergence between theoretical biochemical potential and operational feasibility identified in this study challenges the prevailing selection paradigms in tropical bioenergy. Whilst traditional frameworks often prioritise feedstocks based solely on superior methanogenic yields, the dominance of the annual production criterion in our MCDA underscores that supply chain reliability acts as the governing constraint for sustainable implementation. This “logistics-first” paradigm suggests that the primary risk to project viability in developing economies is not low conversion efficiency, but rather feedstock discontinuity. This aligns with observations in comparable contexts, where the reliance on high-yielding but seasonal residues has frequently led to operational failures due to prohibitive collection costs and periods of reactor idleness [19,20]. Consequently, the universal ranking of cattle manure as the basal substrate serves as a strategic risk mitigation mechanism. By anchoring the co-digestion process to a continuously generated stream, the system is buffered against the seasonality inherent to agricultural residues, ensuring the operational stability required for baseload energy generation.

However, the prioritisation of cattle manure as the universal baseload introduces a critical techno-economic trade-off between logistic reliability and volumetric efficiency. Although manure guarantees a steady supply, its comparatively low specific methane yield implies a lower energy density per unit of reactor volume compared to strictly agro-industrial substrates [13]. This necessitates larger hydraulic retention times and, consequently, higher capital expenditure (CAPEX) for reactor sizing to achieve equivalent energy outputs compared to high-rate reactors treating energy crops.

Nevertheless, the results indicate that this hydraulic penalty is outweighed by the operational security provided. In the absence of established storage infrastructure for seasonal crops—a common limitation in the region [6]—the continuous availability of manure is the only factor that prevents system shutdown during off-harvest periods. Thus, the decision-making framework validates that in tropical supply chains, the cost of larger infrastructure is a necessary premium to insure against the risk of supply interruption.

From a biochemical perspective, the prioritised mixtures demonstrate a functional synergy that validates the necessity of the co-digestion approach beyond simple mass aggregation. The integration of carbon-rich agricultural co-substrates with the nitrogen-rich manure effectively rebalances the C/N ratio towards the optimal biological range, addressing the limitations of mono-digestion [16]. Kinetically, the high buffering capacity of cattle manure [12] is crucial for counteracting the rapid hydrolysis rates of the soluble sugars present in cassava residues or the potential acidification from fruit waste [15]. This interaction minimises the risk of volatile fatty acid (VFA) accumulation—a common failure mode in the digestion of rapidly hydrolysable carbohydrates—and significantly reduces the operational expenditure (OPEX) associated with chemical pH control. Therefore, the framework identifies mixtures where the metabolic complementarity reduces the technical complexity of the process, making it more robust for regional operators.

Furthermore, the model highlights the critical role of market competition in defining the real availability of biomass, effectively addressing the “Feed vs. Fuel” dilemma. Although substrates such as poultry manure and oil palm prunings possess rapid degradation kinetics and high energy densities, their penalisation in the ranking reflects the high opportunity cost associated with their diversion from existing value chains [21]. Diverting such commodities, which are deeply integrated into local agricultural cycles as commercial organic fertilisers, could inadvertently inflate prices for local farmers or displace established nutrient recycling practices.

In contrast, the high feasibility scores assigned to cassava stems and crop stubbles validate a truly circular approach, as these residues are currently treated as disposal liabilities with negligible economic value. This distinction ensures that the proposed bioenergy systems valorise underutilised

waste streams without cannibalising existing local economies, aligning with the principles of sustainable waste management [2].

4.2. Spatial Heterogeneity and Bioenergy Clusters

The spatial identification of the Rice-Livestock cluster in the Mojana and San Jorge sub-regions unveils a high-potential yet technically demanding bioenergy landscape. While the synergy between cattle manure and rice straw offers the highest theoretical energy recovery in the department, the operational viability is contingent upon overcoming the significant recalcitrance of the lignocellulosic matrix. Rice straw is characterised by high silica and lignin fractions, which not only act as physical barriers to microbial hydrolysis but can also cause abrasive wear on mechanical equipment and lead to inert sludge accumulation in reactors [14].

Consequently, the substantial methane potential projected for this cluster must be critically weighed against the parasitic energy demands of necessary pretreatment steps or the enhanced maintenance costs of industrial mixing systems. From an engineering perspective, this implies that the feasibility of biogas projects in this zone is inextricably linked to economies of scale, where the energy surplus is sufficient to offset these intensive processing requirements, prohibiting the simple low-tech deployment often assumed for rural areas.

