Evaluation of the potential for bioenergy production from coyol fruit by anaerobic digestion

Evaluación del potencial de producción de bioenergía a partir del fruto de coyol por digestión anaerobia

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This research contributes to the field of renewable bioenergy by demonstrating the potential of coyol fruit (*Acrocomia aculeata*) as a feedstock for biogas production by anaerobic digestion. It provides data on the efficiency of different components (peel, pulp and seed) and their combinations, highlighting the importance of C/N ratio and volatile solids (VS) content in optimising methane production. This study suggests co-digestion strategies and the use of pre-treatments to improve the biodegradability of lignocellulosic components. The research highlights the importance of characterising biomass components, understanding their C/N ratios and the need for pre-treatments to maximise biogas production. These findings can be applied to other agricultural residues and promote the diversification of sustainable energy sources.

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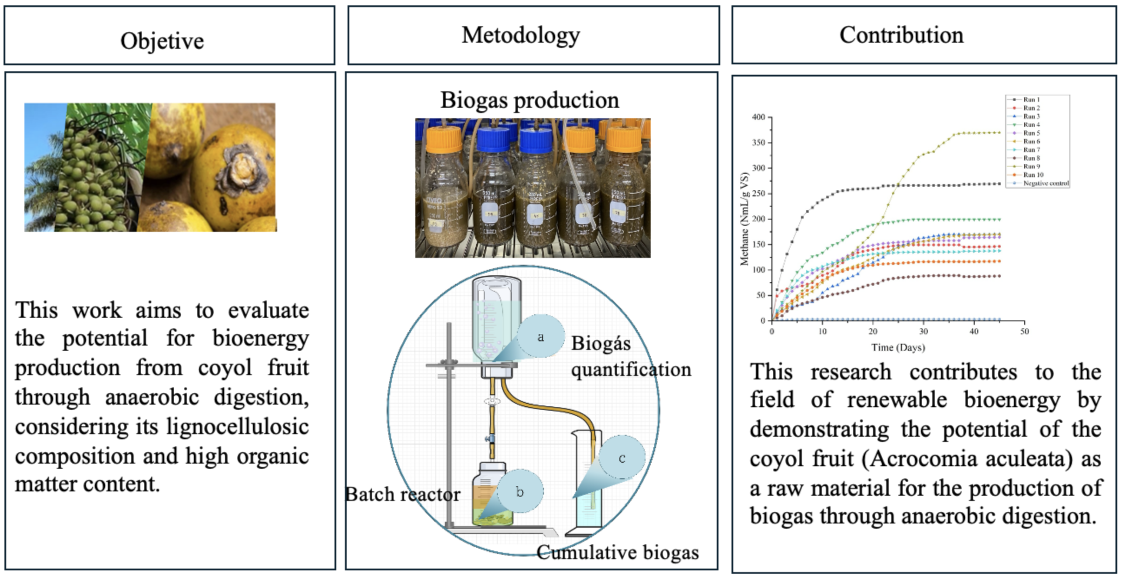
Abstract

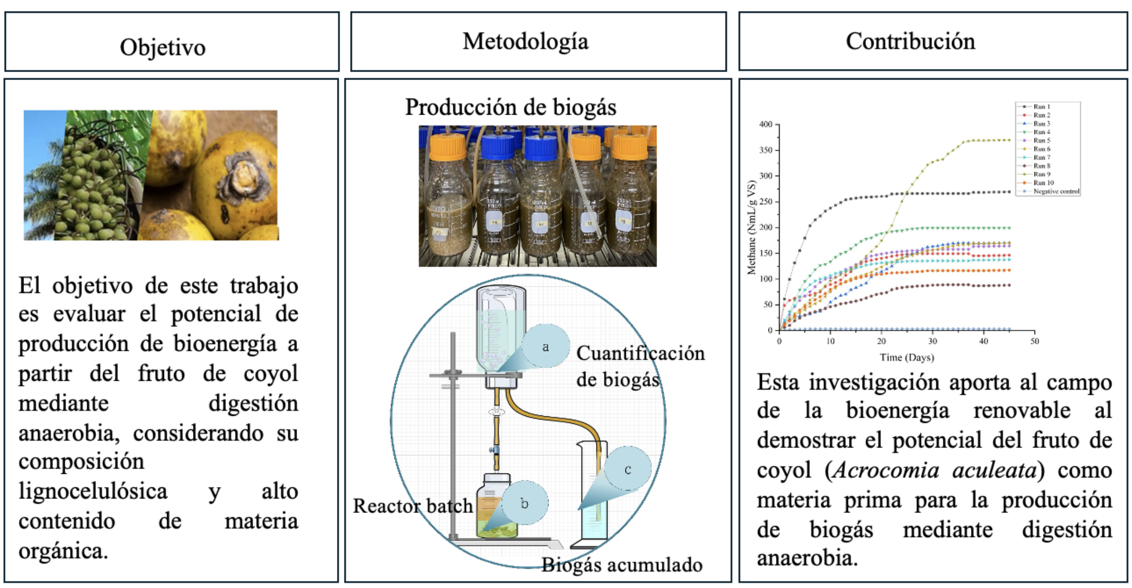
This study aimed to evaluate the biogas production potential from coyol fruit (Acrocomia aculeata) through anaerobic digestion. Combinations of peel, pulp and seed were used, processed in batch reactors with a constant mass of 5 g of volatile solids (SV). The tests were carried out at 37°C for 50 days, evaluating biomethane production. The results showed that run 9, composed of 66.67% peel, 16.67% pulp and 16.67% seed, achieved the highest methane production with 350 NmL/g VS, with the seed standing out as the most efficient component due to its high SV/ST ratio and a C/N of 24.40. Therefore, adequate proportions of the components maximize biogas production, and the use of pretreatments to improve peel degradation is suggested. These findings underscore the viability of coyol as a sustainable bioenergy source.



