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Optimization of Biogas Production from Agricultural Residues Through Anaerobic Co-Digestion and GIS Tools in Colombia

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Abstract

The ongoing global population growth and the corresponding rise in energy demand have contributed to increased greenhouse gas (GHG) emissions. The integration of alternative, locally sourced energy solutions such as biogas presents a promising strategy to partially offset conventional energy consumption. In this context, countries like Colombia—characterized by a high availability of organic waste such as palm oil mill effluent (POME), rice straw, and pig manure—have the potential to harness these residues for biogas production. This study integrates experimental assays of anaerobic co-digestion tests with the spatial analysis of substrate distribution through GIS tools, enabling the identification of optimal regions for biogas production. Methane yields reached 412 mL CH_4/g VS, comparable or superior to those reported in similar studies. In addition to laboratory assays, Geographic Information System (GIS) tools were used to generate a weighted heatmap index based on feedstock availability (POME, rice straw, pig manure) across 40 municipalities in Colombia. This integrated approach supports decentralized renewable energy planning and helps identify optimal locations for biogas plant development.

Keywords: co-digestion; Geographic Information Systems; biogas; pig manure; palm oil mill effluent; rice straw; waste to energy

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1. Introduction

The increase in greenhouse gas (GHG) emissions and the progressive depletion of fossil fuel reserves are driving the search for alternative and sustainable energy sources. In this context, biogas has gained significant attention as a viable and environmentally friendly alternative to conventional fossil fuels. This biofuel, obtained from a wide variety of organic residues through the process of anaerobic digestion [1], serves a dual function: it provides a decentralized energy source and contributes to the mitigation of methane emissions from unmanaged organic waste. Its production and use are closely aligned with circular economy principles by transforming waste streams into valuable energy,

while simultaneously supporting environmental preservation and local economic development [2,3]. Within this framework, a significant portion of current research is focused on the development of innovative technologies to harness biogas and other renewable energy alternatives [4,5]. Biogas, as a renewable energy option, aligns with the principles of circular economy by utilizing organic waste as a valuable resource; furthermore, it promotes economic development while contributing to environmental protection. Anaerobic digestion (AD) is a complex process that involves a combination of biological, biochemical, and physicochemical phenomena [6] not only to yield biogas as valuable product, but also to reduce the organic content and environmental impact of the treated substrates, minimizing the risks associated with their disposal or release into natural ecosystems—as is the case with palm oil processing residues [7].

Biogas possesses a high energy content and is primarily composed of methane, with lower concentrations of carbon dioxide and other gases [8]. It can be used to produce heat and electricity in combined heat and power (CHP) systems, or be upgraded and injected into natural gas networks or used as vehicle fuel [9,10]. Technological improvements in upgrading processes have increased the viability of biogas as a substitute for natural gas in various applications [10].

Extensive research has been conducted on the generation of biogas through the mono-digestion of substrates using anaerobic digestion [11,12]. However, the co-digestion of multiple organic residues has shown significant potential for enhancing biogas production, improving biodegradability, and increasing process efficiency. Co-digestion helps to mitigate limitations inherent to mono-digestion, such as nutrient imbalances, process inhibition due to toxic compounds, or unsuitable moisture content [13]. Numerous studies have examined the co-digestion of different types of organic residues from various sources, including municipal waste, agro-industrial waste, and livestock manure [14,15].

The viability and scalability of centralized biogas and biomethane production plants strongly depend on the availability, distribution, and seasonality of co-substrates in the surrounding region. In this regard, the Colombian agro-industrial sector, particularly the oil palm industry, generates a large volume of biomass with a high organic load. Globally, over 74.8 million tons of palm oil were produced in 2019, representing more than 40% of the total global vegetable oil production [16]. In Colombia, palm oil production plays a strategic economic role, and its processing yields several value-added products, including food, consumer goods, and biofuels. However, this activity also generates significant amounts of polluting solid and liquid residues, such as palm oil mill effluent (POME) [17,18].

Due to its elevated organic content and high biodegradability, POME requires proper treatment but also represents a substrate with significant potential for biogas generation through anaerobic digestion [19]. Although various pretreatment techniques have been shown to improve the degradation of organic matter and methane yields [20], they often involve high energy inputs and increased operational costs. Therefore, as suggested in recent studies, co-digestion with other substrates is recommended to improve overall organic matter conversion and stabilize the process [21–23]. Most co-digestion studies involving POME have used co-substrates such as empty fruit bunches, decanter cake, or microalgae [21,24,25].

In this study, we investigate the potential for biogas production through the anaerobic co-digestion of POME, rice straw, and pig manure—three organic residues that are abundant and readily available in the region of Norte de Santander, located in northern Colombia. Rice straw, due to its high carbon content and fibrous structure, can balance the nutrient profile of the mixture, while pig manure contributes buffering capacity and acts as a microbial inoculum, enhancing process efficiency [26,27].