In contrast, the Cassava-Livestock cluster in the central Sabanas sub-region presents a biochemical profile that favours a distinct, decentralised technological trajectory. The lower lignin content of cassava residues implies faster degradation kinetics; however, this accessibility introduces the risk of rapid acidification if the organic loading rate is not carefully controlled [15]. Here, the consistent baseload of cattle manure acts as a critical alkalinity buffer [12], stabilising the pH during the hydrolysis of cassava's fermentable sugars.

Table 7. Theoretical energy potential and physicochemical characteristics of the prioritized co-digestion mixtures per municipality.

Municipality	Best Agricultural Residue	Best Livestock Residue	Total Availability (kt/year)	Mixing Ratio (Agriculture:Livestock)	Mixture BMP (L CH ₄ /kg VS)	Mixture VS (%)	Global Methane Potential (Million m ³ /year)
Buenavista	A9: Plantain Leaves	A14: Cattle Manure	123.3	1:3339.7	136.4	79.1	13.3
Caimito	A6: Maize Stover	A14: Cattle Manure	136.3	1:29.2	144.5	79.5	15.7
Chalán	A6: Maize Stover	A14: Cattle Manure	14.2	1:5.1	176.6	81.1	2.0
Colosó	A10: Plantain Pseudostem	A14: Cattle Manure	25.1	1:12.3	158.8	79.6	3.2
Corozal	A3: Cassava Stems	A14: Cattle Manure	197.3	1:14.5	138.1	80.1	21.8
Coveñas	A3: Cassava Stems	A14: Cattle Manure	15.3	1:16	137.9	80.0	1.7
El Roble	A3: Cassava Stems	A14: Cattle Manure	76.5	1:17.2	137.8	79.9	8.4
Galeras	A3: Cassava Stems	A14: Cattle Manure	216.1	1:29.4	137.2	79.6	23.6
Guaranda	A11: Rice Straw	A14: Cattle Manure	190.3	1:2.9	161.4	79.2	24.3
La Unión	A3: Cassava Stems	A14: Cattle Manure	101.6	1:48.3	136.9	79.4	11.1
Los Palmitos	A3: Cassava Stems	A14: Cattle Manure	150.5	1:25	137.4	79.7	16.5

Majagual	A11: Rice Straw	A14: Cattle Manure	430.5	1:3.7	157.1	79.2	53.6
Morroa	A10: Plantain Pseudostem	A14: Cattle Manure	58.7	1:19.7	150.8	79.4	7.0
Ovejas	A6: Maize Stover	A14: Cattle Manure	123.1	1:10.8	157.2	80.1	15.5
Palmito	A3: Cassava Stems	A14: Cattle Manure	104.2	1:11	138.6	80.4	11.6
Sampués	A3: Cassava Stems	A14: Cattle Manure	125.1	1:19.3	137.7	79.9	13.8
San Benito Abad	A11: Rice Straw	A14: Cattle Manure	289.6	1:14.7	142.6	79.2	32.7
San José de Toluviejo	A3: Cassava Stems	A14: Cattle Manure	141.4	1:58.8	136.8	79.4	15.4
San Juan de Betulia	A3: Cassava Stems	A14: Cattle Manure	158.5	1:32.4	137.2	79.6	17.3
San Luis de Sincé	A3: Cassava Stems	A14: Cattle Manure	391.9	1:35.1	137.1	79.5	42.7
San Marcos	A11: Rice Straw	A14: Cattle Manure	354.8	1:22.4	140.6	79.1	39.5
San Onofre	A6: Maize Stover	A14: Cattle Manure	308.7	1:84.4	139.3	79.3	34.1
San Pedro	A3: Cassava Stems	A14: Cattle Manure	174.8	1:18.4	137.7	79.9	19.2
Santiago de Tolú	A9: Plantain Leaves	A14: Cattle Manure	159.6	1:1783.9	136.5	79.1	17.2
Sincelejo	A3: Cassava Stems	A14: Cattle Manure	148.2	1:22.6	137.5	79.8	16.3
Sucre	A9: Plantain Leaves	A14: Cattle Manure	324.1	1:5128.9	136.4	79.1	35.0

This self-regulating buffering capacity suggests that this cluster is particularly well-suited for robust, low-maintenance applications that align with the socio-economic structure of smallholder farmers. Furthermore, the metabolic compatibility of this mixture supports a circular fit, where the thermal energy generated can be directly synchronised with local agro-industrial needs—specifically cassava starch drying—thereby closing the production loop at the farm level rather than exporting energy to the grid.

Furthermore, the analysis of the coastal municipalities reveals a distinct manure dominated cluster, characterised by extreme mixing ratios where the agricultural contribution is negligible. This finding has profound implications for the strategic objectives of anaerobic digestion in these territories. With mixtures composed almost exclusively of livestock waste, the system effectively operates as a mono-digestion process, which typically exhibits lower specific methane yields compared to balanced co-digestion due to carbon limitations [13].