Anaerobic digestion, Bioenergy, Methane production, Lignocellulosic components, Sustainable energy

Resumen

El objetivo de este estudio fue evaluar el potencial de producción de biogás a partir del fruto de coyol (Acrocomia aculeata) mediante digestión anaerobia. Se utilizaron combinaciones de cáscara, pulpa y semilla, procesadas en reactores batch con una masa constante de 5 g de sólidos volátiles (SV). Las pruebas se realizaron a 37°C durante 50 días, evaluando la producción de biometano. Los resultados mostraron que la corrida 9, compuesta por 66.67% de cáscara, 16.67% de pulpa y 16.67% de semilla, alcanzó la mayor producción de metano con 350 NmL/g VS, destacando la semilla como el componente más eficiente por su alta relación SV/ST y una C/N de 24.40. Por lo tanto, proporciones adecuadas de los componentes maximizan la producción de biogás, y se sugiere el uso de pretratamientos para mejorar la degradación de la cáscara. Estos hallazgos subrayan la viabilidad del coyol como fuente de bioenergía sostenible.



Digestión anaerobia, Bioenergía, Producción de metano, Componentes lignocelulósicos, Energía sostenible

Introduction

Global dependence on fossil fuels has had significant impacts on both the environment and the global economy (Drosg et al., 2013; Patinvoh et al., 2017). In particular, the combustion of these resources has significantly increased greenhouse gas emissions, directly contributing to climate change, ocean acidification and air pollution (Abatzoglou & Boivin, 2009). Consequently, the search for sustainable and renewable alternatives has emerged as a key priority within global energy policies. In this context, bioenergy is positioned as a viable solution that not only promotes carbon footprint reduction, but also allows harnessing renewable resources efficiently (Horváth et al., 2016; Parsaee et al., 2019, Fang et al. 2024).

Among the various forms of bioenergy, biogas has gained prominence due to its ability to mitigate pollution while providing energy in a cost-effective and sustainable manner. This gas, derived from the anaerobic digestion of organic matter, is mainly composed of methane (CH_4) and carbon dioxide (CO_2), and is widely used to generate heat, electricity or as a vehicle fuel (Abatzoglou & Boivin, 2009; Castellanos-Sánchez et al., 2023; Hung et al., 2017). In contrast to fossil fuels, biogas production promotes a circular economy model by valorising organic waste, which reduces environmental impact and favours sustainable waste management (Hijazi et al., 2016; Sarker et al., 2019, Kwakye et al., 2024).

Furthermore, one of the main advantages of biogas is its low cost compared to other renewable energy sources. Anaerobic digestion plants can be designed to suit various scales, from domestic systems to large capacity industrial facilities. On the other hand, the use of agro-industrial waste as feedstock not only contributes to sustainability, but also fosters the development of rural communities by decreasing their dependence on non-renewable resources (Horváth et al., 2016; Matheri et al., 2017; Parsaee et al., 2019; Sarker et al., 2019).

In this framework, the coyol (*Acrocomia aculeata*) presents itself as a promising option for biogas production. This fruit, native to tropical and subtropical regions, is abundant in Mexico, where currently only a small fraction is used in the production of sweets and artisanal products, while a significant part remains underutilised (F. A. Aguilar-Aguilar et al., 2024; Balick, 1990, César et al., 2015, Magne et al. 2024)). Therefore, anaerobic digestion of coyol not only offers an avenue to harness this underutilised resource, but also contributes to efficient waste management and the development of sustainable circular economy models (Plath et al., 2016). These factors highlight the potential of coyol as an efficient and sustainable feedstock for bioenergy generation.

Objective

The present study aims to evaluate the potential of coyol fruit (*Acrocomia aculeata*) as a feedstock for bioenergy production through anaerobic digestion. This analysis focuses on its lignocellulosic composition and high organic matter content, characteristics that position it as a resource with high energy viability. In particular, the study seeks to demonstrate that coyol can become an efficient source for biogas production, highlighting its comparative advantage over other techniques and substrates used in this process. The central hypothesis postulates that anaerobic digestion of coyol will offer a competitive methane yield against other agricultural residues, thanks to its richness in carbohydrates and lipids, which promotes an efficient conversion of biomass into biogas.

Hypothesis

The main problem identified in this study is the wasteful use of underutilised plant resources with high energy potential. In this context, the transformation of coyol fruit (*Acrocomia aculeata*) into biogas represents a sustainable solution, as it allows the valorisation of a widely available resource while reducing the accumulation of organic waste in local communities. By addressing this challenge, the present work contributes significantly to the diversification of bioenergy sources, promoting an energy model based on sustainability. This approach aims to minimise dependence on fossil fuels and promote cleaner and more environmentally friendly energy development.

Methodology

Obtaining raw material

The coyol fruit (*Acrocomia aculeata*) used in this study was collected in the region of Copainalá, Chiapas. For the experiments, 5 kg of raw material was prepared and separated into its three main components: peel, pulp and seed. Each of these fractions was crushed using a hammer mill to reduce the particle size, which facilitated subsequent analyses and ensured the homogeneity of the material. Subsequently, the shredded material was stored at a controlled temperature of 4°C to preserve its physico-chemical properties before being used in the biochemical potential methane (PBM) tests.