To achieve this objective, Geographic Information Systems (GIS) tools are employed to evaluate substrate availability within the study area. These tools enable the spatial visualization and analysis of biomass distribution, as well as the integration of multiple data sources. In addition, they offer modelling and predictive capabilities, which facilitate estimations and projections that will be the basis for the case study of this work to identify the optimal site for establishing a biogas plant based on the proximity and abundance of available substrates (Figure 1). Beyond mapping, GIS applications play a crucial role in regional energy planning by allowing stakeholders to assess infrastructural feasibility, transport logistics, and environmental constraints. Recent studies have increasingly combined Geographic Information Systems (GIS) with anaerobic digestion technologies to support this mentioned biomass resource mapping, logistic modelling, and biogas infrastructure planning. Table 1 presents a summary of selected research from the last decade, highlighting key methodological approaches, feedstock types, and reported environmental benefits.

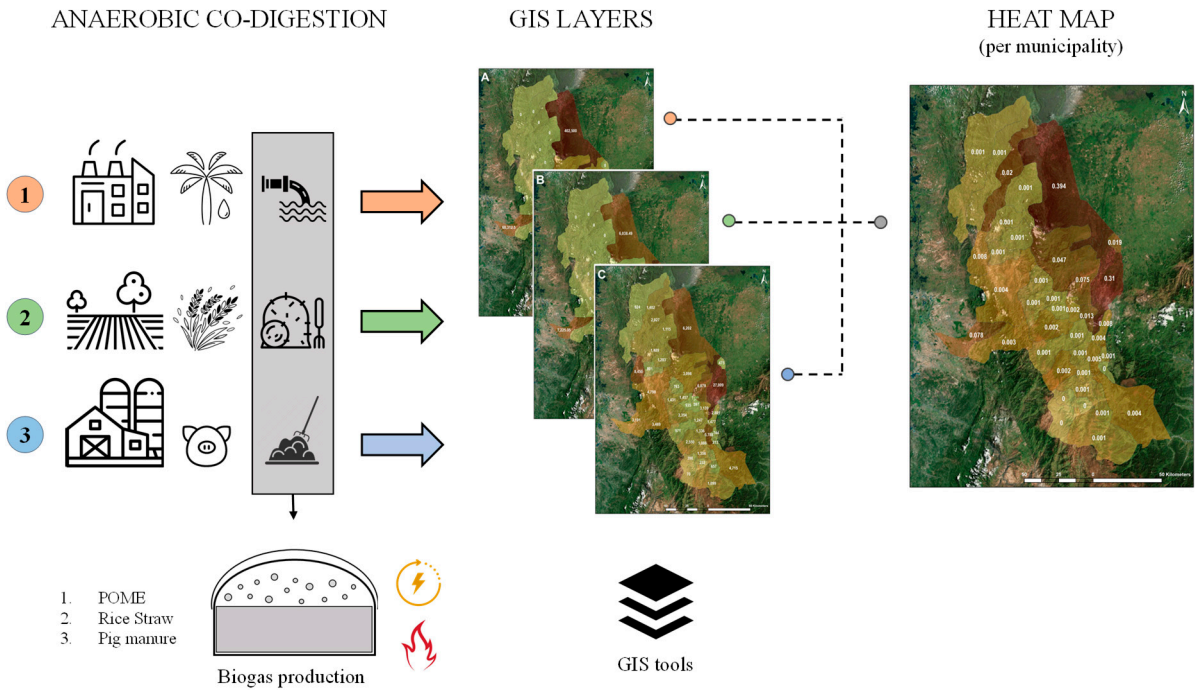


Figure 1. Flow diagram proposed in this study: substrate selection → physicochemical characterization → BMP tests (mono- and co-digestion) → spatial data collection → variable normalization → GIS modelling → identification of high-potential zones for biogas plants.

Several GIS tools are widely used in bioenergy applications, including generally ArcGIS as an Industry-standard software for spatial data processing, mapping, and overlay analysis, QGIS as an open-source tool for spatial data handling, with plugins for environmental modelling or Google Earth Engine as a Cloud-based platform for remote sensing and large-scale geospatial processing. In this study, ArcGIS V10 was used to create thematic layers, integrate biomass data, and generate a weighted index of biogas production potential. This approach supports decision-making in regional planning by identifying the most promising locations based on spatially distributed substrates.

Despite the significant potential of biogas as a renewable energy source, several limitations hinder its large-scale implementation in Colombia. These include the dispersed nature of feedstocks, a lack of centralized infrastructure, and the absence of robust policy frameworks promoting waste-to-energy conversion. Moreover, most existing studies lack spatial analysis tools to support optimal site selection. This work addresses these limita-

tions by combining experimental co-digestion trials with a GIS-based approach to guide decentralized biogas plant development in areas with the highest substrate availability.

Table 1. Summary of recent studies integrating Geographic Information Systems (GIS) with anaerobic digestion technologies.