Therefore, the primary driver for implementation in this cluster shifts from maximised energy revenue to environmental sanitation. The operational focus in these zones should prioritise Hydraulic Retention Time (HRT) for pathogen reduction and the mitigation of nutrient pollution flowing into downstream wetlands [9], viewing biogas as a value-added byproduct rather than the sole financial anchor necessary for project bankability.

This observed spatial heterogeneity refutes the applicability of a uniform bioenergy policy for the Department of Sucre. The transition from the high-solids, recalcitrant mixtures of the south to the liquid, manure-heavy streams of the coast dictates that technology transfer must be strictly site-specific. Ignoring these territorial biochemical signatures—for instance, attempting to replicate the simple operational protocols suitable for the Sabanas sub-region in the recalcitrant-heavy Mojana sub-region—would likely result in process failure due to either substrate stratification or low

conversion efficiencies. Thus, the bioenergy cluster concept serves as a crucial planning tool, ensuring that infrastructure investment is matched to the specific rheological and metabolic realities of the local biomass supply rather than generic regional averages [22].

4.3. Implications for Regional Bioenergy Implementation Strategies

Translating the identified biochemical clusters into engineering solutions implies that reactor configuration must be strictly dictated by the rheological properties of the substrate mixtures rather than a standardising technology policy. The Mojana cluster, characterised by high volumes of silica-rich rice straw, suggests a rheological requirement for Continuous Stirred Tank Reactors (CSTR) capable of providing vigorous mechanical agitation to prevent stratification and crust formation.

However, whilst the scale of the projected methane yields supports the economic case for such centralised facilities, this introduces a critical risk of technological lock-in. The deployment of high-complexity imported infrastructure in rural tropical regions has historically risked becoming ‘white elephants’—facilities that fail not due to biochemical potential, but due to a lack of local technical capacity for maintenance and spare parts supply chains [20]. Thus, the feasibility in this zone is constrained by the availability of skilled labour rather than biomass availability alone.

In contrast, the biochemical profile of the Sabanas cluster points towards a distributed generation paradigm. The rapid biodegradability of cassava residues, combined with the dispersed nature of smallholder farming, aligns coherently with the operational simplicity of low-cost tubular (plug-flow) digesters. Unlike the industrial requirements of the Mojana, the technical simplicity of these reactors matches the socio-economic context of rural producers, where the primary objective is energy autonomy rather than commercial sale. The suitability of the technology is defined by its ability to provide direct thermal energy for on-site agro-industrial processes—such as cassava starch drying—thereby closing the loop at the farm level with minimal maintenance requirements, effectively decoupling the project from the volatility of centralised electricity markets.

However, the feasibility of the Montes de María cluster, which relies on maize stover, faces a critical temporal constraint absent in the continuous manure-based systems. The pulsed generation of maize residues implies that the theoretical co-digestion synergy is contingent upon the implementation of silage infrastructure to bridge the gap between harvest windows and year-round reactor feeding [19]. This requirement mirrors the maize-based biogas models prevalent in Europe, yet in the absence of the feed-in tariffs that sustain those systems, the additional capital expenditure for storage bunkers and the operational costs for inoculants may erode the comparative advantage of this cluster in a developing economy. Consequently, the realisation of bioenergy projects in this zone is likely less dependent on reactor efficiency and more on the establishment of a logistical storage network capable of mitigating the risk of feedstock intermittency.

These findings suggest that successful technology transfer strategies must transcend the pursuit of thermodynamic maximisation to prioritise socio-technical fit. The imposition of uniform technology incentives would likely result in systemic failure given the distinct rheological signatures of the identified clusters. A resilient implementation strategy must therefore accept a trade-off regarding accepting lower specific yields in the Sabanas through low-tech solutions to ensure longevity, whilst reserving high-efficiency industrial systems for the Mojana only where the ‘economies of scale’ are sufficient to buffer the higher operational risks [24]. This site-specific matching of technology to both biomass rheology and local technical capacity is the prerequisite for avoiding the widespread abandonment of biogas facilities observed in similar tropical contexts.

4.4. Limitations and Future Research

Although the proposed Entropy-TOPSIS framework provides a robust initial screening for substrate selection, several limitations inherent to the methodology must be acknowledged to contextualise the findings properly. Firstly, the reliance on annualised residue generation data assumes a continuous biomass flow, effectively smoothing out the temporal variability characteristic of agricultural systems. In reality, residues such as maize stover and rice straw are generated in

discrete seasonal pulses. By treating these resources as static annual aggregates, the model risks creating a 'phantom' availability during off-harvest periods.