The inoculum used in the anaerobic digestion experiments was obtained from an 8 m^3 capacity biodigester, regularly fed with bovine manure. This biodigester generates approximately 3.5 m^3 of biogas per day, with an average methane content of 60.5%. These conditions ensure the presence of an active and adequate microbial community to carry out the anaerobic digestion processes efficiently.

TS and TSS analysis

The analysis of total solids (TS) and volatile solids (VS) in coyol pulp, peel and seed was performed following the methodology described in the Standard Methods for the Examination of Water and Wastewater (2540 Solids), 22nd Edition, 2012, published by the American Public Health Association (APHA).

For each sample, approximately 2 grams of material were dried at 105°C to constant weight in order to determine the STs. Subsequently, the dried samples were incinerated at 550°C in a muffle furnace to measure the SVs, which represent the fraction of organic material present in the samples.

Total solids (TS) were calculated using the following equation [1]:

$$ST\ (\%) = \frac{\text{Weight of dry sample at 105°C (g)}}{\text{Weight of wet sample (g)}} x100 \quad [1]$$

Volatile solids (VS) were calculated using the following equation [2]:

$$SV\ (\%) = \frac{\text{Weight of the sample after 550°C (g)}}{\text{Weight of dry sample at 105°C (g)}} x100 \quad [2]$$

These formulae allow the quantification of total and volatile solids in each sample. The SVs provide an estimate of the organic fraction of the biomass that is available for biodegradation during the anaerobic digestion process.

TGA and DTG analysis

The characterisation of coyol (*Acrocomia aculeata*) fruit components - peel, pulp and seed - was performed by thermogravimetric analysis (TGA) and thermogravimetric derivative analysis (TGA) to evaluate their thermal stability and decomposition behaviour. The samples, previously crushed and dried, were pulverised and sieved to obtain a uniform particle size between 100 and 200 µm, ensuring the necessary homogeneity for the analyses (Ramírez-Estrada et al., 2022).

The experiments were carried out using thermogravimetric analysis equipment coupled to a thermogravimetric derivatization system, which allowed obtaining accurate data on mass loss and the different stages of thermal decomposition of each component. The temperature range used was from 25°C to 800°C, with a constant heating rate of 10°C/min, thus ensuring a uniform and controlled decomposition process. To prevent oxidation of the samples during the analysis, a nitrogen atmosphere with a constant flow rate of 50 mL/min was used. The results obtained were fundamental to identify the decomposition onset temperatures, thermal degradation stages and respective mass losses of the lignocellulosic components of the coyol. This information is key to understanding the thermal stability of the husk, pulp and seed, and contributes significantly to the assessment of their potential for energy applications. Furthermore, the findings support the optimisation of techniques for the use of coyol fruit in the production of bioproducts and biofuels, highlighting its versatility in energy conversion processes.

Elemental analysis

Elemental analysis was carried out to determine the carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) contents of the coyol fruit components: pulp, peel and seed. The main objective was to quantify the elemental composition of each fraction and to evaluate their suitability as substrates in anaerobic digestion processes. For this analysis, a CHNS/O elemental analyser (Thermos) was used, which guarantees accurate and reproducible measurements.

Approximately 2 mg of each sample were weighed and placed in tin capsules, which were combusted at 925°C in a pure oxygen environment, thus ensuring complete combustion of the materials. During this process, the elements present in the samples were transformed into gases: CO_2 (carbon), H_2O (hydrogen), NO_x (nitrogen) and SO_2 (sulphur). These gases were transported by a continuous flow of helium through specific chemical traps, and their concentrations were measured with a thermal conductivity detector.

To ensure the accuracy of the analysis, the instrument was calibrated using methionine as a standard reference material. The results obtained were reported as percentages based on the total mass of each sample, providing detailed information on the chemical characteristics of the pulp, peel and seed. This analysis is key to understand the behaviour of each component in the anaerobic digestion process and to optimise methane production by identifying suitable mixtures and treatments to maximise their bioenergy yield.

Batch reactors

To evaluate the impact of different proportions of coyol pulp, seed and peel on biogas production, a mixture-based experimental design was used. This approach allowed to analyse the behaviour of anaerobic digestion by varying the proportions of the three components, maintaining a constant total mass of 5 g volatile solids (VS) per reactor in batch trials (F. Aguilar-Aguilar et al., 2023a).

Ten different combinations of pulp, seed and peel were designed and carried out, as detailed in Table 1. In each experiment, the sum of the percentages of the components was always equal to 100%, ensuring consistency in the tests and validity of the results obtained. This experimental design made it possible to identify the optimal proportions of coyol components to maximise biogas production and to understand their influence on the efficiency of the anaerobic digestion process.

Box 1

Table 1

Experimental tests of biogas production using different combinations of coyol components

Trials	pulp (%)	Seed (%)	Mask (%)
1	1	0	0
2	0	100	0
3	0	0	100
4	50	50	0
5	50	0	50
6	0	50	50
7	66.67	16.67	16.67
8	16.67	66.67	16.67
9	16.67	16.67	66.67
10	33.33	33.33	33.33

Source: Own elaboration

The experiments were carried out in 250 mL glass bottles sealed with rubber stoppers, thus ensuring fully anaerobic conditions. These bottles were selected for their ability to maintain the experimental conditions and to facilitate both collection and quantification of the biogas produced. A total of 10 reactors were set up in batches, each containing a specific combination of coyol peel, pulp and seed, following the proportions set out in Table 1. The substrate-to-inoculum (S/I) ratio used was 1:1, with 5 g volatile solids (VS) of substrate or mixture and an equivalent amount of inoculum (F. Aguilar-Aguilar et al., 2023a).