Study	Country	Feedstocks	GIS Approach	Impact	Reference
Yalcinkaya (2020)	Turkey	OFMSW and livestock manure	GIS Multi-criteria analysis; ArcGIS V10	Siting, sizing, and economic assessment of centralized biogas plants	[28]
Chukwuma et al. (2021)	Nigeria	Municipal biowaste	GIS Multi-criteria analysis; ArcGIS V10	Biogas plant suitability map	[29]
Ankathi et al. (2020)	USA (Wisconsin)	Food waste + manure	GIS + mixed-integer linear programing + network modelling; ArcGIS V10	Optimized plant locations and sizes	[30]
Aktar et al. (2024)	Bangladesh	Dairy farm manure	GIS + restriction and suitability + cluster analysis; ArcGIS V10	Optimized biogas plant locations	[31]
Bedoić et al. (2021)	Croatia	Multiple biogas feedstocks	Holistic GIS + LCA for environmental impact; QGIS V3	Demonstrated GIS-enabled models can reduce environmental burden	[32]
This study	Colombia	POME + Rice Straw + Pig Manure	GIS + weighted heatmap + overlay	Optimized biogas plant locations	

2. Materials and Methods

The methodology employed integrates physicochemical characterization and batch anaerobic digestion tests, followed by a spatial feasibility analysis using GIS tools.

2.1. Substrates and Anaerobic Inoculum

The primary substrate used was palm oil mill effluent (POME) from "Norte de Santander", a department in the north of Colombia (Figure 1), specifically from an extraction and transformation plant located in the municipality of Zulia (8°11′53.0″ N; 72°32′37.4″ W coordinates). The sample was obtained directly from the plant's sludge disposal site. Rice straw (RS) was obtained from a rice plantation in another location (7°57′17.0″ N; 72°35′48.2″ W coordinates) and underwent mechanical pretreatment involving grinding using an electric mill and sieving at 1 mm. Pig manure (PM) was collected from a pig farm near the city of Cúcuta (7°54′19.4″ N; 72°33′46.8″ W coordinates). The anaerobic inoculum was collected from the anaerobic digester tank at the wastewater treatment plant (WWTP) in Soria, Spain (41°45′12.0″ N; 2°27′40.5″ W). All samples were stored at 4 °C to prevent degradation. The main physical and chemical characteristics of each substrate are shown in Table 2.

Table 2. Characteristics of substrates and inoculum.

Analytic Parameter	POME	Pig Manure	Rice Straw	Inoculum
Total solids (g/kg)	76.1	24.1	911.9	14.8
Volatile solids (g/kg)	63.5	15.8	791.6	10.1
COD (g/L)	132.7	95.3	1319.4 *	19.1
Total carbon (%)	18.98	0.93	38.3	-
Total nitrogen (%)	1.19	0.11	0.46	-
C:N relation	15.9	8.0	82.5	-

* The COD value for rice straw is expressed in mg COD/g vs. due to solid-phase measurement; all other values are expressed in g/L.

2.2. Experimental Setup

Batch-type reactors were prepared to evaluate the maximum potential methane yield (BMP) and set up during a period of 30 days from the mono-digestion of each substrate

and from the various co-digestion mixtures, following the standardized methodology described by Holliger et al. (2016) [33]. For this purpose, 120 mL serum bottles were filled to 70% volume with each combination of POME, rice straw, and pig slurry according to the configuration in Table 3. All tests were conducted in triplicate to ensure statistical reliability.

Table 3. Amount of substrate and inoculum per treatment and C:N ratio.

Experiment	Inoculum (mL)	POME (mL)	Pig Manure (mL)	Rice Straw (mg)	C:N Ratio
Blank	70	0	0	0	-
POME	65	5.6	0	0	15.9
PM	50	0	20.8	0	8
RS	70	0	0	0.32	82.5
POME + PM	60	4.1	6	0	11.2
POME + RS	67	3	0	0.15	19.2
PM + RS	60	0	10	0.23	9.7
POME + PM + RS	66	2	2	0.2	15.4

The operating conditions of the experiment were mesophilic, with a temperature of 35 ± 0.5 °C, measured using an incubator (Medilow-S, Selecta, Barcelona, Spain) with orbital agitation (SHKP 35L, LBx Instruments, Barcelona, Spain). This temperature was chosen as it provides greater stability in the process, despite potentially lower biogas yields compared to thermophilic conditions, as reported by Choong and Lindner [23,34].

The substrate-to-inoculum ratio was set at 0.5 on a volatile solids (VS) basis, following the methodology outlined by García-Álvaro et al. (2023), adding 0.3 g of $CaCO_3$ in each reactor as a buffer to stabilize the pH during the experiment [35]. Each bottle was closed with a plastic septum and an aluminum ring after being flushed with nitrogen to ensure anaerobic conditions within each reactor. Biogas production was measured daily using the water displacement method, and a blank reactor containing only inoculum was used as a control to account for endogenous methane generation. The biogas composition was also measured using a gas analyzer (Biogas 5000, GeoTech, Leamington Spa, UK), which enabled the quantification of methane and carbon dioxide concentrations.