For the Montes de María and Mojana clusters, this implies that the reported global methane potential represents a theoretical upper bound that may be physically impossible to mobilise without the implementation of massive storage capacities—potentially exceeding six months of inventory. Consequently, the operational feasibility is likely lower than the annualised figures suggest, as the system would require significant capital investment in silage infrastructure to bridge the temporal mismatch between generation peaks and continuous reactor feeding.

Secondly, the spatial analysis was conducted at the municipal resolution, treating each administrative unit as a homogeneous supply area. This approach prioritises total mass availability but fails to explicitly quantify the specific transport costs associated with collection logistics in a tropical context. In regions with underdeveloped road infrastructure, Euclidean distance is a poor proxy for economic accessibility due to high road tortuosity and seasonal impassability. Although the Annual Residue Production criterion serves as a proxy for spatial density, it does not distinguish between biomass concentrated in an industrial hub and biomass dispersed across fragmented smallholdings. Therefore, the framework likely overestimates the economically accessible biomass, as the collection radius required to feed a centralised plant in the Rice-Livestock cluster may be logistically prohibitive due to the distribution costs, despite the high theoretical density.

Furthermore, the physicochemical characterisation utilised in this study assumes constant composition values for each substrate type. However, biomass properties are subject to significant biological variability driven by crop varieties, soil quality, and climatic conditions. The use of mean experimental values for parameters like the C/N ratio or Lignin content provides a representative baseline but does not capture the stochastic fluctuations that characterise real-world supply chains.

This stochasticity poses a risk to reactor stability, particularly in the Cassava-Livestock cluster, where deviations in the buffering capacity of manure or the acidity of cassava residues could lead to process inhibition. Future iterations of this decision-making framework should, therefore, incorporate sensitivity analyses to evaluate how these natural deviations in feedstock quality might impact the robustness of the ranking and the projected methane yields.

To bridge the gap between this strategic prioritisation and bankable project implementation, future research lines must transcend static assessments. Specifically, the field requires the development of dynamic spatio-temporal optimisation models rather than simple Techno-Economic Analyses (TEA). Such models should couple the multi-criteria approach with dynamic GIS to simulate the temporal flow of biomass against the logistic constraints of the territory. This would allow for the identification of optimal plant siting based on minimised collection costs and temporal reliability, rather than just mass availability. Only by integrating the seasonality of supply with the tortuosity of transport can future studies validate whether the thermodynamically optimal mixtures identified here remain economically viable when subjected to the harsh logistical realities of the tropical bioeconomy.

5. Conclusions

This study overturns the traditional substrate selection paradigm for the tropical regions, establishing that in developing agro-industrial contexts, logistic reliability invariably overrides biochemical efficiency. By applying the Integrated Entropy-TOPSIS framework, we demonstrate that the primary barrier to bioenergy viability in the Department of Sucre is not the biochemical conversion yield, but the risk of feedstock discontinuity. Consequently, the results mandate a shift in the decision-making process regarding the maximisation of methane potential, which must be subordinated to the security of the supply chain to prevent the operational failures historically associated with seasonal feedstocks.

The universal identification of cattle manure as the basal substrate serves as a quantification of the necessary trade-off between energy density and operational stability. While manure exhibits lower specific methane yields compared to energy crops—implying a requirement for larger reactor

volumes and higher initial capital expenditure (CAPEX)—this volumetric penalty acts as a vital insurance premium. It guarantees a baseload continuity that buffers the system against the ‘phantom’ availability of seasonal residues, transforming theoretically optimal but intermittent mixtures into bankable, operationally stable energy assets.

Furthermore, the spatial delineation of distinct bioenergy clusters confirms that ‘one-size-fits-all’ technology transfer policies are destined to fail. The high-potential Rice-Livestock cluster in the Mojana region is technically contingent upon industrial-scale pretreatment and agitation systems; however, its feasibility is strictly limited by the availability of skilled labour to maintain such complex infrastructure, posing a risk of technological lock-in or ‘white elephant’ projects if local capacity is ignored. Conversely, the Cassava-Livestock cluster in the Sabanas supports a robust, decentralised model where low-tech reactors align with the socio-economic reality of smallholders, prioritising resilience over industrial efficiency.

Ultimately, this research provides a data-driven roadmap for de-risking bioenergy investments in tropical regions. It concludes that the realisation of the theoretical potential in crop-based clusters is physically impossible without a parallel investment in silage and storage infrastructure to bridge harvest gaps. Therefore, policymakers must transition from generic bioenergy incentives to targeted supply chain interventions that subsidise not just the reactors, but the logistical network required to mobilise the biomass. Only by addressing these logistical and temporal constraints can the untapped bioenergy potential of the Latin American Caribbean be effectively harnessed to meet the Sustainable Development Goals.

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