Each reactor was inoculated with 18 mL of inoculum, equivalent to 5 g of SV, and substrates were added according to the defined proportions. To ensure adequate nutrient supply to the microbial consortia, a specific macro- and micronutrient solution was added to each reactor. Macronutrients added included NH_4Cl (1112.0 mg/L), $(NH_4)H_2PO_4$ (132.5 mg/L), $(NH_4)_2HPO_4$ (44.5 mg/L), $MgCl_2$-$6H_2O$ (250.0 mg/L), $CaCl_2$-$2H_2O$ (189.0 mg/L) and $NaHCO_3$ (2500.0 mg/L). Micronutrients added were $FeCl_3$-$6H_2O$ (5.0 mg/L), $ZnCl_2$ (0.13 mg/L), $MnCl_2$-$4H_2O$ (1.25 mg/L), $(NH_4)_6Mo_7O_{24}$-$4H_2O$ (1.6 mg/L), $AlCl_3$-$6H_2O$ (0. 13 mg/L), $CoCl_2$-$6H_2O$ (5.0 mg/L), $NiCl_2$-$6H_2O$ (13.0 mg/L), H_3BO_3 (3.0 mg/L), $CuCl_2$-$2H_2O$ (8.0 mg/L) and HCl (1.0 mg/L) (F. Aguilar-Aguilar et al., 2023b).

To ensure a fully anaerobic environment, air was removed from the headspace of the reactors using a 60 mL syringe. The reactors were maintained at a controlled temperature of 37 ± 3°C in a Memmert oven (model D91126) and incubated for a period of 50 days, or until biogas production stopped. The initial pH of the reactors was adjusted to 7.5 using a 40 g/L buffer solution, ensuring that it remained within the optimal range of 6.5 to 7.5 for anaerobic digestion processes.

Biogas quantification

The biogas volume measurement system used in this study was an adaptation of the method described by Aguilar-Aguilar et al. (F. Aguilar-Aguilar et al., 2023a). This system consisted of an inverted 1000 mL flask (a), containing a 5% HCl solution. The function of this solution was to facilitate the quantification of the total biogas produced in each anaerobic reactor. The flask was modified with a lid that included two orifices: one for the inlet of the gas coming from the anaerobic reactor (b) and one for the outlet of the liquid displaced by the gas, which was collected in a graduated cylinder (c).

Measurements were carried out every 24 hours, starting from the first day of incubation, using the liquid displacement method. The volume of liquid displaced by the biogas was collected in a graduated cylinder, and this volume was converted to standard conditions of pressure and temperature (NmL) - 1 atm and 0°C - by applying the Ideal Gas Law. This approach allowed to obtain accurate and consistent measurements of the volume of biogas produced in the experimental trials.

Box 2

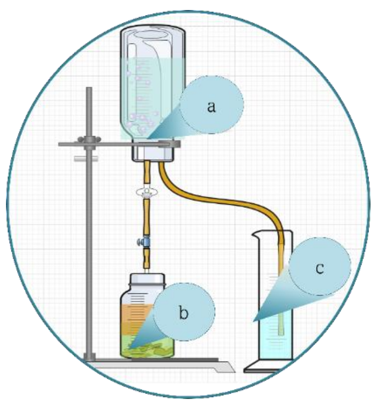


Figure 1

Schematic of the liquid displacement biogas measurement system. (a) 1000 mL inverted flask with 5% HCl solution, (b) anaerobic reactor where biogas is produced, (c) graduated cylinder for collection of the displaced liquid, used to calculate the volume of biogas produced

Source: Own elaboration

Results

Physicochemical characterisation of coyol

Anaerobic digestion occurs in four main stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Understanding the composition of the substrate is essential, as it significantly influences microbial metabolism and, consequently, the efficiency of biogas production. Physicochemical characterisation of coyol fruit peel, pulp and seed allows the assessment of critical parameters such as dry matter (DM), volatile solids (VS), VS/TS ratio, chemical oxygen demand (COD) and pH (Aworanti et al., 2023; Browne & Murphy, 2013; Codignole Luz et al., 2018).

Table 2 presents the physicochemical composition of coyol fruit components. All of them show a VS content higher than 85% with respect to TS, indicating a good potential for biogas production. Previous studies suggest that a VS/TS content above 50% in organic substrates is a positive indicator of high biodegradability, which favours their utilisation in anaerobic digestion (Labatut et al., 2011).

Of the three components, seed stands out with the highest VS/TS ratio (93.44%) and a COD of 233.1 g/kg, which makes it an excellent substrate for biogas production. However, its high protein and oil content may pose a risk of inhibition due to ammonia accumulation and excess oils. The pulp, with a VS/TS ratio of 91.85% and a COD of 183.4 g/kg, presents an adequate balance, with a high availability of sugars that facilitates conversion to methane during anaerobic digestion. On the other hand, the husk, although it has a lower VS/TS content (88.508%) and a COD of 147.2 g/kg, is rich in lignocellulosic material. This characteristic may limit its biodegradability under natural conditions; however, specific pre-treatments can enhance the release of fermentable sugars and increase its potential for biogas production (Sarker et al., 2019).