2.3. Analytical Methods

The analytical characterization of each of the substrates was carried out using the standard methods defined in [36] for total solids, volatile solids, and COD analysis. The elemental content of C and N was measured using an elemental analyzer (EA Flash 2000, Thermo Fisher Scientific, Waltham, MA, USA) after the sample combustion and then the percentage of each element's total weight was measured. The C:N ratio was calculated, based on these data, as a critical parameter in assessing the biodegradability and balance of the substrates for anaerobic digestion.

2.4. Modelling

Experimental data from the BMP tests were fitted using the modified Gompertz model, which is widely used to describe microbial growth kinetics during the anaerobic digestion process. The model provides a reliable description of biogas production over time, accounting for the lag, exponential, and stationary phases of microbial activity. The key parameters estimated include the maximum biogas production rate, the duration of the lag phase, and the total biogas yield. This modelling approach facilitates the evaluation and optimization of anaerobic digestion systems [37,38]. Equation (1) is

$$M(t) = P \cdot exp^{\{-e^{[\frac{R_e}{P} \cdot (\lambda - t) + 1]}\}} \quad (1)$$

where *M(t)* is the cumulative methane production at standard temperature and pressure (mL CH_4/g VS), *P* is the potential methane production (mL CH_4/g VS), *R* is the maximum methane production rate (mL CH_4/g VS·day), λ is the lag phase (days), and *t* is the elapsed time (days).

2.5. Geographic Information System (GIS) Study

The GIS analysis focused on the department of Norte de Santander, Colombia, comprising 40 municipalities (Figure 1). Three key variables were selected and counted for spatial analysis: palm oil cultivation area, rice cultivation area, and swine livestock population, representing the main sources of POME, rice straw, and pig manure, respectively (See Supplementary Materials).

Spatial data processing was conducted using ArcGIS software (ArcGIS Desktop 10.8.1; Environmental Systems Research Institute [Esri], Redlands, USA). Publicly available geospatial datasets were employed, including municipal boundaries and orthophotographs from the national data repository (datos.gov.co). Quantitative data on livestock, POME generation, and rice production were incorporated into new thematic layers for each municipality. This required merging external data tables with spatial layers using unique geographic identifiers, followed by data interpolation in regions with missing information.

Variables were then classified into intervals using a graduated colour scale from light yellow to dark maroon, to visualize variations in substrate availability across municipalities. This facilitated the interpretation of regional disparities and substrate concentration hotspots.

Following the initial mapping, a weighting process was applied to integrate the three variables into a single index of biogas production potential. The weights assigned to each variable were based on their relative influence on methane yield, as determined in the BMP experiments (Section 3.1). The resulting equation (Equation (2)) was as follows:

$$\text{Biogaspotential} = (\text{Rice} \times 0.15) + (\text{POME} \times 0.5) + (\text{Piglivestock} \times 0.35) \quad (2)$$

The weighted values were normalized on a scale from 0 to 1, and a final heatmap was generated to represent the spatial distribution of biogas potential throughout the department. This allowed for the identification of the most favourable areas for establishing biogas plants, based on substrate availability and logistical considerations.

The GIS analysis was carried out using official open-access databases from Colombian institutions (e.g., datos.gov.co, ICA, FedeArroz, FedePalma). For municipalities with missing data, spatial interpolation and proportional estimation based on similar regions were used. All variables were normalized to a 0–1 scale to ensure comparability. In contexts lacking such official datasets, complementary fieldwork and advanced GIS methods—such as remote sensing or land use classification—would be necessary to perform a comparable analysis.

Study Case: Norte De Santander

The "Norte de Santander" department is known for its high palm oil industrial sector, with several oil palm plantations with a planted area of 41,027 hectares, representing 6.44% of the total planted area in Colombia and with a production of 15,374 tons annually, which corresponds to 6.95% of Colombia's total palm oil output [39].

Additionally, Norte de Santander is among the leading rice-producing regions in the country. According to the National Rice Fund, Colombia produces over 1.7 million tonnes annually, with this department contributing more than 200,000 tons—about 10.64% of national rice production [40].

Regarding swine livestock, the department hosts approximately 110,000 animals, representing 1.14% of the national swine population [41].

3. Results and Discussion

3.1. BMP Tests

Following the Biochemical Methane Potential methodology, biomethane production data were obtained from the three individual substrates, as well as their corresponding mixtures. Figure 2 shows the daily and cumulative biogas production over a 25-day anaerobic degradation period. Significant fluctuations in biogas production were observed depending on the type of substrate and the nature of the mixture.

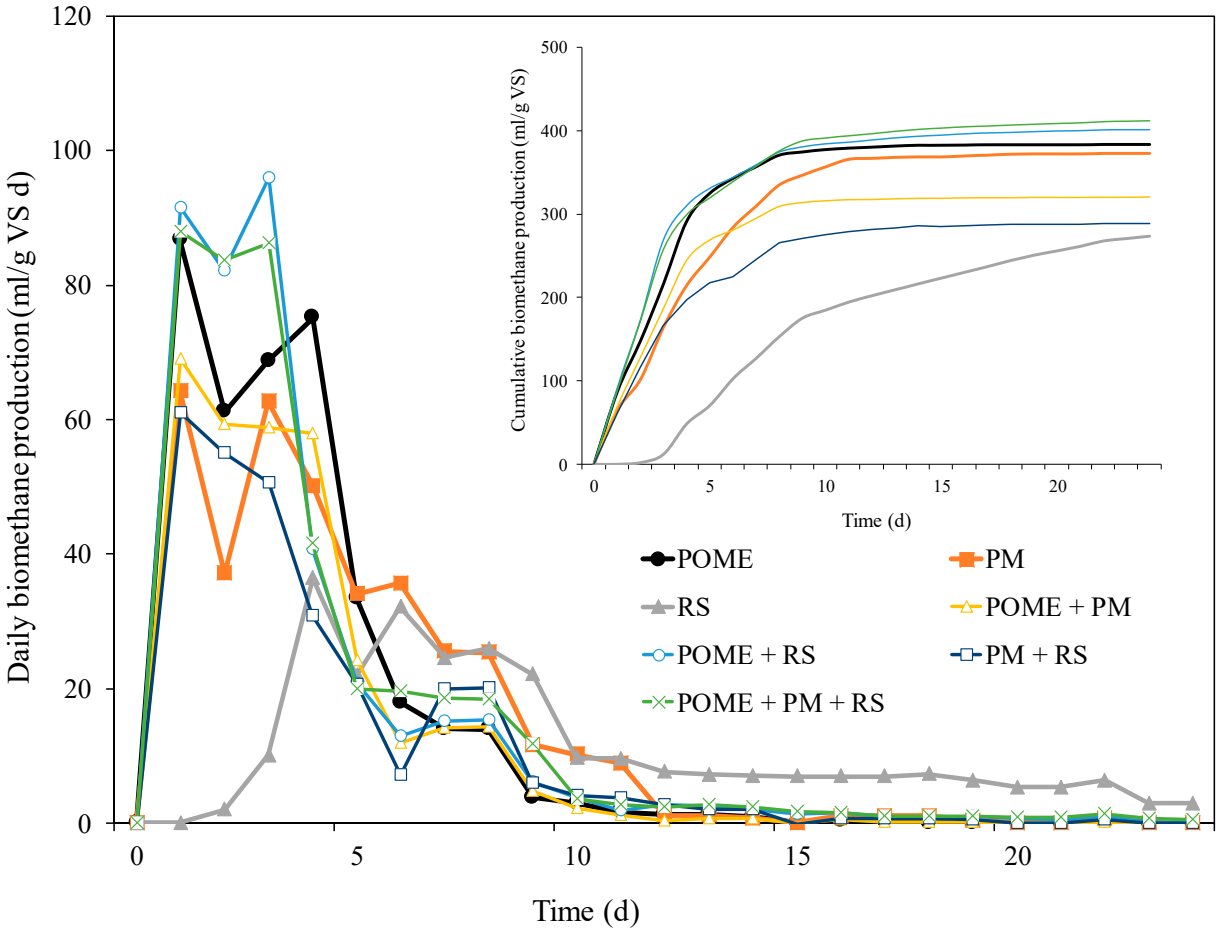


Figure 2. Daily and cumulative methane production in mono- and co-digestion tests. Substrates: POME (palm oil mill effluent), PM (pig manure) and RS (rice straw). Conditions: batch reactors, mesophilic temperature (35 ± 1 °C).

In mono-digestion experiments, the methane production of POME (palm oil mill effluent) exhibited a rapid increase in the first 4 days, reaching 291.7 mL/VS, followed by a deceleration and final production of 383.7 mL/VS. Pig manure showed a similar trend, with production increasing quickly during the first 4–5 days to 248.2 mL/g vs. and subsequently stabilizing at 372.5 mL/g vs. In contrast, rice straw displayed a more gradual methane production profile, reaching 273.6 mL/g vs. by the end of the experiment. These results are attributable to the chemical composition of POME and pig manure, whose organic content is much more quickly biodegradable than rice straw, which is composed mainly of cellulose, hemicellulose, and lignin, which are more slowly biodegradable despite the initial mechanical pretreatment that accelerates anaerobic digestion [42,43].

In co-digestion experiments, the combination of POME and pig manure reached 269.3 mL/VS in the first 4-5 days and decelerated to 320.6 mL/VS. The POME and rice straw mixture exhibited high initial methane production, reaching 310.5 mL/g vs. in the first 4–5 days and continuing to increase to 401.6 mL/g vs. The pig manure and rice straw mixture showed a slower progression, reaching 288.6 mL/g vs. at the end of the test. The co-digestion of all three substrates yielded the highest initial production rate (319.4 mL/g vs. in the first 5 days), with a final value of 412.0 mL/g vs. Regarding methane concentration, minimal variation was observed among the different co-digestion scenarios, with methane contents ranging between 64.8% and 67.5%, as shown in Figure S2 (Supplementary Materials). This maximum value of 412 mL CH_4/g VS obtained in the co-digestion is comparable or superior to previous studies using similar feedstocks, such as the co-digestion of POME with decanter cake (around 500 mL CH_4/g VS), cow manure (around 600 mL CH_4/g VS), or microalgae (around 450 mL CH_4/g VS) [21,23,25].