The carbon-to-nitrogen (C/N) ratio, presented in Table 3, is another key factor for anaerobic digestion, as it affects the nutritional balance necessary for efficient microbial activity. Coyol components show significant variability in this ratio. The shell has a very high C/N ratio (241.47), reflecting a high carbon and low nitrogen content, which could limit its biodegradability without the addition of complementary nitrogen sources. Pulp, with a C/N ratio of 62.67, presents a better balance, although it may require additional nutrient adjustments. Seed, on the other hand, has a C/N ratio of 24.40, which is within the optimal range of 20-30 for anaerobic digestion, positioning it as a promising main substrate for biogas production. These differences underline the need to employ appropriate blends or co-digestion with other materials to maximise the efficiency of the process (Drosg et al., 2013; Kafle et al., 2013; Obata et al., 2020).

Box 3

Table 2

Physicochemical composition of coyol fruit components

Components	ST (g/kg)	SS (g/kg)	SV/ST	DQO (g/kg)	Relation C/N
Peel	963.3	852.6	88.508	147.2	**241.47**
Pulp	957.0	879.0	91.85	183.4	62.67
Seed	981.5	917.1	93.439	233.1	24.40

ST: Total Solids, SV: Volatile Solids, COD: Chemical Oxygen Demand

Source: Own elaboration

Thermogravimetric Analysis

Thermogravimetric analysis (TGA) and thermogravimetric derivative (TGD) of the coyol fruit components - peel, pulp and seed - together with the inoculum, allowed to evaluate their thermal behaviour and stability during decomposition (Figure 2). The TGA plots show how the mass loss of the different components occurs in well-defined stages as the temperature increases up to 800°C.

The shell, depicted in Figure 2, exhibits a significant mass loss in the temperature range of 200°C to 350°C, mainly attributed to the decomposition of hemicellulose and cellulose. A second stage of loss, at temperatures above 500°C, is related to the degradation of more recalcitrant lignocellulosic compounds (Apaydın Varol & Mutlu, 2023; Burhenne et al., 2013).

Pulp, on the other hand, exhibits similar behaviour, although its initial mass loss occurs at slightly lower temperatures, indicating a higher proportion of volatile compounds and easily degradable sugars. This is consistent with its composition rich in simple carbohydrates and its lower lignin content compared to the husk (Coura et al., 2023; Del Río et al., 2016).

In the case of the seed, the highest mass loss is observed in the initial stage (200°C to 350°C), reflecting a significant content of organic compounds such as oils and proteins, which are thermally more labile. A second stage of decomposition, between 450°C and 600°C, is attributed to the degradation of more resistant lipids and proteins (Alpandi et al., 2022; Berton et al., 2013).

On the other hand, the inoculum exhibits a more moderate and stable degradation curve, suggesting a complex composition of organic and microbial material that gradually decomposes over a wide temperature range. The DTG plots (Figure 2B) highlight more pronounced maximum degradation peaks for the seed compared to the shell and pulp, confirming its higher content of readily degradable organic compounds.

Comparatively, TGA and DTG results indicate that the seed has the highest energy potential due to its high organic matter content and its rapid decomposition in the early stages of heating. The shell, with high thermal stability and higher resistance to decomposition, may require pre-treatments to improve its biodegradability. Pulp, on the other hand, shows a balance between thermal stability and decomposition, which makes it suitable for anaerobic digestion processes without significant modifications.

Box 4

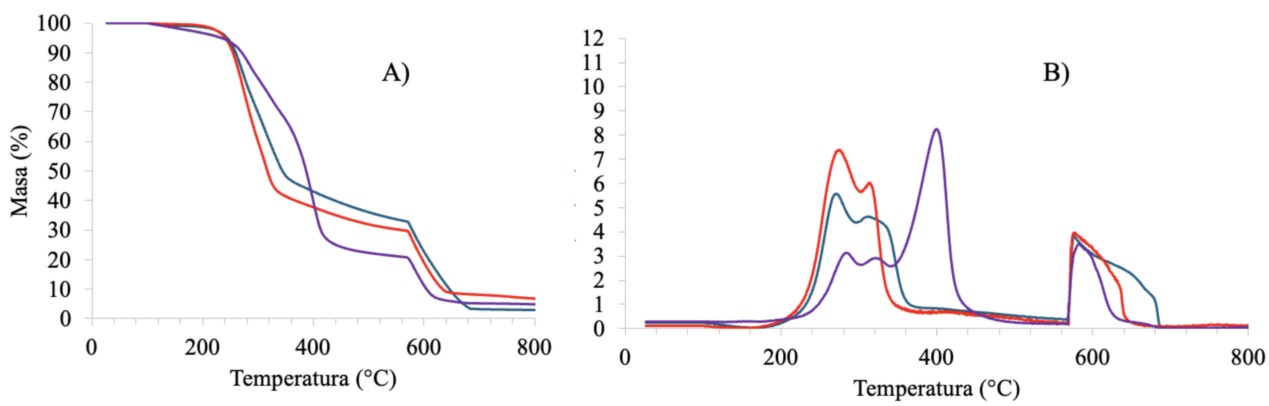


Figure 2
Analysis of A) TGA and B) DTG of coyol and inoculum components used as feedstock for biogas production
Source: *Own elaboration*

Biomethane production kinetics

The kinetics of biomethane production observed in the different experimental trials reveals a significant variation in methane yield, influenced by the proportions of the coyol fruit components (peel, pulp and seed). According to the graph presented, the trial corresponding to run 9, consisting of a mixture of 16.66% pulp, 16.66% seed and 66.66% peel, achieved the highest cumulative methane yield, approximately 350 NmL/g VS (Figure 3). This result indicates that the specific combination of these components favours an optimal environment for methanogenic microbial activity, possibly due to a proper nutrient balance and a favourable C/N ratio (Cazaudehore et al., 2022; Obata et al., 2020).