The maximum biomethane production was observed in co-digestion scenarios involving three substrates and the co-digestion of POME with rice straw. These optimal scenarios consistently corresponded to mixtures exhibiting a C:N ratio ranging from 15 to 20. This C:N ratio is a crucial factor influencing the efficiency of the anaerobic digestion process. According to a study by Mata-Alvarez et al. (2000), a C:N ratio in the range of 15–30 is considered optimal for stable and efficient anaerobic digestion [44]. On the other hand, Cabbai et al. (2013) indicate that an unbalanced C:N ratio can inhibit microbial activity and reduce biogas production. This key consideration emphasizes the importance of properly adjusting the C:N ratio through the co-digestion of substrates, in order to ensure efficient anaerobic digestion and maximize biogas production [45].

The results presented demonstrate the technical viability of biogas production through the co-digestion of agricultural residues, with methane yields above 400 mL CH_4/g VS. However, beyond technical feasibility, the implementation of biogas projects requires a favourable socio-political and regulatory framework. In Colombia, although certain efforts have been made to promote renewable energy, there are currently limited specific incentives targeting the valorization of agricultural or industrial residues for biogas generation [46].

This contrasts with more established frameworks, such as the European Union's Directive 2008/98/EC on waste, which fosters the reuse of organic and industrial waste streams for energy purposes. For instance, Yıldız et al. (2024) analyzed how EU-compliant mining waste regulation in Turkey encouraged valorization pathways that could be replicated in Latin American contexts [47]. Similarly, Jandieri (2022) proposed a generalized model for recycling metal-bearing industrial waste, promoting circularity in the manganese sector in Georgia [48].

3.2. Modelling Results

Based on the parameters of the Gompertz model adjusted to the experimental data, an analysis of the behaviour of the different substrates' degradation and their combinations during anaerobic digestion can be performed, as can be seen in Table 4 and Figure S2.

Among mono-digestion trials, POME exhibited the highest methane production rate, reaching 78.0 mL CH_4/g VS·d, whereas rice straw showed the lowest rate at 22.3 mL CH_4/g VS·d. This aligns with previous studies, such as Triolo et al. (2011), who found that lignocellulosic substrates like rice straw have lower digestibility and, therefore, slower biogas production rates [49].

On the other hand, the values of the lag phase (λ) reveal information about the adaptation of the microorganisms to the different substrates and the biodegradability difficulties of each substrate. The rice straw presents a longer lag phase of 1.81 days due to its lignocellulosic composition, which requires a hydrolysis step that slows down the

start of biogas production [50]. In contrast, POME and pig manure have practically no lag phases. This suggests that microorganisms need more time to adapt to lignocellulose-rich substrates, as reported by Herrmann et al. (2016) in their study on the co-digestion of agricultural residues, and therefore, a good adaptation of the inoculum is essential when digesting lignocellulosic substrates [51,52].

Table 4. Kinetic parameters of methane production for the Gompertz modelling from the AD of POME (palm oil mill effluent), PM (pig manure) and RS (rice straw) and their mixtures. Gompertz modelling.

Experiment	M (mL CH_4/g VS)	R (mL CH_4/g VS·Day)	λ (Days)	R^2 (%)
POME	384	78.0	0.14	99.6
PM	373	55.5	0.16	99.8
RS	274	22.3	1.81	98.8
POME + PM	321	66.5	0.11	99.7
POME + RS	402	83.8	0.00	98.9
PM + RS	228	42.9	0.00	98.2
POME + PM + RS	412	77.2	0.00	98.7

Analyzing the Gompertz model parameters for the co-digestion essays, the maximum biogas production rates were registered for the co-digestion of POME with rice straw (83.8 mL CH_4/g VS·d), and the co-digestion of the three substrates (77.2 mL CH_4/g VS·d) present the highest values, and are even comparable to the rate of POME alone (78.0 mL CH_4/g VS·d). This suggests that the co-digestion of substrates with different characteristics, such as POME (rich in readily biodegradable organic matter) and rice straw (lignocellulosic and more slowly biodegradable), can generate synergies improving the kinetics of biogas production.

These results, in conjunction with the cumulative biomethane production data at the end of the BMP, indicate that the co-digestion of substrates with complementary characteristics, such as POME and rice straw, can improve the overall performance of the process by combining substrates with different composition characteristics and opposed biodegradation rates, which is reflected in a higher biogas production and a shorter lag phase [53].