In contrast, run 1 (Figure 3), composed of 100% mesocarp (pulp), showed a rapid initial behaviour in biomethane production, stabilising at around 250 NmL/g VS. This suggests that, although the pulp contains readily biodegradable sugars, it may lack other essential nutrients to sustain prolonged methane production without the addition of complementary components.

The trials corresponding to runs 3, 5 and 7 showed more moderate yields of around 150-200 NmL/g VS. This yield can be attributed to the predominant lignocellulosic content in the epicarp (peel), which requires more time and, in some cases, pre-treatment to achieve complete biodegradation. These results are consistent with the high lignocellulosic composition and high C/N ratio of the peel, factors that limit its direct conversion to biomethane (Brayan Alexis et al., 2015; Morais et al., 2021).

Co-digestion with other nitrogen-rich waste sources could balance the C/N ratio in mixtures with high peel content, further enhancing methane production and avoiding possible inhibitions (Su et al., 2024). The negative control showed no methane production, confirming the absence of significant biological activity under substrate-free conditions. These findings highlight the importance of specific ratios of coyol components to optimise biomethane production, as well as the potential benefit of combining nutrient-rich components with those of high biodegradability.

Box 5

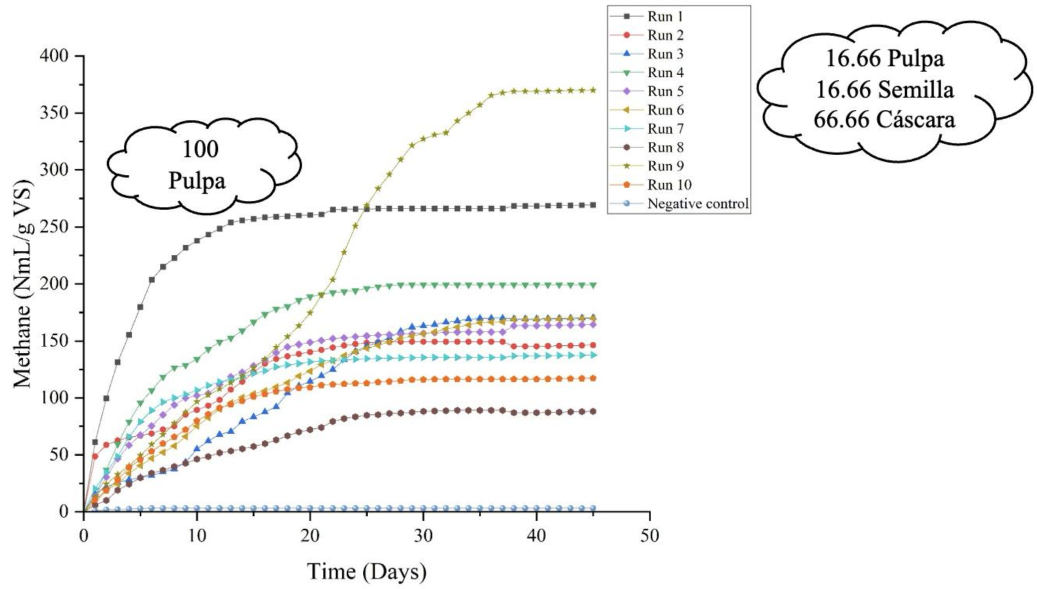


Figure 3
Kinetics of biomethane production from the mixture of coyol components

Source: *Own elaboration*

Energy recovered

The energy recovered from the different experimental runs showed significant variations, directly related to the proportions of pulp, seed and husk used in each mixture (Table 3). The values of total energy and energy in the form of methane (measured in megajoules, MJ) show the potential of each substrate for biogas production and its application as a renewable energy source.

Among the most outstanding results, run 9 presented the highest energy yield, with a total energy of 32,449.08 MJ, of which 18,637.46 MJ were recovered as methane. This run used a mixture composed mostly of husk (66.67%) and smaller proportions of pulp and seed (16.67% each) (Table 3). This result is particularly relevant from an industrial point of view, where maximising energy yield is a priority (Castellanos-Sánchez et al., 2023; Patinvoh et al., 2017).

In contrast, run 1, which used 100% pulp, managed to recover 25,108.42 MJ of total energy, of which 13,558.55 MJ corresponded to energy in the form of methane (Table 3). Although its yield was lower compared to run 9, the results highlight the contribution of readily biodegradable carbohydrates from the pulp in the anaerobic digestion process.

In practical terms, the energy recovered in these runs has great potential for applications such as heating, electricity generation or as fuel for gas-fuelled internal combustion engines (Abatzoglou & Boivin, 2009; Baena-Moreno et al., 2019; Castellanos-Sánchez et al., 2023). For example, the 18,637.46 MJ of methane generated in run 9 is equivalent to approximately 517 litres of gasoline, considering that 1 litre of gasoline produces about 36 MJ of energy. Similarly, this amount of energy could substitute the use of firewood in rural communities; given that 1 kilogram of firewood produces about 15 MJ of energy, the 18,637.46 MJ would be equivalent to about 1,242 kg of firewood (Abatzoglou & Boivin, 2009; Patinvoh et al., 2017; Torrijos, 2016).