Furthermore, these findings are consistent with previous works, highlighting that a strategic selection of co-substrates enhances not only biomethane potential but also the kinetics of anaerobic digestion. The synergy observed between substrates with high biodegradability (e.g., POME) and lignocellulosic materials (e.g., rice straw) underscores the importance of optimizing feedstock formulation—particularly balancing the C:N ratio—to ensure microbial activity and process stability.

In the same manner, the results highlight the possibility of integrating agricultural residues with industrial waste streams for enhanced biogas production in regions with high resource density. Similar strategies have been discussed in the literature, where policy-driven mechanisms have successfully enabled industrial waste recycling. By leveraging these insights, Colombia could advance towards a more integrated bioenergy policy that encourages synergy between different sectors and promotes territorial energy autonomy.

3.3. Study Case

GIS tools enable geographic studies of substrate availability across various areas, serving as a valuable tool for the projection and planning of centralized biogas plants for co-digestion. Figure 3 shows the municipalities of the "Norte de Santander" department as the study region, displaying the data for palm oil plant-planted areas (Figure 3A), rice field

areas (Figure 3B), and the number of pig livestock (Figure 3C). The north of the department shows the highest rice surfaces being the municipality of Cúcuta as the largest planted area with 21,500 hectares, and also has the highest number of pig farms with 27,000 livestock, while Tibú in the East has the largest area of oil palm cultivation with 32,000 hectares (see Table S1).

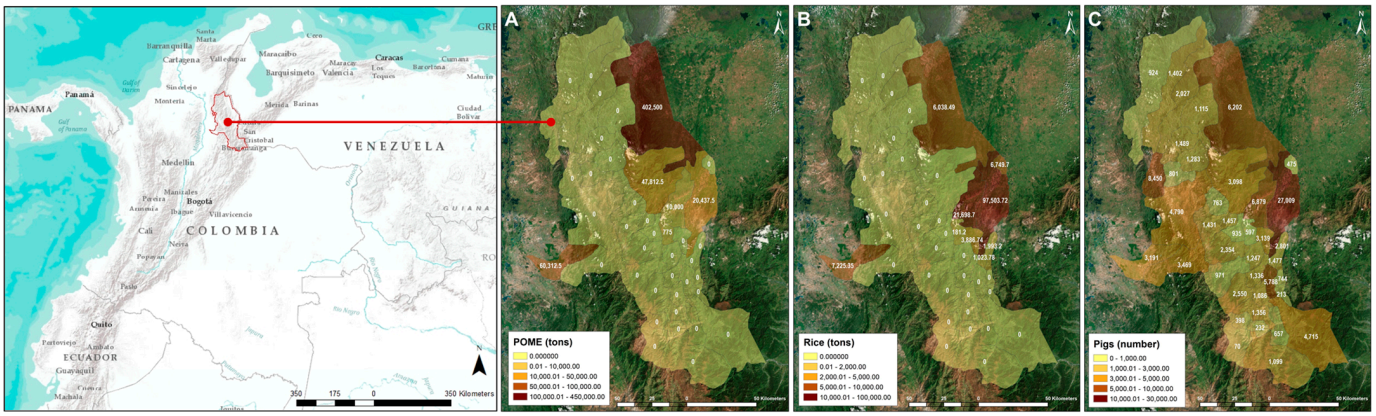


Figure 3. Spatial distribution of substrates in Norte de Santander: (**A**) area cultivated with oil palm (ha)—source of POME; (**B**) area cultivated with rice (ha)—source of RS; (**C**) number of pigs per municipality—source of PM. Data obtained from official agricultural and livestock databases [39–41].

Based on the data on the availability of substrates in the department of "Norte de Santander" and their performance in biogas production, a heat map was developed. Figure 4 shows that the municipalities located in the northern and eastern zones of the department are the ones with the highest potential production values and, therefore, greater interest when it comes to setting up a biogas plant. Specifically, the municipalities of Tibu in the geographic north, with a value of 0.394, and Cúcuta in the east, at 0.310, stand out as the territories with the greatest potential, given the coexistence of the three substrates in a limited geographical area. Likewise, the central-western area of the department, which includes municipalities such as El Zulia (0.075), La Esperanza (0.078), and Ocaña (0.047), also presents relatively high values in the availability of substrates, although to a lesser extent than Tibu and Cúcuta. In contrast, the municipalities located in the southeastern and southwestern areas of the department, such as Chinacota (0.008) and Toledo (0.004), show lower substrate availability, making them less attractive for the development of this type of project.

In addition to the availability of substrates, it is important to consider other logistical and infrastructure factors that can influence the feasibility of installing a biogas plant in the department. Aspects such as proximity to transportation routes, population centres, and power grids can facilitate the supply of raw materials and the distribution of the produced biogas or biomethane. Likewise, the geographical and climatic particularities of the department, as well as the presence of other relevant industries or economic activities, can influence the location and design of the biogas plant.

In this regard, the northern part of the department, the availability of plains, and the warm and humid climate facilitate access and operation, in addition to the proximity to the border with Venezuela, which can be of strategic interest. In the east, the mountainous areas and Andean valleys with good road access and electrical networks are favourable. The central-western area, with important urban centres such as Ocaña and Pamplona, offers good infrastructure. However, in the southeast and southwest, the mountainous geography and cold climate, along with less developed infrastructure, present logistical challenges that could complicate the installation and operation of the plant.

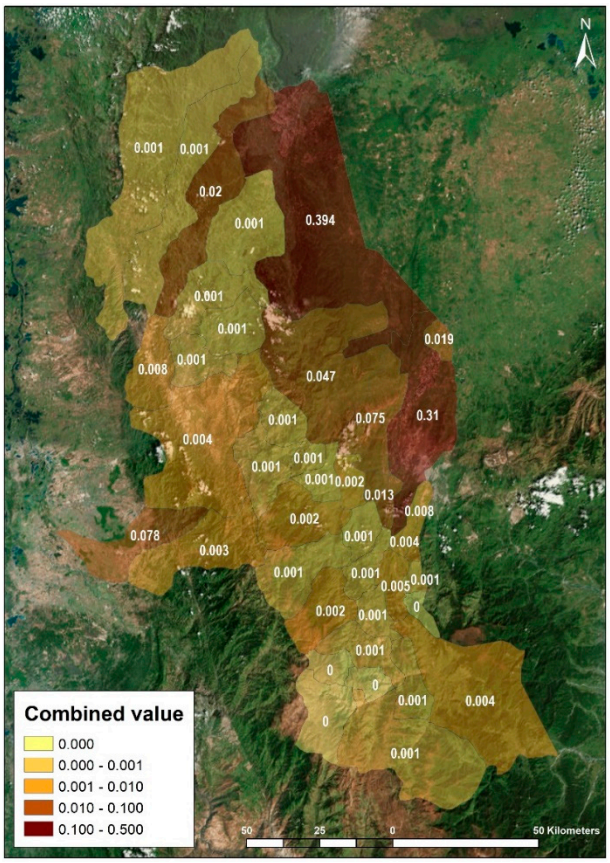


Figure 4. Biogas production potential map of Norte de Santander based on GIS weighted overlay. Variables: substrate density (POME, RS, PM). Output: suitability index (0–1 scale) indicating optimal zones for biogas plant siting.

Based on this, the northeastern zone of the Norte de Santander department can be considered ideal for the installation of a biogas plant due to its high substrate availability and favourable geographical characteristics, as well as good road connectivity and access to power grids, which optimize both the collection of raw materials and the distribution of biogas, ensuring efficient and profitable operation. These characteristics must be carefully considered to maximize the viability and efficiency of the project.

In this study, and more broadly, the use of GIS tools provides significant advantages in identifying strategic areas for projects such as the establishment of biorefineries, taking into account factors such as resource availability, proximity to population centres, and accessibility [54]. Additionally, GIS facilitates the creation of clear and visually interpretable cartography, enabling the effective analysis of predefined patterns. This not only optimizes decision-making in site selection, but also supports the development of business and policy strategies aimed at promoting renewable energy [55]. By offering a robust foundation for planning, GIS empowers companies and public administrations to design sustainable and efficient projects.

4. Conclusions

This study demonstrated that the anaerobic co-digestion of palm oil mill effluent (POME), rice straw, and pig manure can produce high methane yields (up to 412 mL CH_4/g VS), particularly when C:N ratios are balanced between 15 and 20. The use of GIS tools allowed for the identification of optimal locations for biogas plant installation based on the spatial availability of substrates in Norte de Santander, Colombia. This combined approach

supports efficient biomass resource allocation and territorial planning for renewable energy deployment.

While anaerobic digestion offers environmental benefits, potential negative impacts such as greenhouse gas leaks, nutrient leaching from digestate, and land use conflicts must be considered. Future systems should incorporate digestate valorization strategies, closed-loop nutrient recovery, and strict process control to mitigate these risks.

Future research should address the integration of techno-economic assessments and life cycle impacts, as well as the inclusion of industrial waste streams to enhance co-digestion potential. There is also a need for stakeholder engagement studies and policy simulations to ensure the practical feasibility and social acceptance of biogas systems.

In conclusion, the key contribution of this research lies in its integration of experimental anaerobic digestion performance with geospatial modelling tools to support sustainable energy planning in agricultural territories. This interdisciplinary approach offers a replicable framework to inform circular bioeconomy strategies in Colombia and beyond.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/pr13072013/s1, Table S1: Number of hectares of rice straw and palm oil and pigs per municipality in "Norte de Santander" department; Figure S1: Biomethane (blue bars) total production from the anaerobic co-digestion of POME (Palm oil mill effluent), PM (Pig manure) and RS (Rice straw), and the methane concentration obtained (circles) in each experiment; Figure S2: Biomethane production per amount of volatile solid of each mono-digestion and co-digestion test. Substrates used: POME (Palm oil mill effluent), PM (Pig manure) and RS (Rize straw). Gompertz modelling.

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