These results highlight the potential of coyol fruit as a feedstock for renewable energy production, contributing to both energy transition and sustainable development in rural and industrial areas. For future research, it is recommended to explore multi-criteria analysis strategies to optimise biogas production and improve the sustainability of the processes (Liu et al., 2024).

Box 6

Table 3
Substrate composition and energy recovered in the different experimental runs

Race	pulp (%)	Seed (%)	Mask (%)	Biogas (MJ/ton)	Biomethane (MJ/Ton)
1	1	0	0	25108.42	13558.55
2	0	1	0	12838.58	7335.97
3	0	0	1	14560.00	8556.91
4	0.5	0.5	0	18988.67	10065.89
5	0.5	0	0.5	13907.83	8248.74
6	0	0.5	0.5	14355.25	8525.58
7	0.67	0.17	0.17	15341.08	6911.16
8	0.17	0.67	0.17	6552.00	4396.39
9	0.17	0.17	0.67	32449.08	18637.46
10	0.33	0.33	0.33	13111.58	5877.92

Source: Own elaboration

Conclusions

The present study confirmed that coyol fruit (*Acrocomia aculeata*) has significant potential for biogas production by anaerobic digestion. In particular, run 9 stood out as the highest yielding run, reaching approximately 350 NmL/g VS of accumulated methane. This mixture, composed of 66.67% husk, 16.67% pulp and 16.67% seed, showed that a proper balance between components with different C/N ratios and volatile solids (VS) contents is essential to optimise biomethane production. Seed, with its high SV/TS ratio (93.44%) and a C/N ratio close to the optimal range (24.40), proved to be a promising main substrate.

This work contributes to the knowledge on renewable bioenergy by validating the use of coyol as a feedstock for biogas production, positioning it as a viable alternative to diversify sustainable energy sources. Furthermore, the results underline the importance of selecting specific combinations of coyol components to maximise bioenergy yield and improve the efficiency of anaerobic digestion processes.
For future research, it is recommended to explore the use of pre-treatments aimed at improving the biodegradability of the peel, due to its high lignocellulosic content. In addition, co-digestion with nitrogen-rich residues could balance the C/N ratio in mixtures with high husk content, enhancing methane production and minimising inhibition risks. The implementation of these adjustments will allow process optimisation and broaden the industrial applications of anaerobic digestion using coyol feedstock.

Declarations

Conflict of interest

The authors declare that they have no conflicts of interest. They have no financial interests or personal relationships that could have influenced this book.

Authors' contribution

Fidel A. Aguilar-Aguilar: Contributed to the conceptualisation and design of the study, development of the methodology, analysis of the data and drafting of the manuscript.

Violeta Y. Mena-Cervantes: Participated in the supervision of the project, critical analysis of the results and revision of the manuscript.

Alejandro Ramírez-Estrada: Collaborated in the performance of the laboratory experiments and in the collection and processing of experimental data.

Raúl Hernández-Altamirano: Contributed to the technical analysis of the results, validation of the data and technical and academic review of the final document.

Availability of data and materials

The data and materials used in this study are available.

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Abbreviations

SV: Volatile Solids
ST: Total Solids
C/N: Carbon/Nitrogen Ratio
COD: Chemical Oxygen Demand
TGA: Thermogravimetric Analysis
DTG: Thermogravimetric Derivative
PBM: Biochemical Potential Methane
VS/ST: Ratio of Volatile Solids to Total Solids
NmL: Normalised Millilitres

References

Antedecents

Abatzoglou, N., & Boivin, S. (2009). A review of biogas purification processes. In Biofuels, Bioproducts and Biorefining (Vol. 3, Issue 1, pp. 42-71).

Aguilar-Aguilar, F. A., Mena Cervantes, V. Y., García-Solares, S. M., & Hernández Altamirano, R. (2024). Exploring the Biorefinery Potential of Acrocomia aculeata: A Native Mexican Palm for Sustainable Resource Valorization. Waste and Biomass Valorization.

Aguilar-Aguilar, F., Adaya, L., Godoy-Lozano, E. E., Pantoja, L. A., dos Santos, A. S., Eapen, D., & Sebastian, P. J. (2023a). Anaerobic co-digestion of raw glycerol and swine manure: microbial communities. Biomass Conversion and Biorefinery, 13(8), 7127-7138.

Aguilar-Aguilar, F., Adaya, L., Godoy-Lozano, E. E., Pantoja, L. A., dos Santos, A. S., Eapen, D., & Sebastian, P. J. (2023b). Anaerobic co-digestion of raw glycerol and swine manure: microbial communities. Biomass Conversion and Biorefinery, 13(8), 7127-7138.

Alpandi, A. H., Husin, H., Sidek, A., & Abdurrahman, M. (2022). Characterization of Malaysian Jatropha Seed Oil and Discovering the Process of Powdered Jatropha Leaves. Processes, 10(12).

Apaydın Varol, E., & Mutlu, Ü. (2023). TGA-FTIR Analysis of Biomass Samples Based on the Thermal Decomposition Behavior of Hemicellulose, Cellulose, and Lignin. Energies, 16(9).

Aworanti, O. A., Ajani, A. O., Agbede, O. O., Agarry, S. E., Ogunkunle, O., Laseinde, O. T., Kalam, M. A., & Fattah, I. M. R. (2023). Enhancing and upgrading biogas and biomethane production in anaerobic digestion: a comprehensive review. In Frontiers in Energy Research (Vol. 11). Frontiers Media SA.

Baena-Moreno, F. M., Rodríguez-Galán, M., Vega, F., Vilches, L. F., & Navarrete, B. (2019). Review: recent advances in biogas purifying technologies. In International Journal of Green Energy (Vol. 16, Issue 5, pp. 401-412). Taylor and Francis Inc.

Balick, M.J. Production of coyol wine fromAcrocomia*mexicana* (Arecaceae) in Honduras. *Econ Bot* **44**, 84-93 (1990).

Berton, L. H. C., de Azevedo Filho, J. A., Siqueira, W. J., & Colombo, C. A. (2013). Seed germination and estimates of genetic parameters of promising macaw palm (*Acrocomia aculeata*) progenies for biofuel production. Industrial Crops and Products, 51, 258-266.

Brayan Alexis, P.-O., Patricia, T.-L., Luis Fernando, M.-R., Lina Marcela, C.-C., Carlos, V.-F., Wilmar Alexander, T.-L., & José Abdón, O.-A. (2015). Effect of Substrate-Inoculum Ratio on the Biochemical Methane Potential of Municipal Biowastes. Engineering Research and Technology, 1(4), 515-526.

César, A. D. S. S., Almeida, F. D. A., De Souza, R. P., Silva, G. C., & Atabani, A. E. (2015). The prospects of using Acrocomia aculeata (macaúba) a non-edible biodiesel feedstock in Brazil. In Renewable and Sustainable Energy Reviews (Vol. 49, pp. 1213-1220). Elsevier Ltd.

Drosg, B., Braun, R., Bochmann, G., & Al Saedi, T. (2013). Analysis and characterization of biogas feedstocks. The Biogas Handbook: Science, Production and Applications, 52-84.

Horváth, I. S., Tabatabaei, M., Karimi, K., & Kumar, R. (2016). Recent updates on biogas production - A review. In Biofuel Research Journal (Vol. 3, Issue 2, pp. 394-402). Green Wave Publishing of Canada.

Matheri, A. N., Ndiweni, S. N., Belaid, M., Muzenda, E., & Hubert, R. (2017). Optimising biogas production from anaerobic co-digestion of chicken manure and organic fraction of municipal solid waste. Renewable and Sustainable Energy Reviews, 80, 756-764.

Parsaee, M., Kiani Deh Kiani, M., & Karimi, K. (2019). A review of biogas production from sugarcane vinasse. In Biomass and Bioenergy (Vol. 122, pp. 117-125). Elsevier Ltd.

Patinvoh, R. J., Osadolor, O. A., Chandolias, K., Sárvári Horváth, I., & Taherzadeh, M. J. (2017). Innovative pretreatment strategies for biogas production. In Bioresource Technology (Vol. 224, pp. 13-24). Elsevier Ltd.

Plath, M., Moser, C., Bailis, R., Brandt, P., Hirsch, H., Klein, A. M., Walmsley, D., & von Wehrden, H. (2016). A novel bioenergy feedstock in Latin America? Cultivation potential of Acrocomia aculeata under current and future climate conditions. Biomass and Bioenergy, 91, 186-195.

Sarker, S., Lamb, J. J., Hjelme, D. R., & Lien, K. M. (2019). A review of the role of critical parameters in the design and operation of biogas production plants. In Applied Sciences (Switzerland) (Vol. 9, Issue 9). MDPI AG.

Kwakye, J. M., Ekechukwu, D. E., & Ogundipe, O. B. (2024). Systematic review of the economic impacts of bioenergy on agricultural markets. International Journal of Advanced Economics, 6(7), 306-318.

Fang, Y. R., Hossain, M. S., Peng, S., Han, L., & Yang, P. (2024). Sustainable energy development of crop straw in five southern provinces of China: Bioenergy production, land, and water saving potential. Renewable Energy, 224, 120134.

Magne, A., Khatiwada, D., & Cardozo, E. (2024). Assessing the bioenergy potential in SouthAmerica: Projections for 2050. Energy for Sustainable Development, 82, 101535.

Basic

Aguilar-Aguilar, F. A., Mena Cervantes, V. Y., García-Solares, S. M., & Hernández Altamirano, R. (2024). Exploring the Biorefinery Potential of Acrocomia aculeata: A Native Mexican Palm for Sustainable Resource Valorization. Waste and Biomass Valorization.

Aguilar-Aguilar, F., Adaya, L., Godoy-Lozano, E. E., Pantoja, L. A., dos Santos, A. S., Eapen, D., & Sebastian, P. J. (2023a). Anaerobic co-digestion of raw glycerol and swine manure: microbial communities. Biomass Conversion and Biorefinery, 13(8), 7127-7138.

Aguilar-Aguilar, F., Adaya, L., Godoy-Lozano, E. E., Pantoja, L. A., dos Santos, A. S., Eapen, D., & Sebastian, P. J. (2023b). Anaerobic co-digestion of raw glycerol and swine manure: microbial communities. Biomass Conversion and Biorefinery, 13(8), 7127-7138.

Ramírez-Estrada, A., Mena-Cervantes, V. Y., Mederos-Nieto, F. S., Pineda-Flores, G., & Hernández-Altamirano, R. (2022). Assessment and classification of lignocellulosic biomass recalcitrance by principal components analysis based on thermogravimetry and infrared spectroscopy. International Journal of Environmental Science and Technology, 19(4), 2529-2544.